# Arithmetic Processing in Children with Dyscalculia: an Event-Related Potential Study

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## ABSTRACT

**Introduction.** Dyscalculia is a specific learning disorder that affects a person's ability to learn certain mathematical processes. Children with dyscalculia are a heterogeneous group, in part due to variability in their working memory. In this study, we used both behavioural responses and event-related potentials (ERPs) to explore arithmetic processing in children with dyscalculia (DYS), and determine if this was correlated with working memory.

**Materials & Methods.** The N400 and LPC ERPs were indexed in 22 children with DYS and 22 children with good academic performance (GAP) while they performed an addition verification task. ERPs were synchronized congruent and incongruent probes, and included only epochs with correct answers. Accuracy and rate of behavioural responses were compared between groups using mixed ANOVAs, and ERP amplitudes were analysed using multivariate nonparametric permutation tests and correlation coefficients.

**Results.** The GAP group obtained more correct answers than the DYS group. An arithmetic N400 effect was observed in the GAP group but not in the DYS group. Both groups displayed an LPC effect. The larger the LPC amplitude was, the higher the working memory index. Two subgroups were found within the DYS group: one with an average WM index and the other with a lower than average WM index. These subgroups displayed different ERPs patterns.

**Discussion.** The results indicated that the group of children with dyscalculia was very heterogeneous and therefore failed to show a robust LPC effect. Some of these children had WM deficits. When WM deficits were considered together with dyscalculia, an atypical ERP pattern that reflected their processing difficulties emerged. Their lack of the arithmetic N400 effect

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**Deleted:** To assess the brain response to arithmetic data recovery, we applied an arithmetic verification task during an event-related potential (ERP) recording. Two effects have been reported: the N400 effect (higher negative amplitude for incongruent than for congruent condition), associated with arithmetic incongruency and caused by the arithmetic priming effect, and the LPC effect (higher positive amplitude for the incongruent compared to the congruent condition), associated with a reevaluation process and modulated by the plausibility of the presented condition.¶
This study aimed

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**Conclusion.** Given that dyscalculia is a very heterogeneous deficit, studies examining dyscalculia should consider exploring deficits in WM because the whole group of children with dyscalculia seems to contain at least two subpopulations that differ in their calculation process.

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## 1. Introduction

According to the Diagnostic and Statistical Manual of Mental Disorders, 5th Edition (DSM-5), dyscalculia refers to difficulties with number sense, number facts, and calculation (i.e., having a poor understanding of numbers, their magnitudes and relationships, counting on fingers to add single-digit numbers instead of recalling math facts as peers do, becoming lost in the midst of arithmetic computation, and switching procedures). The academic skills of children with dyscalculia are substantially below those expected for their chronological age, which can have a significant impact on their daily lives. Dyscalculia is not better accounted for by intellectual disabilities, uncorrected visual or auditory acuity, other mental or neurological disorders, psychosocial adversity, lack of proficiency in the language of academic instruction, or inadequate educational instruction (American Psychiatric Association, 2013).

~~Mental disorders are heterogeneous at many levels, ranging from genetic risk factors to symptoms (American Psychiatric Association, 2013), and dyscalculia is not an exception. This, added to the varying degrees of severity of the disorder, provides an idea of the high levels of heterogeneity that exist within the group of individuals with dyscalculia.~~ Many studies have reported that children with dyscalculia could also have deficits in working memory (WM) (Berninger, 2008; Geary et al., 1999; Hitch & McAuley, 1991; Mabbott & Bisanz, 2008; Mammarella et al., 2017; Rotzer et al., 2009; Schuchardt et al., 2008; Shen et al., 2018; Swanson & Siegel, 2001). The WM system provides online storage of information and its subsequent manipulation through four subsystems: the phonological loop, the visuospatial sketch, the episodic buffer, and the central executive (Baddeley, 2000). In terms of mathematics, the phonological loop holds arithmetic results in form of linguistic information, and hence plays a role in mathematical abilities that involve the articulation of numbers, such as counting and

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arithmetic fact retrieval (Geary, 1993; Shen et al., 2018). The visuospatial sketch supports the construction of visual representations of numerical information, and so is related to spatial aspects of calculation, such as decomposition strategies (Foley et al., 2017; Simms et al., 2016). The episodic buffer provides temporary storage that links information from the two slave subsystems and long-term memory, and hence may support multicode number representations (Camos, 2018). Finally, the central executive coordinates and monitors simultaneous processing and keeps track of math tasks that have already been performed (DeStefano and LeFrevre, 2004; Fuchs et al., 2005; Holmes & Adams, 2004).

Numerous studies have found that children with dyscalculia have difficulties with at least one fo the four subsystems of working memory: XXX Therefore, children with dyscalculia have difficulty in verbal short-term memory and verbal WM (Attout & Majerus, 2015; Peng & Fuchs, 2016; Shen et al., 2018), visuospatial short-term memory and visuospatial WM (McDonald & Berg, 2018; Mammarella et al., 2017; Rotzer et al., 2009; Schuchardt et al., 2008), the central executive (Meyer et al., 2010), and processing speed (Geary et al., 1999; Landerl et al., 2004; Shalev et al., 2005). Moreover, in a meta-analysis that included 36 studies, Szűcs (2016) concluded that within the group of children with dyscalculia, there were two different subgroups; curiously, their differences consisted in aspects related to WM.

