Arithmetic processing in children with dyscalculia: An event-related potential study

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Introduction. Dyscalculia is a specific learning disorder affecting the ability to learn certain math processes, such as arithmetic data recovery. The group of children with dyscalculia is very heterogeneous, in part due to variability in their working memory (WM) deficits. 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 to a) compare arithmetic processing between children with dyscalculia and children with good academic performance using ERPs during an addition verification task and b) explore, among children with dyscalculia, the relationship between WM and ERP effects.

Materials & Methods. EEGs of 22 children with dyscalculia (DYS group) and 22 children with good academic performance (GAP group) were recorded during the performance of an addition verification task. ERPs synchronized with the probe stimulus were computed separately for the congruent and incongruent probes, and included only epochs with correct answers. Mixed 2-way ANOVAs for response times and correct answers were conducted. Comparisons between groups and correlation analyses using ERP amplitude data were carried out through multivariate nonparametric permutation tests.

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 suggested that the processing in this step was not useful enough to produce an answer; thus, it was necessary to reevaluate the arithmetic-calculation process (LPC) in order to deliver a correct answer.

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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2   **Event-Related Potential Study**

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23 **ABSTRACT**

25 **Introduction.** Dyscalculia is a specific learning disorder that affects a person's ability to learn

26 certain mathematical processes. Children with dyscalculia constitute a heterogeneous group,

27 partly due to the variability in their working memory. In this study, we used both behavioural

28 responses and event-related potentials (ERPs) to explore arithmetic processing in children

29 with dyscalculia and children with good academic performance by assessing ERPs during an

30 addition verification task and examining whether these were associated with working memory

31 (WM).

32 **Materials & Methods.** ERPs synchronised with congruent and incongruent probes were

33 obtained in 22 children with dyscalculia (DYS group) and 22 children with good academic

34 performance (GAP group) while they performed an addition verification task. The arithmetic

35 N400 and late positive component (LPC) effects were defined by significant differences between

36 the corresponding wave amplitudes for incongruent and congruent probes. Accuracy and speed

37 of the behavioural responses were compared between groups by using mixed analyses of

38 variance (ANOVAs) and ERP amplitudes were analysed using multivariate nonparametric

39 permutation tests and correlation analyses. In subsequent analyses, the DYS group was divided

40 into two subgroups: one with average WM indices and the other with lower-than-average WM

41 indices, and differences between these subgroups were explored.

42 **Results.** Participants in the GAP group obtained more correct answers than those in the DYS

43 group, but no intergroup differences were observed in the response times. An arithmetic N400

44 effect was observed in the GAP group but not in the DYS group. Both groups displayed LPC

45 effects. In the DYS group, the larger the LPC effect was, the higher the working memory index.

46   The two subgroups of the DYS group displayed different ERP patterns: while children with

47   dyscalculia and an average WM index showed a similar ERP pattern to children with good

48   academic performance, those with dyscalculia and a low WM index showed an atypical ERP

49   pattern.

50   **Discussion.** The results indicated that the group of children with dyscalculia was very

51   heterogeneous. The absence of an arithmetic N400 effect in these children suggests that the

52   processing at this stage was not useful enough to calculate and identify the correct result of the

53   operation; thus, a re-evaluation of the arithmetic-calculation process (that elicits an LPC effect)

54   was necessary in order to deliver a correct answer. Some of the children with dyscalculia had

55   WM deficits. The atypical ERP pattern shown by children with dyscalculia and WM deficits

56   reflects their difficulties in mathematical processing.

57   **Conclusion.** Since dyscalculia is a very heterogeneous deficit, studies examining dyscalculia

58   should consider exploring deficits in WM because these deficits may affect their calculation

59   process.

60

61

63 **1. Introduction**

64 According to the Diagnostic and Statistical Manual of Mental Disorders, 5th Edition (DSM-5;

65 American Psychiatric Association, 2013), dyscalculia refers to difficulties with number sense,

66 number facts, and calculation (i.e., having a poor understanding of numbers, their magnitudes

67 and relationships, counting on fingers to add single-digit numbers instead of recalling math facts

68 as peers do, becoming lost in the midst of arithmetic computation, and switching procedures).

69 The academic skills of children with dyscalculia are substantially below those expected for their

70 chronological age, which can cause significant difficulties in academic performance and in

71 activities of daily living (American Psychiatric Association, 2013). Dyscalculia cannot be better

72 accounted for by intellectual disabilities, uncorrected visual or auditory acuity, other mental or

73 neurological disorders, psychosocial adversity, lack of proficiency in the language of academic

74 instruction, or inadequate educational instruction (American Psychiatric Association, 2013).

75 Dyscalculia is a heterogeneous cognitive disorder (Kaufmann et al., 2013). A known source of

76 this heterogeneity is working memory (WM), which varies markedly between children with

77 dyscalculia (Andersson & Lyxell, 2007; Geary, 1993; Mammarella et al., 2017). The WM

78 system provides online storage of information and its subsequent manipulation through four

79 subsystems: the phonological loop, the visuospatial sketchpad, the episodic buffer, and the

80 central executive (Baddeley, 2006). In the domain of mathematics, the phonological loop holds

81 intermediate arithmetic results in the form of linguistic information, and plays a role in

82 mathematical abilities that involve the articulation of numbers, such as counting, problem-

83 solving, and arithmetic fact retrieval (Geary, 1993; Shen et al., 2018). The visuospatial sketchpad

84 supports the construction of visual representations of numerical information and is, thus, related

85 to spatial aspects of calculation, such as decomposition strategies (Foley et al., 2017; Simms et

86 al., 2016). The episodic buffer provides a temporary storage that links information from the two

87 slave subsystems and long-term memory, allowing the maintenance of multi-code number

88 representations (Camos, 2018). Finally, the central executive coordinates and monitors

89 simultaneous processing and keeps track of math tasks that have already been performed

90 (DeStefano & LeFrevre, 2004; Fuchs et al., 2005; Holmes & Adams, 2006). Children with

91 dyscalculia may show difficulty in verbal short-term memory and verbal WM (Attout &

92 Majerus, 2015; Berninger, 2008; Hitch & McAuley, 1991; Peng & Fuchs, 2016; Shen et al.,

93 2018; Swanson & Siegel, 2001), visuospatial short-term memory and visuospatial WM (McDonald

94 & Berg, 2018; Mammarella et al., 2017; Rotzer et al., 2009; Schuchardt et al., 2008), and the

95 central executive (Andersson & Lyxell, 2007; Meyer et al., 2010; Vanbinst & De Smedt, 2016).

96 In addition, these children have been reported to show a slower processing speed (Geary et al.,

97 1999; Landerl et al., 2004; Shalev et al., 2005).

98 Behavioural performance (accuracy and response time) in arithmetic tasks depends on the

99 arithmetic ability of the subject (Cipora & Nuerk, 2013; LeFevre & Kulak, 1994; Núñez-Peña &

100 Suárez-Pellicioni, 2012) as well as individual characteristics such as age (De Smedt et al., 2009;

101 Geary & Wiley, 1991; Geary et al., 1992) and school grade (Geary, 2004; Imbo & Vandierendock,

102 2008). Behavioural performance also depends on the task features. In an arithmetic verification

103 task, in which the arithmetic operation (context) is followed by a possible solution (probe) that

104 may or may not match the correct result of the operation, the priming phenomenon manifests as a

105 shorter response time in the presence of facilitation provided by the context, i.e., when the probe

106 digit coincides with the result of the proposed arithmetic operation (congruent condition). One

107 explanation for this phenomenon is that the congruent solution is more quickly recovered from

108 memory (Niedeggen & Rösler, 1999; Niedeggen et al., 1999). Thus, to provide a correct answer,

109   a child needs to perform adequate arithmetic processing (to choose the correct probe) as well as

110   adequately maintain the result in verbal WM via the verbal short-term memory, which leads to

111   facilitation.

112   All previously mentioned studies used behavioural variables to draw their conclusions. Although

113   behavioural assessments of performance during tasks can yield data for variables such as

114   response time and percentage of correct answers, they ignore the subject's cerebral and cognitive

115   processes. In contrast, the high temporal resolution of event-related potentials (ERPs) can

116   elucidate these processes by representing the processing through each millisecond and thereby

117   allowing chronologic analysis of brain function through different cognitive processes.

118   ERPs have previously been used to study arithmetic processing. Evaluation of arithmetic

119   verification processing in healthy young adults by using ERPs reported a negative wave with

120   greater amplitude in an incongruent condition (i.e., when there is no facilitation provided by the

121   context) than in a congruent condition (i.e., with facilitation provided by the context) (Dong et al.,

122   2007; El Yagoubi et al., 2003; Hinault & Lemaire, 2016; Prieto-Corona et al., 2010; Szűcs &

123   Csépe, 2005). The arithmetic N400 component is a negative waveform that begins at around 250

124   ms, peaks at around 400 ms, and is maximal over the centroparietal area on the scalp (Dickson &

125   Federmeier, 2017; Hinault & Lemaire, 2016; Jost et al., 2004; Niedeggen et al., 1999;

126   Niedeggen & Rösler, 1999; Prieto-Corona et al., 2010). If the arithmetic N400 component in

127   the incongruent is larger than in the congruent condition, the significant difference in amplitude

128   between these components is known as the arithmetic N400 effect, which reflects the strength of

129   the probe's relationship with the context (i.e., arithmetic operation) (Niedeggen & Rösler, 1999).

130   N400 is thought to reflect the automatic retrieval of arithmetic facts from long-term memory and

131   its magnitude represents the strength of the probe's relationship with the context (i.e., arithmetic

132   operation) (Niedeggen & Rösler, 1999). However, lack of concordance between automatic

133   recovery of the correct results and the probe may involve additional inhibitory processes (Hinault

134   & Lemaire, 2016).

135   Studies with different populations have indicated that the arithmetic N400 effect is modulated by

136   arithmetic abilities. For example, the effect is greater in adults or teenagers with better arithmetic

137   abilities than in adults or teenagers, respectively, with poorer arithmetic abilities (Núñez-Peña et

138   al., 2011; Núñez-Peña & Suárez-Pellicioni, 2012; 2015; Soltész et al., 2007; Soltész & Szűcs,

139   2009; Thevenot et al., 2007). Comparisons between children and adults have revealed differences

140   in latency and topographical distributions of the arithmetic N400 effect (Prieto-Corona et al., 2010).

141   Further, younger children show longer latencies than older children (Dong et al., 2007).

142   Another ERP component that has been used to investigate arithmetic processing in adults and

143   children is the late positive component (LPC). This follows the arithmetic N400 component,

144   appearing between 500 and 700 ms. The LPC is a positive deflection in the ERP waveform that

145   shows a parietal (Jasinski & Coch, 2012; Niedeggen & Rösler; Núñez-Peña & Suárez-Pellicioni,

146   2015; Xuan et al., 2007) or centro-parietal (Núñez-Peña & Escera, 2007; Núñez-Peña & Suárez-

147   Pellicioni, 2012; Prieto-Corona et al., 2010) topography, mainly over the right hemisphere

148   (Jasinski & Coch, 2012; Niedeggen & Rösler, 1999; Niedeggen et al., 1999). The significant

149   difference in amplitudes between LPC components elicited by incongruent and congruent

150   conditions is known as the LPC effect when amplitude in an incongruent condition is larger than

151   in a congruent condition (Jost et al., 2004; Niedeggen et al., 1999; Núñez-Peña & Suárez-

152   Pellicioni, 2012; Prieto-Corona et al., 2010; Szűcs & Csépe, 2005; Szűcs & Soltész, 2010). The

153   LPC effect is associated with processing re-evaluation (Núñez-Peña & Suárez-Pellicioni, 2012;

154   Prieto-Corona et al., 2010; Szűcs & Soltész, 2010), and its amplitude is modulated by the

155   plausibility of a presented condition (Niedeggen & Rösler, 1999; Núñez-Peña & Escera, 2007;

156   Núñez-Peña & Honrubia-Serrano, 2004; Núñez-Peña & Suárez-Pellicioni, 2015; Szűcs &

157   Soltész, 2010). Some authors have proposed that the LPC effect reflects surprise due to an out-

158   of-context stimulus (Donchin & Coles, 1997; Núñez-Peña & Suárez-Pellicioni, 2012; Polich,

159   2007). The LPC effect is greater in adults than in children (Zhou et al., 2011) and in individuals

160   with better arithmetic abilities than in those with arithmetic deficits (Iguchi & Hashimoto, 2000;

161   Núñez-Peña et al., 2011; Núñez-Peña & Honrubia-Serrano, 2004; Núñez-Peña & Suárez-

162   Pellicioni, 2012; 2015; Szűcs & Soltész, 2010).

163   In summary, children with dyscalculia may show deficits in WM in addition to the characteristic

164   mathematical problems, making them a heterogeneous group. Although ERPs have shown that

165   neural processing in these children differs from that in children with typical abilities, the effects

166   of an additional WM deficit on the processing of an arithmetic verification task at the neural

167   level remain unknown. Since ERPs can reveal or highlight mechanisms that remain undetected

168   by behavioural measures, the body of knowledge about dyscalculia may be enhanced by

169   comparing ERPs of children with dyscalculia and those with typical development while the

170   children perform an arithmetic verification task. Thus, the first aim of the current study was to

171   compare the arithmetic processing between children with dyscalculia and children with good

172   academic performance by assessing their ERPs during an addition verification task. The second

173   aim was to explore the relationship between WM and ERPs in children with dyscalculia. We

174   hypothesised that, in comparison with children with good academic performance, children with

175   dyscalculia would show (1) less accurate or slower behavioural responses on an arithmetic

176   verification task, (2) smaller or later arithmetic N400 and LPC effects, and (3) poorer

177   performance on WM tests. In addition, we explored the possibility of a relationship between WM

178   performance and the N400 and LPC effects in children with dyscalculia.

179

180   **2. Methods**

181   2.1 Ethics

182   This research was conducted in accordance with the ethical principles of the Declaration of

183   Helsinki. The Bioethics Committee of the Neurobiology Institute at the Universidad Nacional

184   Autónoma de México approved the experimental protocol (INEU/SA/CB/145). Children and

185   their parents gave written informed consent to participate in this study.

186   2.2 Participants

187   Forty-four right-handed children aged between 9 and 11 years participated in this study. The

188   participants were selected from a sample of 167 children from public and private elementary

189   schools in Querétaro, México. The study was carried out in 2015-2016. The interview,

190   examinations and psychological and neuropsychological tests were administered around two

191   months before the ERPs. After completing a semi-structured interview, we excluded 16 children

192   due to low socioeconomic status (the mother had not completed elementary school and/or per

193   capita income was less than 100% of the minimum wage; Harmony et al., 1990) and two

194   children who presented with epilepsy. In addition, we excluded six children with intellectual

195   disability (i.e., IQ < 70; Wechsler Intelligence Scale for Children, 4th Edition, Spanish version;

196   Wechsler, 2007), 52 children who showed psychiatric disorders (i.e., ADHD, behaviour disorder,

197   and/or oppositional defiant disorder as identified with MiniKid (Ferrando et al., 1998) and

198   neuropsychiatric assessments), and two children with uncorrected hypoacusis were excluded as

199   well.

200   The remaining 89 children completed the arithmetic subtest of the Child Neuropsychological

201   Assessment (Matute et al., 2005), which is standardised and includes norms for the Mexican

202   population. Its arithmetic domain consists of three subdomains (counting, number management,

203   and calculus). Thirty participants who performed at or below the 9th percentile in at least one

204   arithmetic subdomain were assigned to a group of children with dyscalculia (DYS group), and 28

205   participants at or above the 37th percentiles in all subdomains were assigned to a group with

206   good academic performance (GAP group). The remaining 31 participants that did not belong to

207   either of these two groups were excluded. Of the selected children, five from the DYS group

208   and two from the GAP group were excluded because their correct answers were below the

209   chance level (58%). Another three children from the DYS group and four from the GAP group

210   were later excluded due to poor ERP data (see the ERP section below). Thus, the DYS and

211   GAP groups were each represented by 22 participants (11 and 14 girls in the DYS and GAP

212   groups, respectively). The groups did not differ in age, gender ($\chi^2(1) = 0.834$, p = 0.361), or

213   monthly family income per capita.

214   Both groups underwent assessments for the four neuropsychological indices of the Wechsler

215   Intelligence Scale for Children: verbal comprehension index, working memory index, processing

216   speed index, and perceptual reasoning index. The children in the GAP group had scores of 85 or

217   higher in all indices, while those in the DYS group showed significantly lower scores on all the

218   indices except the processing speed index, as shown in Table 1. Figure 1 shows the boxplots of

219   the arithmetic subtests of the Child Neuropsychological Assessment and the WM index of the

220   Wechsler Intelligence Scale for Children. All participants had normal or corrected-to-normal

221   visual acuity, and they did not present any history of neurological or psychiatric disorders.

222   Children from both groups were selected from the same schools and were therefore from the

223   same educational environments.

224   **- Please insert Table 1 -**

225   **- Please insert Fig. 1 -**

226   2.3 Stimuli

227   Each trial of the task started with a warning stimulus (a right-pointed arrow), which was

228   followed by an addition operation with two single-digit operands between 1 and 9. Each addition

229   operation combined the two Arabic digits using the plus sign (+), resulting in 81 different

230   addition operations. Every operation was presented once with each of the correct and incorrect

231   results (congruent and incongruent conditions). The incorrect result was constructed by either adding

232   2 to the correct result (for 41 facts) or by subtracting 2 from it (for the remaining 40 facts).

233   2.4. Arithmetic verification task

234   Figure 2 illustrates the time chart of the task. In each of the 162 trials, a white warning stimulus

235   was presented at the centre of the black screen for 200 ms, followed by a black screen that lasted

236   for 300 ms. A white addition operation then appeared for 1500 ms, followed by another black

237   screen for 1500 ms. Subsequently, a white number (probe stimulus) was presented for 1000 ms

238   on a black screen, which either did or did not match the sum of the numbers (for the congruent or

239   incongruent conditions, respectively). Finally, a black screen was presented for 500 ms. Half of

240   the trials were congruent and half incongruent. Trials were randomised and delivered by Mind-

241   Tracer 2.0 software (Neuronic Mexicana, S.A.; Mexico City, Mexico).

242   **- Please insert Fig. 2 -**

243   2.5 Procedure

244   Children were seated in a comfortable chair 70 cm from the computer screen in a sound-

245   attenuated dimly-lit Faraday recording chamber. The experiment began after a training period to

246   familiarise the children with the task, which consisted of 16 trials with feedback. This was

247   followed by 162 trials divided into four blocks (two with 40 and two with 41 trials). Blocks were

248   separated by 1-minute rest periods.

249   All children were instructed to relax and maintain their gaze towards the centre of the screen and

250   to avoid blinking when the probe stimulus appeared. They were asked to blink after the response

251   was given, just before the warning stimulus. The children were instructed to respond as quickly

252   and accurately as possible when the probe stimuli were presented. Half the children were

253   instructed to press the mouse key with the right thumb if they thought the probe was correct

254   (congruent condition) and with the left thumb if they thought it was incorrect (incongruent

255   condition). The other half of the children were instructed to do the opposite.

256   2.6 ERP acquisition and analysis

257   A 19-channel EEG (Ag/AgCl electrodes held in position with a cap according to the 10-20

258   International System; Electro-Cap™ International, Inc.; Ohio, USA), referenced to linked

259   earlobes (A1A2), was recorded using a MEDICID™ IV system (Neuronic S.A.; Mexico City,

260   Mexico) and a Track Walker v5.0 data system while the child was performing the task. The

261   bandwidth of the amplifiers was 0.5-50 Hz, and the sampling frequency was 200 Hz. Impedances

262   in all the recordings were maintained below 5 kΩ. Electro-oculograms were recorded with

263   electrodes located on the superciliary arch and the external canthus of the right eye.