When the causal relationship between WM and arithmetic skills has been explored, three subsystems of WM have shown a predictive role for learning arithmetic; however, this prediction seems to depend on school grade. At preschool ages, visuospatial WM skills have been used to predict symbolic numerical skills (Gashaj et al., 2019), while De Smedt et al. (2009) were successful on observing differences between the prediction of arithmetic skills that the visuospatial sketchpad and the phonological loop yielded at only one year of follow-

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up, from first to second grade. At these same ages, Swanson and Beebe-Frankenberger (2004) found that central executive ability predicted mathematics skills. When the follow-up lasted more years, as in the longitudinal study from preschool to sixth grade carried out by Träff et al. (2020), all the components have a predictive capacity; these authors found that low verbal arithmetic, logical reasoning and spatial processing skills constitute risk factors for low mathematical abilities.

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Although the precise associations between WM and mathematical abilities are very complex, it seems that WM scores are distributed along a continuum with children with typical development reaching maximum scores and children with dyscalculia achieving low scores (Mammarella et al., 2017), which suggests a high variability between individuals.

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Behavioral performance (accuracy and response time) in arithmetic tasks depends on individual characteristics, which include age (De Smedt et al., 2009; Geary & Wiley, 1991; Geary et al., 1992), gender (Fennema et al., 1998; Geary et al., 2000), school grade (Geary, 2004; Imbo & Vandierendock, 2008), arithmetic ability (Cipora & Nuerk, 2013; LeFevre & Kulak, 1994; Núñez-Peña & Suárez-Pellicioni, 2012), daily practice (Imbo et al., 2007), and cultural knowledge (Campbell & Xue, 2001). More correct answers and a lower response time are observed in older children than in young children (Imbo & Vandierendock, 2008) and in young adults than in children (Prieto-Corona et al., 2010; Van Beek et al., 2014; Zhou et al., 2011). Additionally, children with typical development have fewer errors and are faster than children with arithmetic difficulties (Geary, 1993; Geary et al., 1992; 1999).

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Behavioral performance also depends on the task features. In an arithmetic verification task, in which the arithmetic operation (context) is followed by a possible solution (probe) that may or may not match the correct result of the operation, the priming phenomenon is manifested as a shorter response time when there is facilitation provided by the context; i.e., when the probe digit coincides with the result of the proposed arithmetic operation (congruent solution). An explanation for this phenomenon has been offered by those who claim that the congruent solution is more quickly recovered from memory (Niedeggen & Rösler, 1999; Niedeggen et al., 1999). This implies that to give a correct answer, the child needs not only to perform adequate arithmetic processing (to choose the correct probe) but also adequately maintain the result in verbal WM via the verbal short-term memory, which leads to facilitation.

All previously mentioned studies have used behavioral variables to draw their conclusions. Without downplaying the relevance of behavioral studies, we assessed event-related potentials (ERPs) during the performance of an arithmetic verification task in this study. ERPs occur in the range of milliseconds, permitting the chronologic analysis of the different cognitive processes. ERPs allow us to find or highlight mechanisms that behavioral measures fail to detect; therefore, it may be possible to increase the body of knowledge about dyscalculia by comparing children with dyscalculia with children who have typical development.

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ERPs have aptly been used to study the processing of arithmetic. Studies in healthy young adults where arithmetic verification processing was evaluated using ERPs have reported a negative wave with greater amplitude in an incongruent condition (i.e., when there is no facilitation) than in a congruent condition (i.e., when there is facilitation) (Dong et al., 2007; El Yagoubi et al., 2003; Hinault & Lemaire, 2016; Prieto-Corona et al., 2010; Szűcs & Csépe, 2005). The difference in amplitude between N400 components elicited by incongruent and congruent conditions is known as the arithmetic N400 effect. It begins at approximately 250 ms (with a maximum peak close to 400 ms) over centroparietal brain regions and is caused by the arithmetic priming effect (Dickson

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& Federmeier, 2017; Hinault & Lemaire, 2016; Jost et al., 2004; Niedeggen et al., 1999; Niedeggen & Rösler, 1999; Prieto-Corona et al., 2010). The arithmetic N400 effect reflects facilitation of the probe stimulus that matches the correct result (Prieto-Corona et al., 2010). N400 is thought to involve automatic retrieval of arithmetic facts from long-term memory (Niedeggen & Rosler, 1999). If the automatic recovery of the correct results does not coincide with the incongruent prime, then additional inhibitory processes are required (Hinault & Lemaire, 2016). This explains why a higher latency is observed in the incongruent condition than in the congruent condition.

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Interestingly, temporal and topographic characteristics of the arithmetic N400 do not differ from those of the semantic N400, described originally by Kutas and Hillyard (1980), which has led us to think that semantic and arithmetic lexicons probably share the same mechanisms (Hinault & Lemaire, 2016; Niedeggen et al., 1999). Other researchers have called this effect, arithmetic mismatch negativity, because the expected and proposed solutions do not match (Hsu & Szűcs, 2011). Studies with different populations have indicated that the arithmetic N400 effect is modulated by arithmetic abilities. A greater arithmetic N400 effect was found in adults with better arithmetic abilities compared to adults with poorer arithmetic abilities (Núñez-Peña et al., 2011; Núñez-Peña & Suárez-Pellicioni, 2012; 2015; Thevenot et al., 2007) and in control teenagers compared to teenagers with dyscalculia (Soltész et al., 2007; Soltész & Szűcs, 2009). When children and adults were compared, both showed an arithmetic N400 effect, but no significant effect differences between groups were found, maybe because their topographical distributions were different (Prieto-Corona et al., 2010); however, in 8-year-old children, amplitudes were significantly larger than in 11-year-old children (Dong et al., 2007). Longer latencies of the arithmetic N400 effect have been found in children compared to adults (Prieto-Corona et al.,

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2010) and in younger compared to older children (Dong et al., 2007).

Another ERP component that has been observed in healthy adults and children during an arithmetic task is the late positive component (LPC), which follows the arithmetic N400 and appears between 500 and 700 ms. LPC has been observed with a parietal (Jasinski & Coch, 2012; Niedeggen & Rosler; Núñez-Peña & Suárez-Pellicioni, 2015; Xuan et al., 2007) or centroparietal (Núñez-Peña & Escera, 2007; Núñez-Peña & Suárez-Pellicioni, 2012; Prieto-Corona et al. 2010) topography, mainly over the right hemisphere (Jasinski & Coch, 2012; Niedeggen & Rösler, 1999; Niedeggen et al., 1999), and has shown a greater amplitude in problems with an incongruent condition than in problems with a congruent condition (Jost et al., 2004; Niedeggen et al., 1999; Núñez-Peña & Suárez-Pellicioni, 2012; Prieto-Corona et al., 2010; Szűcs & Csépe, 2005; Szűcs & Soltész, 2010). The difference in amplitude between LPC components elicited by incongruent and congruent conditions is known as the LPC effect (Prieto-Corona et al., 2010; Szűcs & Soltész, 2010). This effect is associated with processing reevaluation (Núñez-Peña & Suárez-Pellicioni, 2012; Prieto-Corona et al., 2010; Szűcs & Soltész, 2010), and its amplitude is modulated by the plausibility of the presented condition (Niedeggen & Rösler, 1999; Núñez-Peña & Escera, 2007; Núñez-Peña & Honrubia-Serrano, 2004; Núñez-Peña & Suárez-Pellicioni, 2015; Szűcs & Soltész, 2010). Some authors have assumed that the LPC effect reflects surprise due to an out-of-context stimulus (Donchin & Coles, 1997; Núñez-Peña & Suárez-Pellicioni, 2012; Polich, 2007). The LPC effect is greater in adults than in children (Zhou et al., 2011); and in individuals with better arithmetic abilities than in individuals with arithmetic deficits (Iguchi & Hashimoto, 2000; Núñez-Peña et al., 2011; Núñez-Peña & Honrubia-Serrano, 2004; Núñez-Peña & Suárez-Pellicioni, 2012; 2015; Szűcs & Soltész, 2010).

Shen et al. (2018) reported that better math achievement in children with typical development



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was related to better performance in a verbal WM task and a different ERP pattern. If differences in ERPs were found in two groups of children with typical development but different WM performance, it is reasonable to hypothesize that children with dyscalculia and WM deficits will have different electroencephalographic patterns than children with dyscalculia and without WM problems.

The first aim of the current study was to compare the arithmetic processing between children with dyscalculia and children with good academic performance using ERPs during an addition verification task. The second aim was to explore, among children with dyscalculia, the relationship between WM and ERPs. We hypothesised that compared to children with good academic achievement, children with dyscalculia will have (1) less accurate or slower behavioural responses on XXX; (2) smaller or later arithmetic N400 and LPC effects; and (3) poorer performance on working memory tests that is related to smaller N400 and LPC effects.

## 2. Methods

### 2.1 Ethics

Children and their parents gave their written informed consent to participate in this study. This research was carried out following the ethical principles of the Declaration of Helsinki. The Bioethics Committee of the Neurobiology Institute at the Universidad Nacional Autónoma de México approved the experimental protocol (Ref: 017-H-RM).

### 2.2 Participants

Forty-four right-handed children between 9 and 11 years old participated in this study. The participants were selected from a sample of 167 children from public and private elementary

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schools in Querétaro. After completing a semi-structured interview, 16 children were excluded due to low socioeconomic status (the mother had not completed elementary school and/or per capita income was less than 100% of the minimum wage; Harmony et al., 1990) and two more children were excluded due to presenting epilepsy. Six children with intellectual disability (i.e., IQ<70; according to the Spanish version of the Wechsler Intelligence Scale for Children, 4th Edition; Wechsler, 2007) were also excluded. MiniKid (2000) and neuropsychiatric explorations revealed that 52 children presented psychiatric disorders other than a learning disorder (mainly ADHD, behavior disorder, and/or oppositional defiant disorder) and two children suffered uncorrected hypoacusis so they were excluded as well.

The remaining 89 children completed the arithmetic subtest of the Child Neuropsychological Assessment (Matute et al., 2005), which has been standardized for the Mexican population. Its arithmetic domain consists of three subdomains (counting, number management, and calculus). Thirty participants who performed at or below the 9th percentile in at least one arithmetic subdomain were assigned to a group with dyscalculia (DYS) and the 28 participants at or above the 37th percentiles in all subdomains were assigned to a group with good academic performance (GAP). Of these children, XX and XX were later excluded due to poor ERP data, respectively (see the ERP section below). Thus, the DYS group was represented by data from 22 participants (11 female) and the GAP group also by 22 participants (14 female).

Figure 1 the demographics of the DYS and GAP groups, along with outcomes on the recruitment??? tests. The groups did not differ in age, gender ($\chi^2(1) = 0.834$, $p = 0.361$), or monthly family income per capita. The children with dyscalculia showed significantly lower scores on all the indices generated by the Wechsler Intelligence Scale for Children compared to those with good academic performance, except for the processing speed index. All participants

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had normal or corrected-to-normal visual acuity, and they did not present any history of neurological or psychiatric disorder. The children from both groups were selected from the same schools and therefore from the same educational environments.