264 ERPs were computed offline using 1000-ms EEG epochs from each subject in each experimental

265 condition. The epochs consisted of a baseline period that started 200 ms before the probe onset

266 and ended 800 ms after the probe onset. Baseline correction was performed using the 200-ms

267 pre-stimulus period. An EEG epoch was rejected if visual inspection revealed blinking or ocular

268 movements, electrical activity exceeding 100 microvolts, or amplifier blocking for more than 50

269 ms at any electrode site. Seven participants (three in the DYS group) had fewer than 20 artifact-

270 free trials per condition, so these participants were excluded. The number of EEG epochs per

271 condition was approximately equal per subject. On average, the DYS and GAP groups had 33

272 and 39 artifact-free epochs, respectively, for each condition. Accepted EEG epochs associated

273 with correct answers were averaged together to produce one ERP each for the congruent and

274 incongruent conditions for each child. The former was subtracted from the latter (i.e.,

275 incongruent minus congruent) to produce one ERP difference wave per child.

276 2.7 Statistical analysis

277 2.7.1 Behavioural data analysis

278 Statistical analyses of behavioural data were performed using the statistical program SPSS (IBM

279 Statistic 20, Chicago Illinois, USA). We conducted mixed 2-way ANOVAs for response times and

280 for correct answers. The percentage of correct answers was transformed by arcsine [square root

281 (percentage/100)] (Zar, 2010). Group (GAP, DYS) was included as the between-subjects factor,

282 and condition (congruent, incongruent) was included as the within-subjects factor. The least

283 significant differences method was used for *post-hoc* pairwise comparisons.

284 2.7.2 ERP data analysis

285   Figure 3 shows the scheme of statistical analyses for the ERP data. All assessments were

286   performed using nonparametric tests with permutations (Galán et al., 1998) due to the

287   multiplicity of comparisons and dependent variables and the consequently increased probability

288   of type I errors (Luck, 2014). Analyses were carried out using eLORETA software (Pascual-

289   Marqui et al., 2011). Five thousand permutations were performed. Global significance for the

290   statistical test (i.e., significant p-value level considering all the electrodes) was reported as T max

291   and its extreme p-value. Because this statistical test is based on an empirical probability

292   distribution, extreme p-values were corrected by multiple comparisons.

293   **- Please insert Fig. 3 -**

294   Time windows of the ERP components are usually defined by the outcomes of previous studies.

295   However, most studies relevant to this experiment tested young adults, who have faster

296   processing than children. To determine appropriate time windows for the arithmetic N400 and

297   LPC effects in children, we performed a non-parametric permutation test to identify significant

298   differences between the ERP waveforms for congruent and incongruent conditions per time point

299   between -200 to 800 ms at all electrode sites (Fig. 3A). In each group of children, we defined the

300   time windows of the arithmetic N400 and LPC.

301   The next step was to explore the topography of the N400 and LPC effects per group across all

302   electrode sites (Fig. 3B). In addition, eLORETA was used to conduct three analyses that

303   compared the ERP difference waveforms (incongruent minus congruent) between the two groups

304   (GAP, DYS) (Fig. 3C). Five thousand permutations were performed. Significant t-values over

305   electrode sites are represented in colour maps (only t-values with p < 0.05).

306   We also used eLORETA to perform three correlation analyses in the DYS group between each

307   ERP difference wave form and the WM index across all electrode sites (Fig. 3D). Five thousand

308   permutations were performed. Significance for the statistical test was reported (r max and its

309   extreme p-value). Specific significant correlations (r value) over electrode sites are represented

310   in colour maps (only r-values with p < 0.05).

311   All statistical results for the ERPs were reported taking into consideration all 19 electrodes.

312

313   **3. Results**

314   3.1 Behavioural results

315   The behavioural results are shown in Fig. 4. The participants in the GAP group showed a

316   significantly higher percentage of correct answers than those in the DYS group ($F_{(1,42)}$ = 27.39, p

317   < 0.0001, η_p^2 = 0.395). The percentage of correct answers in the incongruent condition was

318   significantly higher than that in the congruent condition ($F_{(1,42)}$ = 8.67, p = 0.005, η_p^2 = 0.171),

319   independently of the group. No significant group by condition interaction was noted ($F < 1$).

320   The responses for all children were significantly faster in the congruent condition than in the

321   incongruent condition ($F_{(1,42)}$ = 131.922, p < 0.0001, η_p^2 = 0.759), but the response times were

322   not significantly different between the groups ($F < 1$). No significant group by condition

323   interaction ($F_{(1,42)}$ = 1.114, p = 0.297, η_p^2 = 0.026) was observed for this assessment. This finding

324   could be attributed to the large age range of the participants, since the automation of solutions to

325   arithmetic problems is a developing process in children of these ages. We tested this possibility

326   by exploring the association between age and response time using Spearman rank correlation

327   analyses within groups. The GAP group showed significant negative correlations for congruent

328   (r = -0.57, p = 0.006) and incongruent (r = -0.60, p = 0.003) conditions; however, the DYS group

329   showed no significant correlations for any condition (congruent: r = -0.29, p = 0.195;

330   incongruent: r = -0.22, p = 0.337).

331   **- Please insert Fig. 4 -**

332   3.2 Electrophysiological results

333   3.2.1 Time windows for the N400 and LPC effects in the DYS and GAP groups

334   The statistical results showed significant differences between conditions from 305 to 385 ms and

335   from 510 to 630 ms in the GAP group (T max = -3.387, extreme p = 0.0004). Figures 5A and 5B

336   show the topography of the significant differences in the first and second windows, which

337   correspond to the arithmetic N400 and LPC effects, respectively, in terms of their latency and

338   polarity (negative and positive, respectively). The LPC effect elicited by the GAP group was

339   named the LPC1 effect. The topographic distribution of both ERP effects corresponds with the

340   findings reported in previous studies in young adults. The arithmetic N400 effect was localised

341   over the frontal midline (Megías & Macizo, 2016; Prieto-Corona et al., 2010) and left

342   centroparietal area (Avancini et al., 2014, 2015; Dickson & Federmeier, 2017). The LPC effect

343   was observed over the centro-parieto-temporal area, mainly in the right hemisphere (Avancini et

344   al., 2015; Dickson & Federmeier, 2017; Jasinski & Coch, 2012; Niedeggen & Rösler, 1999). In

345   contrast, the DYS group only displayed a significant difference between 680 and 700 ms (T max

346   = 4.84, extreme p = 0.021), as shown in Fig. 5C, which could correspond to a late LPC effect

347   (named the LPC2 effect).

348   **- Please insert Fig. 5 -**

349 The grand averages of the ERPs in the T3 and C3 electrodes in the two task conditions for both

350 groups are shown in Fig. 6. This figure clearly illustrates that the lack of arithmetic N400 effect

351 in the DYS group is not associated with a lack of response, but with similarly large amplitudes

352 for both arithmetic N400 components in each condition.

353            **- Please insert Fig. 6 -**

354 3.2.2 ERP difference waveforms in the DYS and GAP groups

355 Having identified appropriate time windows for the N400 and LPC effects in each group, three

356 statistical analyses for independent samples were performed using the permutation technique

357 (considering all electrodes) to compare the ERP difference waves in the GAP and DYS groups

358 per time window identified (305-385 ms, 510-630 ms, and 680-700 ms). The GAP children

359 showed a significantly larger amplitude for the arithmetic N400 effect over T5 (T max = -3.58,

360 extreme p = 0.007) and a significantly larger LPC1 effect over Fp2 (global T max = 3.01,

361 extreme p = 0.032) than the DYS children. In the LPC2 time window, no differences between

362 groups were observed (T max = 1.46, extreme p = 0.45). Figure 7 shows the statistical colour

363 maps of the arithmetic N400 effect and LPC effect comparisons between the two groups (GAP

364 vs. DYS).

365            **- Please insert Fig. 7 -**

366 3.2.3 Associations between WM and ERPs

367 The heterogeneity that characterises behavioural performance in dyscalculia (Kaufmann et al.,

368 2013) is also likely reflected on ERPs since ERPs correspond to the brain processing that

369 underlies performance, which indicates that data dispersion is higher in the DYS group.

370   Moreover, the DYS group showed more outliers than the GAP group (Fig. 8). One source of this

371   heterogeneity has been proposed to be WM (Andersson & Lyxell, 2007; Geary, 1993).

372   **- Please insert Fig. 8 -**

373   The children with dyscalculia were assessed according to their WM indices and distributed into

374   two subgroups: one with average WM indices (scores equal to 85 or higher; n = 13, 6 girls) and

375   the other with lower-than-average WM indices (scores < 85; n = 8, 4 girls). Figure 9 displays the

376   grand average of the difference wave for these two subgroups of children with dyscalculia, as

377   well as children with good academic performance. The children with dyscalculia and a low WM

378   index score seemed to show one N200 peak, one arithmetic N400 peak, and two LPC peaks,

379   representing an atypical ERP pattern for this task. In contrast, children with dyscalculia, but with

380   average WM index scores, showed a similar ERP pattern to children with good academic

381   performance.

382   **- Please insert Fig. 9 -**

383   For the children with dyscalculia, correlation analyses between the WM index scores and the

384   amplitude values of the difference wave at each electrode site were performed in every ERP

385   window. No significant correlation was found between the WM index and the difference wave in

386   the N400 window. However, in both LPC windows, significant positive correlations were found

387   between the WM index and LPC difference waves. In the LPC1 time window, a greater WM

388   index correlated with a greater amplitude in the LPC effect over O2 and T6 (r_{max} = 0.68, extreme

389   p = 0.0056) and, in the LPC2 time window, a greater WM index correlated with a greater

390   amplitude of the LPC effect over T6 (r_{max} = 0.61, extreme p = 0.0178). Figure 10 shows

391   statistical colour maps for the correlations between the WM index and the LPC effects.