**- Please insert Table 1 -**

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2.3 Stimuli

Each trial of the task started with a warning stimulus (a right-pointed arrow), which was followed by an addition operation with two single-digit operands (between 1 and 9). Each addition operation combined two Arabic digits using the plus sign (+), resulting in 81 addition operations. Every operation was presented once with the correct result (congruent condition) and another time with an incorrect result (incongruent condition). The incorrect result was constructed by either adding 2 to the correct result (for 41 facts) or by subtracting 2 from the correct result (for the remaining 40 facts).

2.4 Arithmetic verification task

Figure 2 illustrates the components of the task across time. In each of 162 trials, a white warning stimulus was presented at the center of a black screen presented for 200 ms, followed by a black screen that lasted 300 ms. A white addition operation symbol then appeared for 1500 ms, followed by another black screen for 1500 ms. Subsequently, a white number (probe stimulus) was presented for 1000 ms on a black screen, which either did or did not match the sum of the numbers (for congruent or incongruent trials, respectively). Finally, a black screen was presented for 500 ms.

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Half of the trials were congruent and half incongruent. Trials were randomized and delivered by Mind-Tracer 2.0 software (Neuronic Mexicana, S.A.; Mexico City, Mexico).

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## 2.5 Procedure

Children were seated in a comfortable chair 70 cm from the computer screen in a Faraday sound-attenuating-and-dimly-lit recording chamber. The experiment began after a training period to familiarize the children with the task, which comprised 16 trials with feedback. This was followed by 162 trials that were divided into four blocks (two with 40 trials and two with 41 trials). Blocks were separated by 1-minute rest periods.

All children were instructed to relax and maintain their gaze towards the center of the screen and to avoid blinking when the probe stimulus appeared; if they needed to blink, they should do it once the response was given, just before the warning stimulus. The children were instructed to respond as quickly and accurately as possible when the probe stimuli were presented. Half the children were instructed to press the mouse key with the right thumb if they thought the probe was correct (congruent condition) and with the left thumb if it was incorrect (incongruent condition); the other half of the children were instructed to do the opposite.

## 2.6 ERP Acquisition and analysis

Electroencephalograms (EEGs) were recorded using 19 Ag/AgCl electrodes (what were these??) held in position with a cap according to the 10-20 International System (Electro-Cap™ International, Inc.; Ohio, USA) paired with a MEDICID™ IV system (Neuronic S.A.; Mexico City, Mexico) and a Track Walker v5.0 data system. All electrodes were referenced to linked

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ERPs were computed offline using 1000-ms EEG epochs from each subject in each experimental condition. The epochs consisted of a baseline period that started 200 ms preceding the probe onset, and ended 800 ms after the probe onset. Baseline correction was performed using the 200-ms prestimulus period. An EEG epoch was reject if visual inspection revealed in blinking or ocular movements, electrical activity exceeding 100 microvolts, or amplifier blocking for more than 50 ms at any electrode site. Seven participants (three in the DYS group) had fewer than 20 artifact-free trials per condition, so these participants were excluded. Another seven children (5 in the DYS group) were also excluded because their correct answers were close to chance level (58%). The number of EEG epochs per condition was approximately equal per subject. On average, the DYS group had 33 and the GAP group had 39 artifact-free epochs for each condition. Accepted EEG epochs associated with correct responses were averaged together to produce one ERP for the congruent condition and one for the incongruent condition for each child. The former was subtracted from the latter (ie incongruent minus congruent) to produce one difference ERP per child.

### 2.7 Statistical Analysis

Statistical analyses of behavioral data were carried out with the statistical program SPSS (IBM Statistic 20, Chicago Illinois, USA). We conducted mixed 2-way ANOVAs for response times and for correct answers. The percentage of correct answers was transformed by arcsine [square root

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(percentage/100)] (Zar, 2010). Group (GAP, DYS) was included as the between-subjects factor, and Condition (congruent, incongruent) was included as the within-subjects factor. The least significant differences method was used for *post hoc* pairwise comparisons.

Statistical analyses for the ERP data used nonparametric tests with permutations (Luck, 2014) since there are a multiplicity of comparisons and dependent variables and, therefore, an increased probability of Type I error. Analyses were carried out using eLORETA software (Pascual-Marqui et al., 2011), which involved comparisons of difference-ERPs between Conditions and Groups. Five thousand permutations were performed. Global significance for the statistical test (i.e., significant p-value level considering all the electrodes and all-time points) was reported (T max and its p-value). Specific significant t-values over electrode sites are represented in color maps (only t-values with $p < 0.05$).

We also used eLORETA to perform two correlation analyses using a nonparametric permutation test for the arithmetic N400 and LPC data. In the DYS group, the WM index was correlated with the values of the amplitude differences between conditions (incongruent minus congruent) across all electrode sites. Five thousand permutations were performed. Global significance for the statistical test was reported (r max and its p-value). Specific significant correlations (rho) over electrode sites are represented in color maps (only r-values with $p < 0.05$). All statistical results for the ERPs are reported taking into consideration all 19 electrodes.

## 3. Results

### 3.1 Behavioral Results

The behavioral results are shown in Figure. 3. The participants in the GAP group showed a

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significantly higher percentage of correct answers than those in the DYS group ($F_{(1,42)} = 27.39$, $p < 0.0001$, $\eta_p^2 = 0.395$). Both groups displayed a significantly higher percentage of correct answers in the congruent condition than in the incongruent condition (main effect of Condition: $F_{(1,42)} = 8.67$, $p = 0.005$, $\eta_p^2 = 0.171$). There was no significant Group by Condition interaction ($F < 1$).