392   **- Please insert Fig. 10 -**

393

394   **4. Discussion**

395   The first objective of this study was to compare arithmetic verification processing in children

396   with dyscalculia with that in children with good academic performance during an addition

397   verification task by using ERPs. To our knowledge, this is the first study to compare the ERPs of

398   these two populations of children. We expected poorer behavioural performance (lower

399   percentage of correct answers and/or longer response times) in the children with dyscalculia than

400   in the children with good academic performance. For the ERP patterns, we hypothesised that the

401   children with dyscalculia would display longer latencies and smaller arithmetic N400 and LPC

402   effects than the children with good academic performance.

403   4.1 Behavioural differences between the DYS and GAP groups

404   Our behavioural results partially confirmed our hypothesis. We observed a significantly lower

405   percentage of correct answers in the DYS group than in the GAP group. This result corroborates

406   the findings of other behavioural studies (Castro & Reigosa, 2011; Geary, 1993; Geary et al.,

407   1992; 1999; Landerl et al., 2004). The poor performance of children with dyscalculia has been

408   explained by their use of procedural strategies such as counting on, counting all, and

409   decomposition, which are more prone to errors, instead of the long-term-memory retrieval

410   strategies that are used by children with typical arithmetic abilities when facing one-digit

411   addition problems (Geary, 2004). Unfortunately, in the present study, the strategies used were

412   not systematically recorded for each child. This constitutes a limitation of the study because it

413   precludes us from proving that the observed differences were attributable to the strategies used.

414   On the other hand, there was no significant group difference in response times. This could be

415   explained by the high dispersion in the data in both groups, mainly in the DYS group (see Fig.

416   4). As expected, in the GAP group, older children showed shorter response times, perhaps

417   because the automation of arithmetic facts tested herein is still developing in that age range.

418   Interestingly, children with dyscalculia did not show this association of performance with age.

419   This may be because, independently of age-related maturational process, children with

420   dyscalculia experience problems in this automation process.

421   4.2 ERP differences between the DYS and GAP groups

422   4.2.1 N400 effect

423   Only the GAP group exhibited the arithmetic N400 effect (a higher amplitude for the incongruent

424   condition than for the congruent condition). This effect was observed over the left temporo-

425   parieto-occipital and right fronto-temporal regions and peaked earlier than 400 ms. The findings

426   for the frontal region coincide with the topography observed in some studies in young adults

427   (Megías & Macizo, 2016; Prieto-Corona et al., 2010) and the left posterior localisation coincides

428   with those found in other studies (Avancini et al., 2014, 2015; Dickson & Federmeier, 2017).

429   This more-distributed effect in children corresponds with the findings reported by Prieto-Corona

430   et al. (2010), who observed that the N400 effect in children involves more cortical regions than

431   that in adults to perform the same task, and by Dong et al. (2007), who compared younger and

432   older children during the performance of arithmetic verification tasks.

433   Only a few studies have assessed these effects in children, and the majority of them used

434   different arithmetic operations, which activate different brain regions (Zhou et al., 2011).

435   Another point of difference from these studies is that we obtained ERPs time-locked to the onset

436   of the probe stimuli, whereas almost all studies obtained ERPs time-locked to the arithmetic

437   problem or equation (Van Beek et al., 2014; Xuan et al., 2007). Only the study by Xuan et al.

438   (2007) shows the same characteristics as ours; however that study observed the N400 effect over

439   the vertex. One concern regarding ERP topography could be the use of non-parametric statistics

440   because they are not commonly used. However, Picton et al. (2000) has argued that this is a

441   better approach for ERP assessment than parametric analyses because it makes no assumptions

442   about the distribution of the data, and is especially useful in the analysis of multichannel scalp

443   distributions, as in our study. This is supported by Megías and Macizo (2016) who analysed their

444   ERP data by using parametric and nonparametric statistical analysis and obtained similar

445   findings with both methods, with the nonparametric permutations appearing to be more sensitive

446   to differences.

447   Since we are using an arithmetic verification task to evoke the ERPs, it is important to determine

448   which processes could manifest in it. Among the four processes involved in the arithmetic

449   verification task proposed by Avancini et al. (2015), two were controlled in our task: (1) the

450   number of congruent and incongruent probes was equal, so violations of strategic expectations

451   should not have manifested as ERP effects; and (2) precisely the same probe stimuli were used

452   for both conditions, so the physical characteristics of the visual stimuli would not have affected

453   the ERPs. The other two effects are the magnitude effect and the violation of the operands'

454   semantic constraints when an incongruent probe is shown. Although all the incongruent probes

455   were 2 units away from the correct solution in our paradigm, a magnitude effect may have been

456   present; therefore, the priming effect and the magnitude effect could be mixed. A stronger left

457   posterior effect related to distance was observed by Avancini et al. (2014), consistent with the

458   studies indicating the association of this area with the verbal code according to the triple-code

459   model (Dehaen & Cohen, 1996). In our study, the GAP group showed a higher N400 effect than

460   the DYS group precisely in the left posterior temporal area (Fig. 8).

461   In contrast, children with dyscalculia showed no significant arithmetic N400 effect, and when

462   their ERPs were compared to those of the controls, significant differences were observed over

463   the left posterior temporal region. This finding is consistent with those of studies reporting a

464   smaller arithmetic N400 effect in adults or teenagers with dyscalculia compared to age-matched

465   controls (Núñez-Peña & Suárez-Pellicioni, 2012; Soltész et al., 2007). The lack of a significant

466   N400 effect in children with dyscalculia could be explained as a failure to process congruent

467   results. In these children, any probe (congruent or incongruent) is perceived as a mismatch with

468   what is stored in the arithmetic lexicon (in Fig. 6, a negative deflection is elicited in both

469   conditions). Thus, they must revert to conducting the arithmetic calculation. The group

470   differences in the left temporal region may reflect the fact that simple addition problems

471   activate phonological processes, as has been described for multiplication problems (Zhou et al.,

472   2009).

473   4.2.2 LPC effect

474   The LPC effect was displayed in both groups, but with different latencies and topographies. The

475   DYS group showed a delayed LPC effect of shorter duration. Since the LPC effect is modulated

476   by the expectation or plausibility of the solution and children with dyscalculia had lower

477   arithmetic abilities, we expected a smaller LPC effect in the DYS group than in the GAP group.

478   Our results support this hypothesis because a significantly lower amplitude of the LPC effect was

479   observed in the DYS group in the right frontopolar region. Like other studies (Iguchi &

480   Hashimoto, 2000; Núñez-Peña et al., 2011; Núñez-Peña & Honrubia-Serrano, 2004; Núñez-Peña

481 & Suárez-Pellicioni, 2012; 2015; Szűcs & Soltész, 2010), we observed that the LPC effect is

482 greater in individuals with better performance, and that this difference was located in the right

483 frontal region. Meiri et al. (2012), who used functional near-infrared spectroscopy, observed that

484 the right frontal region is activated during simple additions, and this region is believed to be

485 responsible for holistic arithmetic processing (Dehaen et al., 2003; El Yagoubi et al., 2003). This

486 suggests that children in the GAP group perform a greater re-evaluation of incorrectness when

487 the proposed result was incongruent than when it was congruent, while children with dyscalculia,

488 perhaps due to the lack of arithmetic knowledge, re-evaluated almost all the results without

489 distinction between congruent and incongruent conditions.

490 Differences in topography were also observed between groups: The GAP group showed the LPC

491 effect in the expected right posterior location, while the DYS group exhibited this effect in the

492 left posterior region (see Fig. 5). The right lateralisation of the LPC effect in children with

493 good academic performance is consistent with the more deliberative and prolonged role of the

494 right hemisphere during probe evaluation, which has been found in adults during a

495 multiplication verification task (Dickson & Federmeier, 2017). According to these authors,

496 after an initial period of evaluation of the provided response (probe), the left hemisphere

497 classifies it as correct or incorrect and no longer performs follow-up evaluations, while the

498 right hemisphere engages in a deliberate assessment of the additional features of the probe,

499 perhaps using spatial skills, to provide an evaluation that is less categorical. It is therefore

500 possible that children with dyscalculia intentionally search for the correct answer from their

501 long-term memory (left hemisphere), but failing to find the answer, they then perform the

502 arithmetic calculation. Although the topography recorded from the scalp does not necessarily

503 indicate the generators' location, different topographies indicate the presence of distinct

504   generators (Nunez & Srinivasan, 2006). Our results may suggest that the left lateralisation of

505   the LPC effect observed in children with dyscalculia is a compensatory phenomenon to obtain

506   the correct answer.

507   4.3 Heterogeneity within the DYS group

508   In contrast to our expectations, we found few differences between groups in the arithmetic N400

509   and LPC effects. The heterogeneity in the children's behaviour (Fig. 1 and Fig. 4), which was

510   enhanced in the WM behavioural scores (Fig. 1.B), and ERP patterns (Fig. 7) of the DYS group,

511   could explain this finding. Two main hypotheses have been proposed to explain atypical brain

512   functioning that is reflected as neurobiological disorders of cognitive processing (Silver et al.,

513   2008) that underlie learning disorders (Landerl et al., 2009). In addition to the *domain-specific*

514   *hypothesis*, which refers to abilities specifically related to mathematical competencies, the

515   *common-deficit hypothesis* postulates that certain processing patterns are common to all children

516   with learning disorders. Supporting this hypothesis, Swanson (1987) proposed that children with

517   learning disorders experience failures in executive functioning mechanisms, which also points to

518   WM deficits as essential problems (Berninger, 2008; Swanson, 2015; Swanson & Siegel, 2001).

519   In children with arithmetic disabilities, WM has been frequently reported to play an essential role

520   in the arithmetic domain (Swanson, 2015). In our study, once children had performed the

521   addition operation, they had to store the result in WM until the probe digit appeared (1500 ms

522   later) to perform the response verification process and finally provide an answer. Therefore, the

523   arithmetic verification task that we used is particularly efficient for highlighting WM problems.

524   4.4 Working memory and dyscalculia

525   Consistent with our hypothesis, the children with dyscalculia showed a lower WM index than

526   those in the GAP group. This finding aligns with previous studies where WM was found to

527   predict learning arithmetic (Meyer et al., 2010; Vanbinst & De Smedt, 2016), as well as a

528   study by Mammarella et al. (2017), which reported that children with dyscalculia had low

529   scores for WM. Since the arithmetic N400 effect reflects a facilitation for the probe stimulus that

530   matches the correct answer, it may be the case that the absence of this effect is associated with

531   poor WM. Keeping the information of the addition in WM, as children with good academic

532   performance likely do, facilitates recognition or rejection of the proposed result.

533   However, it is important to emphasise that the WM performance in the DYS group was not

534   homogeneous. And while exploring the relationship between WM and arithmetic processing in

535   the DYS group, we discovered that children with higher WM index scores showed a greater

536   amplitude of the LPC effect in the right posterior region. This region coincides with the LPC

537   topography observed in previous studies (Niedeggen & Rösler, 1999; Núñez-Peña & Escera,

538   2007; Núñez-Peña & Honrubia-Serrano, 2004) and in our control participants.

539   This relationship between WM and the LPC effect was elucidated in the present study and

540   contributes to the understanding of dyscalculia in children. For a more thorough exploration of

541   the WM effect in children with dyscalculia, children in the DYS group were classified into two

542   groups (average and lower-than-average) according to their WM index. Visual inspection of ERP

543   patterns from these two groups showed that the children with dyscalculia and an average WM

544   index had a similar ERP pattern to that in the children with good academic performance, while

545   the children with dyscalculia and a lower-than-average WM index showed an atypical ERP

546   pattern (Fig. 9). Visual inspection of the ERPs suggests that this atypical pattern consisted of two

547   negative peaks (at 195 ms and 405 ms) over the parieto-occipital and centro-parieto-temporal

548   regions and two positive peaks (at 525 ms and 685 ms) over the parietal regions. The two

549 negativities could correspond to the N200 and arithmetic N400 effects, while the two positivities

550 may correspond to the two LPC effects. The N200 effect might be interpreted as evidence that

551 children with dyscalculia and poor WM engaged additional attentional resources (Xuan et al.,

552 2007). However, this N200 effect had a posterior topography; which may instead reflect a strong

553 early sensory attention (Schmajuk et al., 2006) before the comparison between the probe

554 stimulus and the sum result, which produces an arithmetic N400 effect. Later, the children

555 probably re-evaluated the arithmetic error (Núñez-Peña & Suárez-Pellicioni, 2012) twice.

556 It is noteworthy that the categorisation of the ERP patterns of the DYS group into two subgroups

557 was based on visual inspection. Ideally, we would have compared the ERPs of the children with

558 dyscalculia with poor WM and typical WM statistically, but the sample sizes of these two

559 subgroups were too small. It would be useful if future studies could conduct these statistical

560 comparisons to help clarify whether the atypical ERP pattern that we observed is reliably

561 association with dyscalculia, poor WM, or both difficulties combined.

562

563 **5. Conclusions**

564 Children with dyscalculia did not show the arithmetic N400 effect found in children with typical

565 development during an arithmetic verification task; however, both groups showed an LPC effect.

566 The great heterogeneity within the group of children with dyscalculia precluded a robust LPC

567 effect in these children; however, the higher the WM deficits were, the lower the LPC effect was

568 in the right posterior region. In children with dyscalculia and WM deficits, an atypical ERP

569 pattern (i.e., N200, N400 and two LPC effects) was evinced. Therefore, future studies of both

570 working memory and ERPs in children with dyscalculia must be mindful of the heterogeneous

571   nature of dyscalculia at both the level of behaviour and the brain function.

572

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584   The authors declare that they have no competing interests.

585

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859

860

861   **FIGURE CAPTIONS**

862   Fig. 1. **Variability of arithmetic subdomains and WM index in both groups.** (A) Box-and-

863   whisker plots of the subdomains (counting, number management, and calculus) of the arithmetic

864   subtest of the Child Neuropsychological Assessment in both groups of children (GAP and DYS).

865   (B) Box-and-whisker plots of the working memory index of the Wechsler Intelligence Scale for

866   Children, 4th Edition, Spanish version. The error bars represent the standard deviation.

867   Fig. 2. **Depiction of a trial of the addition verification task.** Flowchart of stimuli presentation

868   during individual trials, W: warning stimulus.

869   Fig. 3. **Workflow of the statistical analyses of ERP data using non-parametric permutation**

870   **tests**. (A) Definition of analysed time windows, where significant differences between

871   incongruent and congruent conditions (effects) were evinced; comparison between conditions

872   using multiple t-tests, shown at each point of time throughout the electrode sites (colour lines in

873   the coordinate axis). Magenta horizontal lines represent the threshold of t-values for $p = 0.05$,

874   and grey shadowed boxes represent the analysed time windows where significant differences

875   were found. Colour lines in the coordinate axis represent t-values at different electrode sites. (B)

876   Exploration of the topography of ERP effects (incongruent minus congruent) obtained from (A);

877   t- tests were computed using the mean amplitude values in each condition for each analysed time

878   window (N400 and LPC in the group GAP and LPC in the group DYS) across all electrode sites.

879   (C) Comparison of the ERP-difference wave between the DYS and GAP groups. Mean

880   amplitude values of the difference waves were used to compute the t-tests. (D) Correlation

881   analyses between the working memory index and ERP difference waves for the DYS group, for

882   each electrode site and each ERP window.

883   Fig. 4. **Behavioural data in both groups of children (GAP and DYS) in the arithmetic**

884   **verification task.** The correct answer (A) and mean response time (B) in both conditions

885   (congruent and incongruent) and both groups of children. Error bars represent the standard

886   deviation. The DYS group showed a lower percentage of correct answers than the GAP group.

887   ***p < 0.0001

888   Fig. 5. **Statistical parametric maps of the arithmetic N400 and LPC effects in both groups.**

889   Top: GAP group. (A) Differences between conditions at 305 to 385 ms (arithmetic N400). (B)

890   Differences between conditions at 510 to 630 ms (LPC effect). Bottom: DYS group. (C)

891   Differences between conditions at 680 to 700 ms (LPC effect). Blue and red colours represent

892   the t-values that were above the threshold of significance (p < 0.001). In the GAP group, the

893   arithmetic N400 effect was elicited at P3, O1, T4, T5, Fz, and Pz, and the LPC effect was elicited

894   at C4, P4, O1, O2, T4, T6, Cz, and Pz, while in the DYS group, the LPC effect was observed at

895   P3 and O1. All p < 0.001

896   Fig. 6. **ERP wave grand averages.** (A) T3 electrode. (B) C3 electrode. The GAP group

897   responses to congruent and incongruent conditions are represented by the black continuous and

898   discontinuous lines, while the DYS group responses to congruent and incongruent conditions are

899   represented by the red continuous and discontinuous lines, respectively. Negativity is plotted

900   downwards.

901   Fig. 7. **Differences between groups in arithmetic N400 and LPC effects.** (A) Statistical map

902   of the comparison between groups based on the difference between conditions (incongruent

903   minus congruent) for the arithmetic N400 (305–385 ms) at T5. (B) Statistical map of the

904   comparison between groups based on the difference between conditions (incongruent minus

905   congruent) for the LPC (510–630 ms) at Fp2. The blue and red spots represent significant

906   differences between groups (t-values p < 0.05).

907   Fig. 8. **Variability of arithmetic N400 and LPC effects.** (A) Box-and-whisker plots of both

908   groups of children (GAP and DYS) using the amplitude values of the arithmetic N400 (305–385

909   ms) effect. (B) Box-and-whisker plots of both groups of children using the amplitude values of

910   the LPC (510–630 ms) effect.

911   Fig. 9. **Grand averages of the difference waves (i.e., incongruent minus congruent**

912   **condition).** Blue solid lines represent the ERPs for the GAP group. Red solid lines represent the

913   ERPs for the DYS group with high WM index scores and red dotted lines represent those for the

914   DYS group with low WM index scores. Positive is plotted up. The arithmetic N400 effect and

915   the LPC effect in the GAP group are marked with grey-shadow boxes. Black arrows indicate

916   double-negative peaks (195 ms and 405 ms) and double-positive peaks (525 ms and 685 ms) in

917   the DYS group with low WM scores at P3 and C3, but such effects can be observed over other

918   electrode sites. Each letter represents an electrode. (A) Fp1. (B) Fp2. (C) F3. (D) F4. (E) C3. (F)

919   C4. (G) P3. (H) P4. (I) O1. (J) O2. (K) F7. (L) F8. (M) T3. (N) T4. (O) T5. (P) T6. (Q) Fz. (R)

920   Cz. (S) Pz.

921   Fig. 10. **Relationship between working memory and LPC effect in the DYS group.** (A)

922   Statistical map of the correlations between the WM index and the ERP amplitude difference

923   between conditions (incongruent minus congruent) at 510 to 630 ms (LPC effect) across

924   electrode sites. The red spot represents the significant r values (p < 0.05) over the T6 and O2

925   electrodes. (B) Ascending regression line showing that higher values of the working memory

926   index (X axis) are associated with greater LPC effects in the electrode T6 (Y axis). (C)

927   Ascending regression line showing that higher values of the working memory index (X axis) are

928   associated with greater LPC effect in the electrode O2 (Y axis).