The responses for all children taken together were significantly faster in the congruent condition than in the incongruent condition ($F_{(1,42)} = 131.922$, $p < 0.0001$, $\eta_p^2 = 0.759$), but the response times were not significantly different between the groups ($F < 1$). No significant Group by Condition interaction ($F_{(1,42)} = 1.114$, $p = 0.297$, $\eta_p^2 = 0.026$) was observed. We explored if this was due to the large age-range of participants using Spearman Rank correlation analyses between reaction times and age within groups. In the GAP group, there was a significant negative correlation for congruent (r=-0.57, p=0.006) and incongruent (r=-0.60, p=0.003) conditions. This was not the case in the DYS group (congruent: r=-0.29, p=0.195; incongruent: r=-0.22, p=0.337).

**- Please insert Fig. 3 -**

3.2 Electrophysiological Results

The grand averages of the ERPs in T3 and C3 electrodes in the two task conditions for both groups are shown in Figure 5. Figure 4 illustrates XXX. We used nonparametric permutation tests considering all the electrodes and all time points to identify significant differences between conditions (congruent and incongruent) in each group separately. The GAP group displayed significant differences between conditions from 305 to 385 ms and from 510 to 630 ms (T max = -3.387, extreme p = 0.0004). Figures 4A and 4B show the topography of the significant differences in the first window and second windows, which correspond to the arithmetic N400

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**Deleted:** (510–630 ms), respectively, in the GAP group. The latencies to the occurrence and the polarity of the components in the first and second time windows and the LPC RTPs, respectively, in terms of latency and distribution of positive and negative activity in young adults (Dickson & Federmeier, 2017; Hinault & Lemaire, 2016; Jasinski & Coch, 2012; Jost et al., 2004; Niedeggen & Rösler, 1999; Niedeggen et al., 1999; Núñez-Peña & Escera, 2007; Núñez Peña & Suárez-Pellicioni, 2012, 2015; Prieto-Corona et al., 2010; Xuan et al., 2007). In contrast, the DYS group only displayed a significant difference between 680 and 700 ms (T max = 4.84, extreme p = 0.021), as shown in Fig. 4C.

**- Please insert Fig. 4 -**

**- Please insert Fig. 5 -**

Based on previous research with other developmental disorders, it is inevitable that some children with dyscalculia will show atypical ERPs and some will not. In considering individual differences within the DYS group, and probably the control group, and how widespread the atypical ERPs were, we explored the variance in the ERPs in both groups of children. Figure 6 shows the boxplot of the differences in amplitude between conditions (incongruent minus congruent) for each group. Children with dyscalculia displayed wider whiskers across electrode sites in the time window of the arithmetic N400 than the children with good academic performance, and there were more outliers.

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Once the statistical analyses to determine the windows were performed, three statistical analyses for independent samples were performed using the permutation technique to compare the mean amplitude per time window identified in the GAP group (N400: 305–385 ms; LPC1: 510–630 ms) and the DYS group (LPC2: 680-700 ms), considering the two levels of the condition (H0: A1-A2 = B1-B2, where A1 and A2 correspond to the congruent and incongruent condition in the

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GAP group, and B1 and B2 correspond to the congruent and incongruent condition in the DYS group). The GAP children showed a significantly larger amplitude for the arithmetic N400 effect over T5 (T max = -3.58, extreme p = 0.007) and a significantly larger LPC1 effect over Fp2 (global T max = 3.01, extreme p = 0.032) than the DYS children. In the LPC2 time window, no differences between groups were observed (T max = 1.46, extreme p = 0.45). Figure 7 shows statistical color maps of the arithmetic N400 effect and LPC effect comparisons between the two groups of children (GAP vs. DYS).

**- Please insert Fig. 7 -**

The children with dyscalculia were assessed according to their WM index. They were divided into two subgroups: one with an average WM index (scores equal to 85 or higher) and the other with a lower than average WM index (scores < 85). Figure 8 displays the grand average of the difference wave for the dyscalculia children, with low scores and high scores for the WM index, and of children with good academic performance. The children with dyscalculia and low WM index scores showed an atypical ERP pattern. They seemed to show an N200 peak, one arithmetic N400 peak, and two LPC peaks. In contrast, those children with dyscalculia but with high WM index scores showed a similar ERP pattern as children with good academic performance, but the amplitude effects were lower.

**- Please insert Fig. 8 -**

For the children with dyscalculia, correlation analyses between the WM index scores and the amplitude values of the differences between conditions across all electrode sites were performed. No significant correlation was found between the WM index and the arithmetic N400 effect. However, in both LPC windows, significant positive correlations were found between WM index

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and LPC effect. In the LPC1 time window, a greater WM index correlated with a greater amplitude in the LPC effect over O2 and T6 (r max = 0.68, extreme p = 0.0056) and, in the LPC2 time window, a greater WM index correlated with a greater amplitude of the LPC effect over T6 (r max = 0.61, extreme p = 0.0178). Figure 9 shows a statistical color map with the correlations between the WM index and the LPC effect.

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## 4. Discussion

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The first objective of this study was to compare arithmetic verification processing in children with dyscalculia with that in children who had good academic performance during an addition verification task using ERPs. To our knowledge, this is the first study to explore the electroencephalographic differences between these two populations of children. We expected poorer behavioral performance (lower percentage of correct answers and/or a longer response times) in the children with dyscalculia than in the children with good academic performance. Regarding the ERP patterns, we hypothesized that the children with dyscalculia would display lower amplitudes and/or higher latencies for the arithmetic N400 and LPC effects than the children with good academic performance.