929

930

Differences between groups in terms of demographic features, arithmetic performance and intelligence quotient

ENI: Child Neuropsychological Assessment (Matute et al., 2005); **WISC-IV**: The Wechsler Intelligence Scale for Children, 4th Edition Spanish version (WISC-IV; Wechsler, 2007); **GAP**: children with good academic performance; **DYS**: children with dyscalculia.

	Mean ± SD		t(42)	p-value
	GAP	DYS		
Age (years)	9.41 ± 1.182	9.77 ± 0.813	-1.189	0.241
Monthly economic income	2421 ± 1188.81	1983 ± 1209.76	1.211	0.233
ENI subscales (arithmetic domain)				
Counting	65.27 ± 15.03	24.55 ± 23.86	6.772	< 0.001
Number management	59.73 ± 23.03	13.91 ± 17.68	7.400	< 0.001
Calculus	68.18 ± 20.99	20.91 ± 26.08	6.622	< 0.001
Logical mathematical reasoning	68.45 ± 22.28	51.41 ± 35.02	1.926	0.061
WISC-IV indexes				
Intelligence quotient	105.95 ± 10.86	89.55 ± 10.82	5.017	< 0.001
Verbal comprehension index	102.41 ± 20.69	86.23 ± 21.62	2.536	0.015
Perceptual reasoning index	100.59 ± 18.71	85.68 ± 20.83	2.947	0.017
Working memory index	104.23 ± 11.48	89.36 ± 13.85	3.875	< 0.001
Processing speed index	97.95 ± 20.71	91.68 ± 14.32	1.168	0.249
WISC-IV subtests				
Similarities	10.77 ± 2.72	8.59 ± 4.22	2.035	0.048
Vocabulary	11.64 ± 2.82	8.55 ± 2.24	4.024	< 0.001
Comprehension	10.82 ± 3.11	8.09 ± 2.87	3.019	0.004
Block design	10.86 ± 2.76	8.68 ± 2.62	2.684	0.010
Picture Concepts	10.59 ± 2.70	8.86 ± 2.66	2.137	0.038
Matrix reasoning	10.45 ± 2.28	8.41 ± 1.91	3.217	0.002
Digit span	10.73 ± 2.12	7.68 ± 2.41	4.442	< 0.001
Letter-number sequencing	11.23 ± 2.20	8.14 ± 2.73	4.133	< 0.001
Arithmetic	14.00 ± 3.14	9.75 ± 2.86	4.417	< 0.001
Coding	10.23 ± 2.56	8.64 ± 1.94	2.322	0.025
Symbol search	10.41 ± 2.21	9.27 ± 2.18	1.711	0.094

Figure 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. The error bars represent the standard deviation.

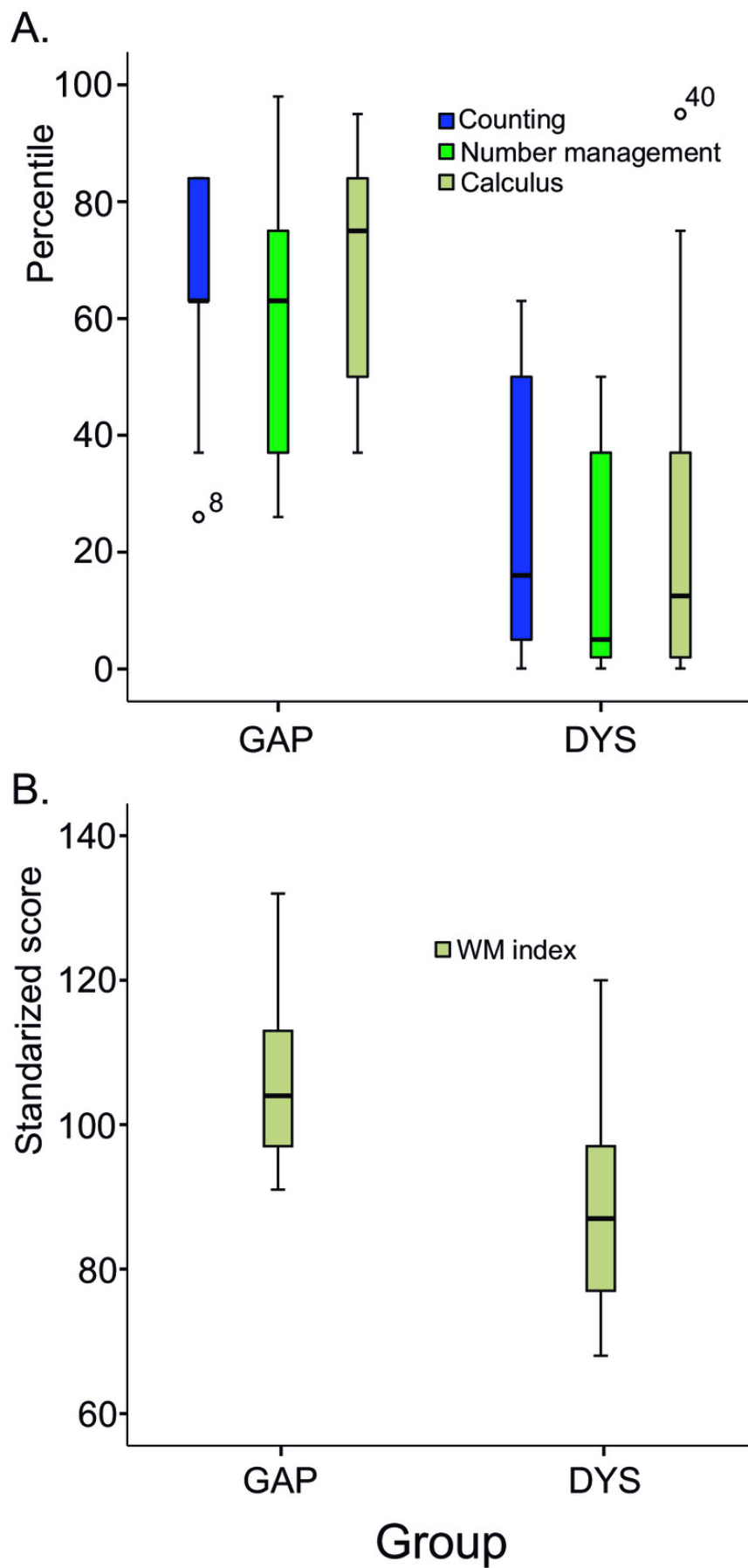



Figure 2

Depiction of a trial of the addition verification task.

Flowchart of stimuli presentation during individual trials, W: warning stimulus.

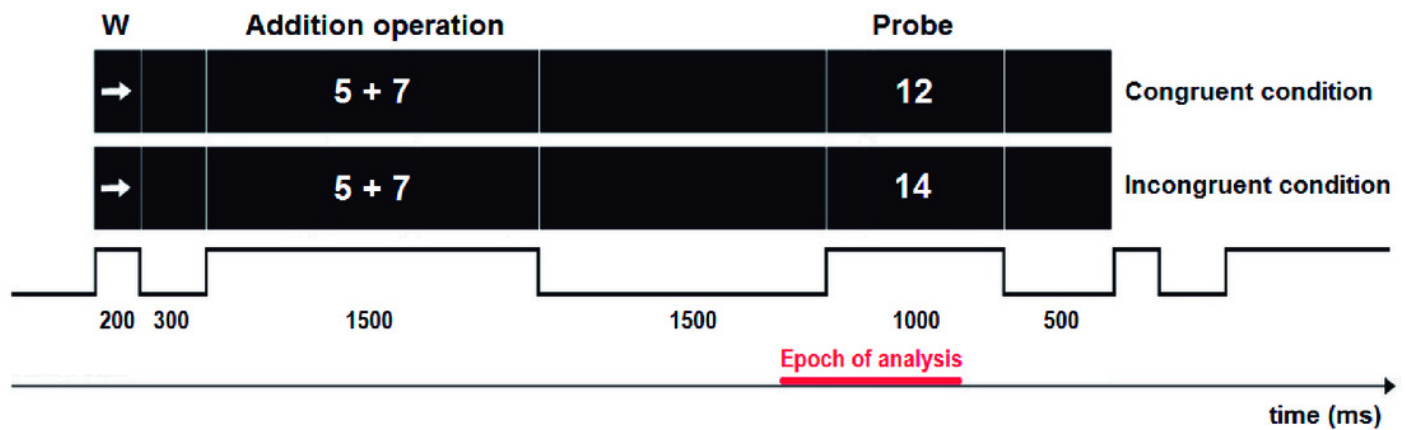
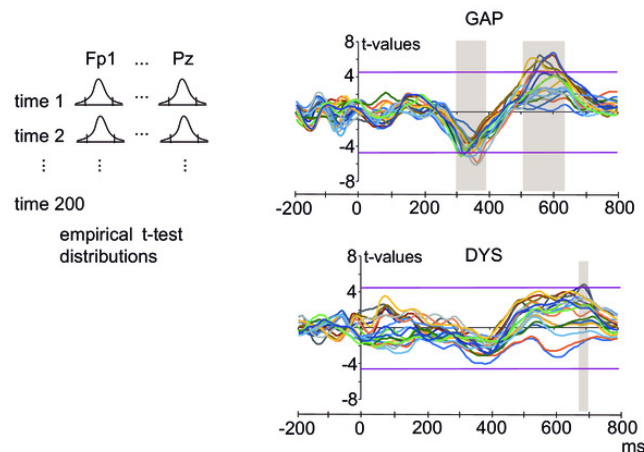
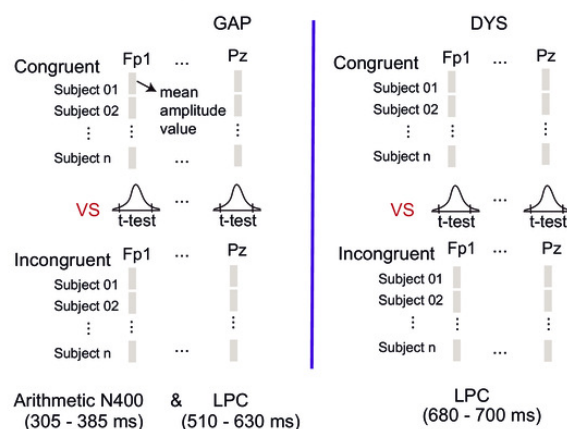
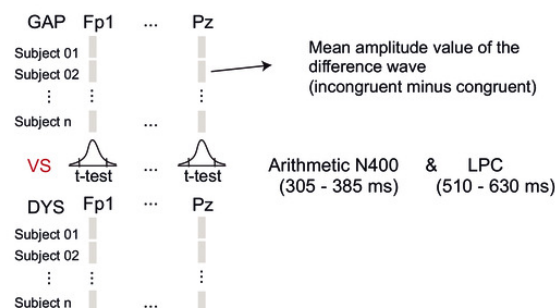



Figure 3

Workflow of the statistical analyses of ERP data using non-parametric permutation tests.

(A) Definition of analysed time windows, where significant differences between incongruent and congruent conditions (effects) were evinced; comparison between conditions using multiple t-tests, shown at each point of time throughout the electrode sites (colour lines in the coordinate axis). Magenta horizontal lines represent the threshold of t-values for p = 0.05, and grey shadowed boxes represent the analysed time windows where significant differences were found. Colour lines in the coordinate axis represent t-values at different electrode sites. (B) Exploration of the topography of ERP effects (incongruent minus congruent) obtained from (A); t- tests were computed using the mean amplitude values in each condition for each analysed time window (N400 and LPC in the group GAP and LPC in the group DYS) across all electrode sites. (C) Comparison of the ERP-difference wave between the DYS and GAP groups. Mean amplitude values of the difference waves were used to compute the t-tests. (D) Correlation analyses between the working memory index and ERP difference waves for the DYS group, for each electrode site and each ERP window.

A. Defining analysis time-window

B. Topographical exploration of ERP effects

C. Between-group comparison of ERP effects

D. Correlation analyses

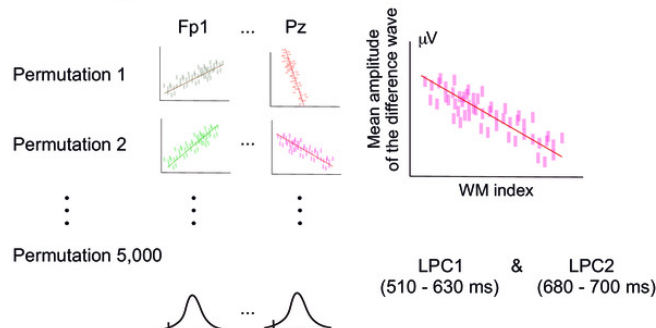



Figure 4

Behavioural data in both groups of children (GAP and DYS) in the arithmetic verification task.

The correct answer (A) and mean response time (B) 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

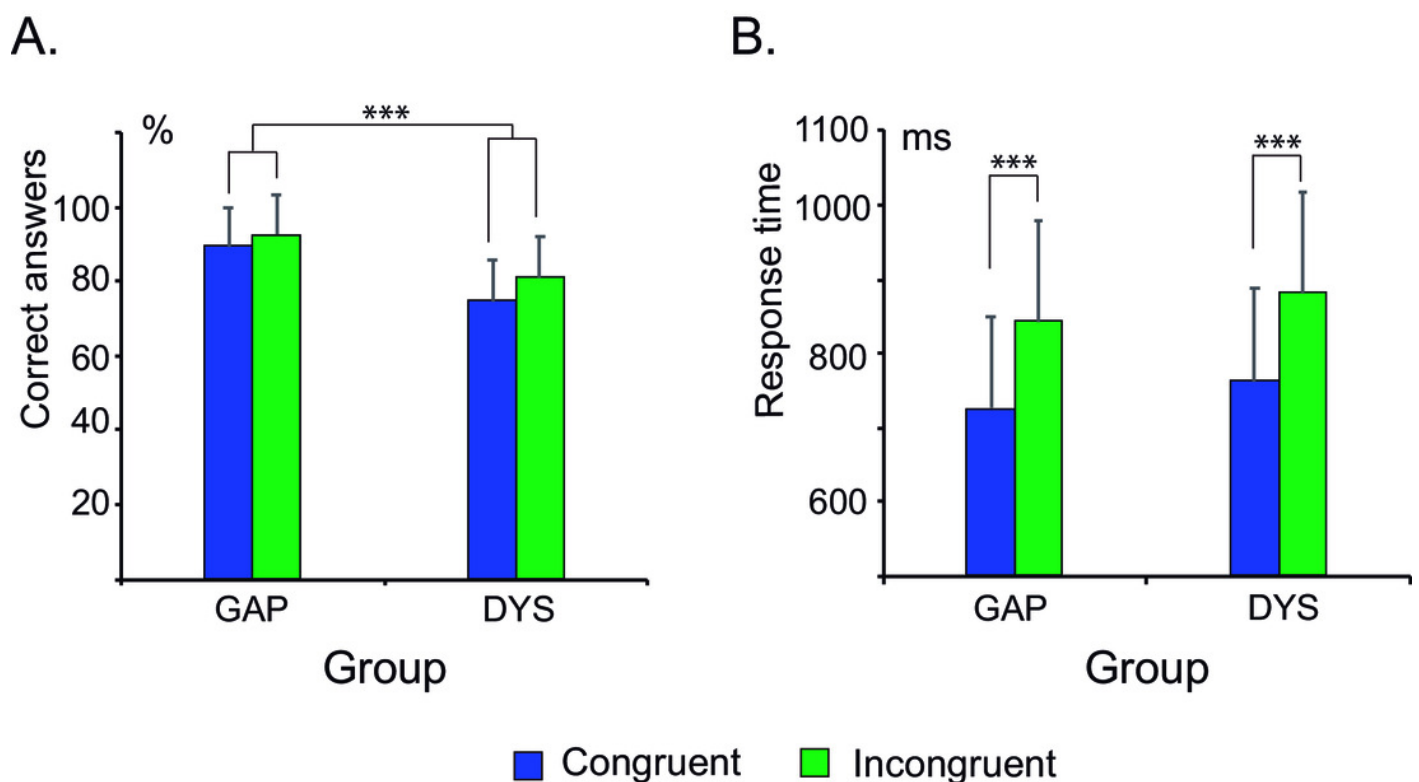



Figure 5

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 colours 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

A.

B.

GAP group

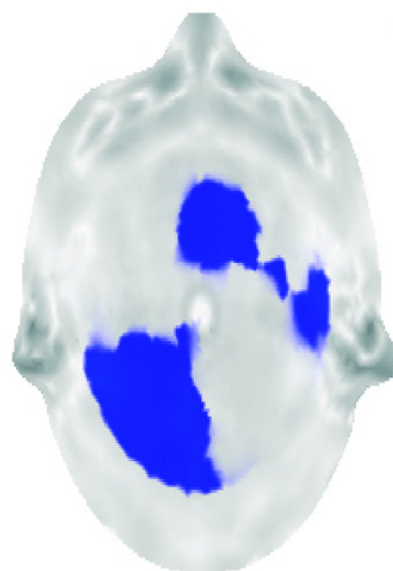
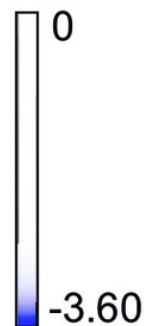
t-values

0

-3.60

Arithmetic N400
(305 - 385 ms)

3.58

0

LPC
(510 - 630 ms)

C.

DYS group

t-values

3.68

0

LPC
(680 - 700 ms)

Figure 6

ERP wave grand averages.

(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.