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Our behavioral results partially confirmed our hypothesis. We observed a significantly lower percentage of correct answers in the DYS group than in the GAP group. This result corroborates the findings of other studies (Castro & Reigosa, 2011; Geary, 1993; Geary et al., 1992; 1999; Landerl et al., 2004). The poor performance of children with dyscalculia has been explained by their use of procedural strategies to solve problems, which are more prone to errors, instead of long-term-memory retrieval strategies, that are used by control children when facing one-digit

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addition problems (Geary, 2004). However, in the present study, the strategies used were not systematically recorded for each child. This constitutes a limitation of the study because it does not allow us to be certain that the observed differences were a consequence of the type of strategy used. On the other hand, there was no significant difference between groups regarding response times; an explanation for this fact could be that the dispersion in the data in both groups, mainly in the DYS group, was very high (see Fig. 3). When correlation analyses between age and response times were performed, we observed that, as expected in the GAP group, the older the children were, the shorter their response times, because automation of the arithmetic facts tested here still develops in that age range. Interestingly, children with dyscalculia did not show this behavioral relation with age. This could be because, independently of maturation, children with dyscalculia have problems in the automation process; another interpretation is that chronological development do not coincide with arithmetic processing development in children with this developmental disorder.

When ERPs were explored, only the GAP group exhibited the arithmetic N400 effect (the amplitude for the incongruent condition was higher than that for the congruent condition). This effect was observed spread over left temporo-parieto-occipital and right fronto-temporal regions and peaked earlier than 400 ms. This spreading effect is compatible with results by Prieto-Corona et al. (2010) where children were compared with young adults, and by Dong et al. (2007) in younger compared to older children during the performance of arithmetic verification tasks. The topography of the N400 effect observed in the GAP group is difficult to contrast with the topography found in other studies because our experiment is different from the others in several ways: 1) our study was done in children, who probably involve more cortical areas than adults to perform the same arithmetic task (Prieto-Corona et al., 2010); 2) our task include addition as the arithmetic operation, and addition produces greater right posterior negativity around 400 ms than multiplication (Zhou et al., 2011); 3) we specifically used an addition verification task because the N400 effect is elicited by the incongruent proposed solution; and 4) we obtained ERPs time-locked to the onset of the probe stimuli, whereas almost all studies obtain ERPs time-locked to the arithmetic problem or equation. There are not previous studies that meet all these characteristics. However, the use of non-parametric statistics should not alter the results. Megías and Macizo (2016) analyzed their ERP data using parametric and nonparametric statistical analysis and they found that results obtained from both methods were similar; even more, nonparametric permutations seemed to be more sensitive to differences.

Conversely, if the four processes involved in the arithmetic verification task proposed by Avancini et al. (2015) are considered, two of them were controlled in our task: 1) the number of congruent was equal to the number of incongruent probes, therefore, the process of violation of the strategic expectations should not have been manifested in the effects; and 2) exactly the same probe stimuli were used for both conditions, so the physical characteristics of the visual stimuli must not have produced an effect in the ERPs. The other two effects are the violation of the semantic constraints defined by the operands when an incongruent probe is shown, and the magnitude effect. Although in our paradigm all the incongruent probes were 2 units away from the correct solution, possibly there was a magnitude effect; therefore, the priming effect and the magnitude effect could be mixed. A stronger left posterior effect related to distance was observed by Avancini et al. (2014). This is in line with the studies indicating this area is associated to the verbal code, according to the triple-code model (Dehaen & Cohen, 1996). In our study, the GAP group showed a higher N400 effect than the DYS group, precisely in the left posterior temporal area (Fig 8).

In contrast, the children with dyscalculia showed no significant arithmetic N400 effect, and when their ERPs were compared to those of the controls, there were significant differences over the left posterior temporal region. This finding agrees with studies that reported a higher arithmetic N400 effect in control teenagers than in teenagers with dyscalculia (Soltész et al., 2007) or in adults with good arithmetic abilities compared to adults with poor arithmetic abilities (Núñez-Peña & Suárez-Pellicioni, 2012). The lack of a significant N400 effect in the children with dyscalculia could be explained as a failure in the processing of congruent results. It seems that any result presented (congruent or incongruent probe) is detected as a conflict or mismatch with what is stored in the arithmetic lexicon (in Fig. 5, a negative deflection elicited in both conditions can be observed). In this way, it seems that this stage of processing does not lead them to correct answers, and they have to face the problem and carry out the arithmetic calculation. The fact that the differences between groups are in the left temporal region may be because the learning of simple addition problems may result in higher activation of phonological process, as was described for multiplication problems (Zhou et al., 2009).

Given that the N400 effect could reflect the detection of a conflict between the expected and the presented answer, the selection of the plausibility-checking strategy can be triggered, which is reflected in the occurrence of LPC. The LPC effect was displayed in both groups, but with different latencies and topography. The DYS group showed a delayed LPC effect of shorter duration. Considering that the LPC effect is modulated by the expectation or plausibility of the solution and that the children with dyscalculia had lower arithmetic abilities, we expected a smaller LPC effect in the DYS group than in the GAP group. This hypothesis was supported by our results because significant lower amplitude of the LPC effect was observed in the DYS group in the right frontopolar region. Like other authors (Iguchi & Hashimoto, 2000; Núñez-Peña et al., 2011; Núñez-Peña & Honrubia-Serrano, 2004; Núñez-Peña & Suárez-Pellicioni, 2012; 2015;

Szűcs & Soltész, 2010), we have found that the LPC effect is greater in individuals with better performance. This difference was located in the right frontal region. Meiri et al. (2012), using functional near-infrared spectroscopy, observed that right frontal region is activated during the simple additions and it is believed to be responsible for holistic arithmetic processing (Dehaen et al., 2003; El Yagoubi et al., 2003). Therefore, this result suggests that children in the GAP group perform a greater reevaluation of the incorrectness when the proposed result is incongruent than when it is congruent, while children with dyscalculia, perhaps due to lack of security in their arithmetic knowledge, re-evaluate almost all the results without distinction between the congruent and the incongruent conditions.

Differences in topography were also observed between groups: while the GAP group showed the LPC effect in the expected right posterior location, the DYS group exhibited this effect in the left posterior region (see Fig. 4). The right lateralization of the LPC effect in children with good academic performance is consistent with a more deliberative and prolonged role of the right hemisphere during the probe evaluation, which has been found in adults in a multiplication verification task (Dickson & Federmeier, 2017). According to these authors, after an initial period of evaluation of the provided response (probe), the left hemisphere classifies it as correct or incorrect and no longer performs follow-up evaluations, while the right hemisphere engages in a deliberate assessment of additional features of the probe, perhaps using spatial skills, to make an evaluation that is less categorical. In this sense, it is possible that children with dyscalculia intentionally search the correct answer from the long-term memory (left hemisphere) and do not find the answer, which eventually leads them to perform the arithmetic calculation. Although the topography recorded from the scalp does not necessarily indicate the location of the generators, different topographies indicate that the generators must be distinct

(Nunez & Srinivasan, 2006). Perhaps our results suggest that the left lateralization of the LPC effect observed in children with dyscalculia is a compensatory phenomenon to obtain the correct response.

In contrast to our expectations, we found scarce differences between groups in the arithmetic N400 and LPC effects. This could be explained by the heterogeneity in the children's behavioral (Fig. 1 and Fig. 3) and ERP (Fig. 6) patterns, which was more apparent in the DYS group. The heterogeneity within this group could be associated with their WM deficits (Fig. 1.B). To explain atypical brain functions that are reflected as neurobiological disorders of cognitive processing (Silver et al., 2008) that underlie learning disorders, there are two main hypotheses (Landerl et al., 2009). In addition to the *domain specific hypothesis*, which refers to abilities that are specifically related to mathematical competencies, the *common deficit hypothesis* postulates that certain patterns of processing are common to all children with learning disorders. Supporting this hypothesis, Swanson (1987) proposed that children with learning disorders experience failures in mechanisms of executive functioning, which also points to WM deficits as essential problems (Berninger, 2008; Swanson, 2015; Swanson & Siegel, 2001). In children with math disabilities, it has been frequently reported that WM plays an essential role in the arithmetic domain (Swanson, 2015). In our study, once children had performed the addition operation, they had to keep the result in WM until the probe digit appeared (1500 ms later) to finally perform the response verification process and give an answer. Therefore, the arithmetic verification task that we used is particularly efficient for highlighting WM problems.

As we hypothesized, the children with dyscalculia had a lower WM index than the children in the GAP group. This finding agrees with previous studies where WM had a predictive role in learning arithmetic (Meyer et al., 2010; Vanbinst & De Smedt, 2016), and with the

Mammarella et al. (2017) study where children with dyscalculia achieved low scores for WM. Considering that an arithmetic N400 effect reflects a facilitation for the probe stimulus that matches the correct answer, the absence of this effect in the children with dyscalculia is consistent with the fact that these children have an alteration in WM. Keeping the information of the addition in WM, as children with good academic performance likely do, leads to facilitation in recognizing or rejecting the proposed result.

However, the DYS group was not homogeneous regarding the WM index measured. Thus, in exploring the relationship between WM and its possible effect on arithmetic processing in the DYS group, it was not surprising to find that children with higher WM index scores had a greater amplitude in the LPC effect at the right posterior region. This region coincides with the LPC topography observed in previous studies (Niedeggen & Rösler, 1999; Núñez-Peña & Escera, 2007; Núñez-Peña & Honrubia-Serrano, 2004) and in our own control participants.

This relationship between WM and the LPC effect was elucidated in the present study and contributes to the understanding of children with dyscalculia. To deeply explore the WM effect in those with dyscalculia, the children with dyscalculia were classified into two groups according to their WM index: average and lower than average. Visual inspection of ERP patterns from these two groups showed that the children with dyscalculia and an average WM index had a similar ERP pattern to that in the children with good academic performance, while the children with dyscalculia and a WM index lower than average showed an atypical ERP pattern (Fig. 8). Visual inspection of the ERPs suggests that this atypical pattern consisted of two negative peaks (at 195 ms and 405 ms) over the parietooccipital and centro-parieto-temporal regions and two positive peaks (at 525 ms and 685 ms) over the parietal regions. These two negativities could correspond to the N200 and arithmetic N400 effects, while these two positivities may correspond to two LPC effects. One possible interpretation is that children with dyscalculia and WM deficits elicited a N200 effect because they required additional attentional resources (Xuan et al., 2007). However, the N200 displayed by these children had a posterior topography; therefore, this could be a reflection that for them, it is relevant to initiate a strong inhibitory-control mechanism (Schmajuk et al., 2006) before matching the sum result with the probe stimulus, which produces an arithmetic N400 effect. Later, they probably reevaluated the arithmetic error (Núñez-Peña & Suárez-Pellicioni, 2012) twice.

Given the interpretation by visual inspection of the ERP patterns in two subgroups of the DYS group, we would have liked to compare the processing in children with dyscalculia and WM deficits with the processing in the children with dyscalculia without WM deficits using an arithmetic verification task. However, the sample sizes were too small to statistically compare these subgroups. This should be done in future research because this could shed light on whether it is dyscalculia that produces the atypical ERP pattern or if the atypical pattern observed in the ERPs is characteristic of children who, in addition to dyscalculia, have WM problems. A third possibility is that this atypical ERP pattern is an exclusive consequence of WM deficits.

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## 5 Conclusions

Children with dyscalculia did not show the arithmetic N400 effect that children with typical development did in an arithmetic verification task; however, both groups showed an LPC effect. The great heterogeneity within the group of children with dyscalculia resulted in a failure to show a robust LPC effect in these children; however, the higher the WM deficits were, the lower the LPC effect amplitude in the right posterior region. When WM deficits were combined with dyscalculia, an atypical ERP pattern emerged. Therefore, studies examining dyscalculia should explore deficits in WM because the whole group of children with dyscalculia seems to contain at least two subpopulations that differ in their calculation processing.

**Acknowledgements:**

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**Competing Interest statement:**

The authors declare that they have no competing interests.

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**FIGURE CAPTIONS**

Fig. 1. **Variability of arithmetic subdomains and WM index in both groups.** (A) Box-and-whisker plots of the subdomains (counting, number management, and calculus) of the arithmetic subtest of the Child Neuropsychological Assessment in both groups of children (GAP and DYS). (B) Box-and-whisker plots of the working memory index of the Wechsler Intelligence Scale for Children, 4th Edition, Spanish version. Error bars represent the standard deviation.

Fig. 2. **Depiction of a trial of the addition verification task.** Flowchart of stimuli presentation during individual trials, W: warning stimulus.

Fig. 3. **Behavioral data in both groups of children (GAP and DYS) in the arithmetic verification task.** Top: Box-and-whisker plots for the behavioral data in both groups of children (GAP and DYS) in the arithmetic verification task. The response times (A) and percentage of correct responses (B) in the DYS group are more widespread than those of the GAP group. Bottom: The response time (C) and correct answer (D) means in both conditions (congruent and incongruent) and both groups of children. Error bars represent the standard deviation. The DYS group showed a lower percentage of correct answers than the GAP group. *** $p < 0.0001$

Fig. 4. **Statistical parametric maps of the arithmetic N400 and LPC effects in both groups.** Top: GAP group. (A) Differences between conditions at 305 to 385 ms (arithmetic N400). (B) Differences between conditions at 510 to 630 ms (LPC effect). Bottom: DYS group. (C) Differences between conditions at 680 to 700 ms (LPC effect). Blue and red colors represent the t-values that were above the threshold of significance ($p < 0.001$). In the GAP group, the arithmetic N400 effect was elicited at P3, O1, T4, T5, Fz, and Pz, and the LPC effect was elicited

at C4, P4, O1, O2, T4, T6, Cz, and Pz, while in the DYS group the LPC effect was observed at P3 and O1. All $p < 0.001$

Fig.5. **ERP wave grand average.** (A) T3 electrode. (B) C3 electrode. The GAP group responses to congruent and incongruent conditions are represented by the black continuous and discontinuous lines, while the DYS group responses to congruent and incongruent conditions are represented by the red continuous and discontinuous lines, respectively. Negativity is plotted downwards.

Fig.6. **Variability of arithmetic N400 and LPC effects.** (A) Box-and-whisker plots of both groups of children (GAP and DYS) using the amplitude values of the arithmetic N400 (305 – 385 ms) effect. (B) Box-and-whisker plots of both groups of children using the amplitude values of the LPC (510 – 630 ms) effect.

Fig. 7. **Differences between groups in arithmetic N400 and LPC effects.** (A) Statistical map of the comparison between groups that considered the difference between conditions (incongruent minus congruent) for the arithmetic N400 (305–385 ms) at T5. (B) Statistical map of the comparison between groups that considered the difference between conditions (incongruent minus congruent) for the LPC (510–630 ms) at Fp2. Colored blue and red spots represent significant differences between groups (t-values $p < 0.05$).

Fig. 8. **Grand averages of the difference waves (i.e., incongruent minus congruent condition).** Blue solid lines represent the ERPs for the GAP group. Red solid lines represent the ERPs for the DYS group with high WM index scores and red dotted lines represent those for the DYS group with low WM index scores. Positive is plotted up. The arithmetic N400 effect and the LPC effect in the GAP group are marked with gray-shadow boxes. Black arrows indicate double

negative peaks (195 ms and 405 ms) and double positive peaks (525 ms and 685 ms) in the DYS group with low WM scores at P3 and C3, but such effects can be observed over other electrode sites. Each letter represents an electrode. (A) Fp1. (B) Fp2. (C) F3. (D) F4. (E) C3. (F) C4. (G) P3. (H) P4. (I) O1. (J) O2. (K) F7. (L) F8. (M) T3. (N) T4. (O) T5. (P) T6. (Q) Fz. (R) Cz. (S) Pz.

Fig. 9. **Relationship between working memory and LPC effect in the DYS group.** (A) Statistical map of the correlations between the WM index and the ERP amplitude difference between conditions (incongruent minus congruent) at the 510 to 630 ms (LPC effect) across electrode sites. The red spot represents the significant r-values ($p < 0.05$) over the T6 and O2 electrodes. (B) Ascending regression line showing that higher values of the working memory index (X axis) are associated with greater LPC effect in the electrode T6 (Y axis). (C) Ascending regression line showing that higher values of the working memory index (X axis) are associated with greater LPC effect in the electrode O2 (Y axis).