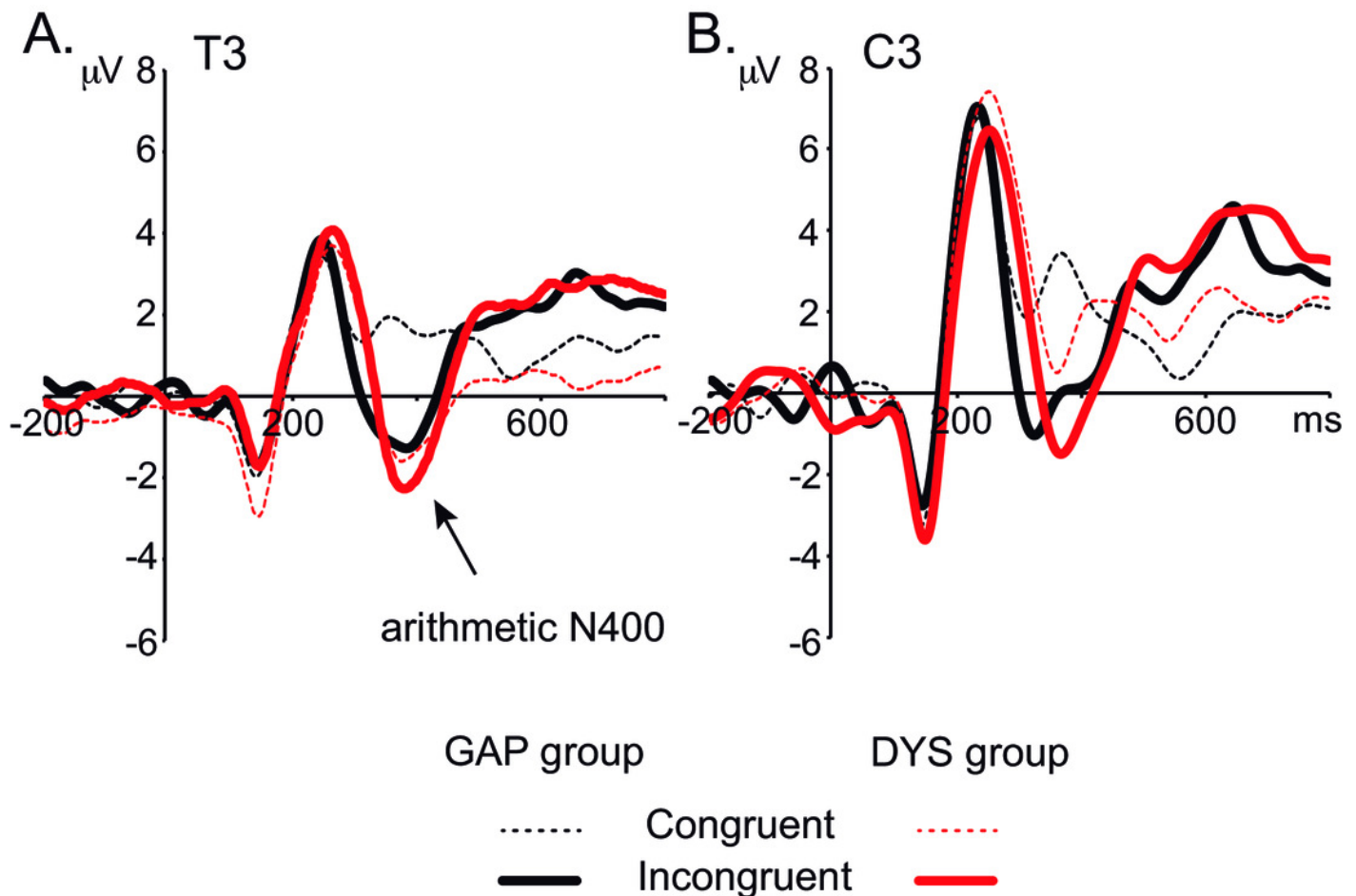



Figure 7

Differences between groups in arithmetic N400 and LPC effects.

(A) Statistical map of the comparison between groups based on the difference between conditions (incongruent minus congruent) for the arithmetic N400 (305–385 ms) at T5. (B) Statistical map of the comparison between groups based on the difference between conditions (incongruent minus congruent) for the LPC (510–630 ms) at Fp2. The blue and red spots represent significant differences between groups (t-values p < 0.05).

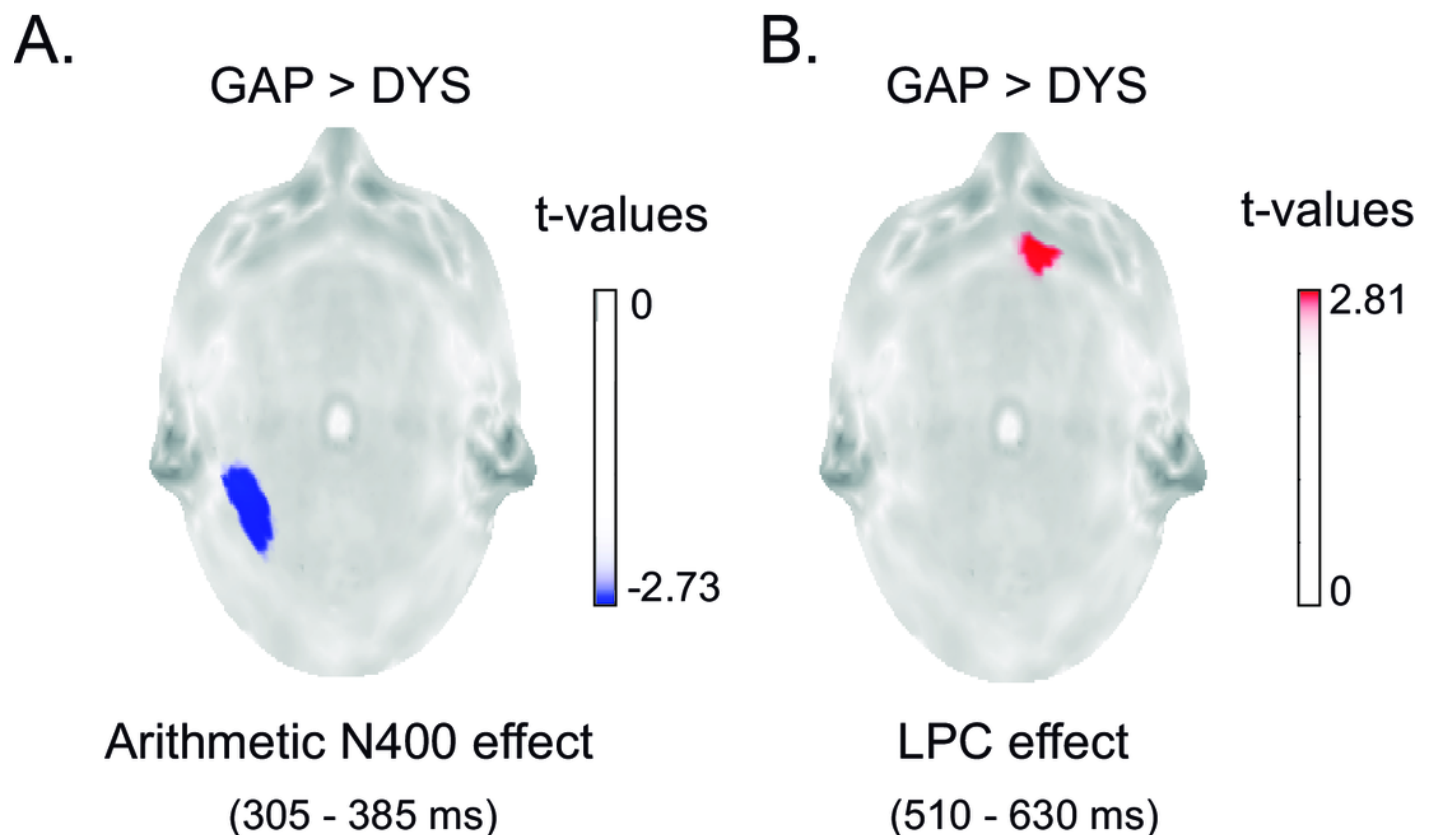



Figure 8

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.

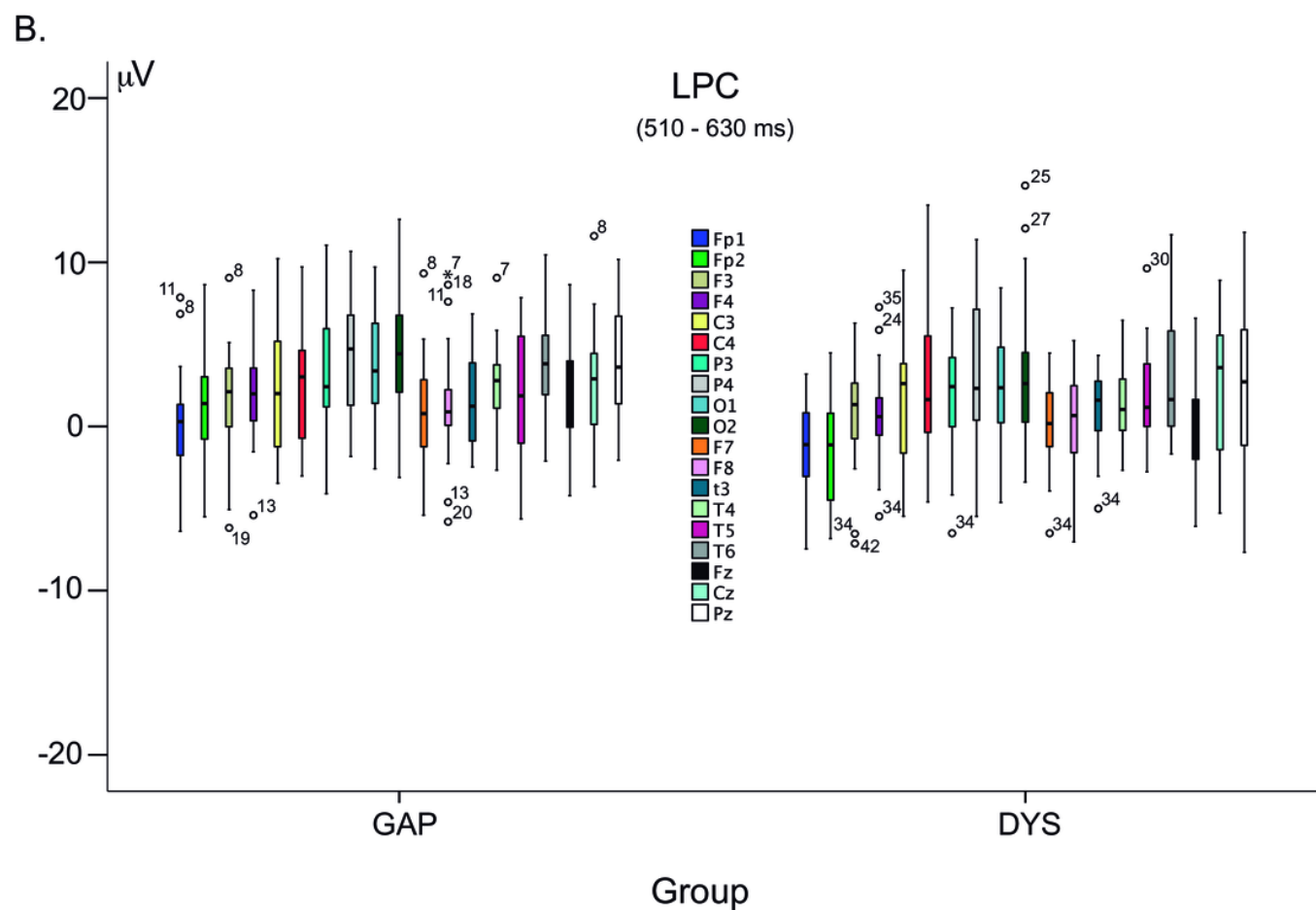
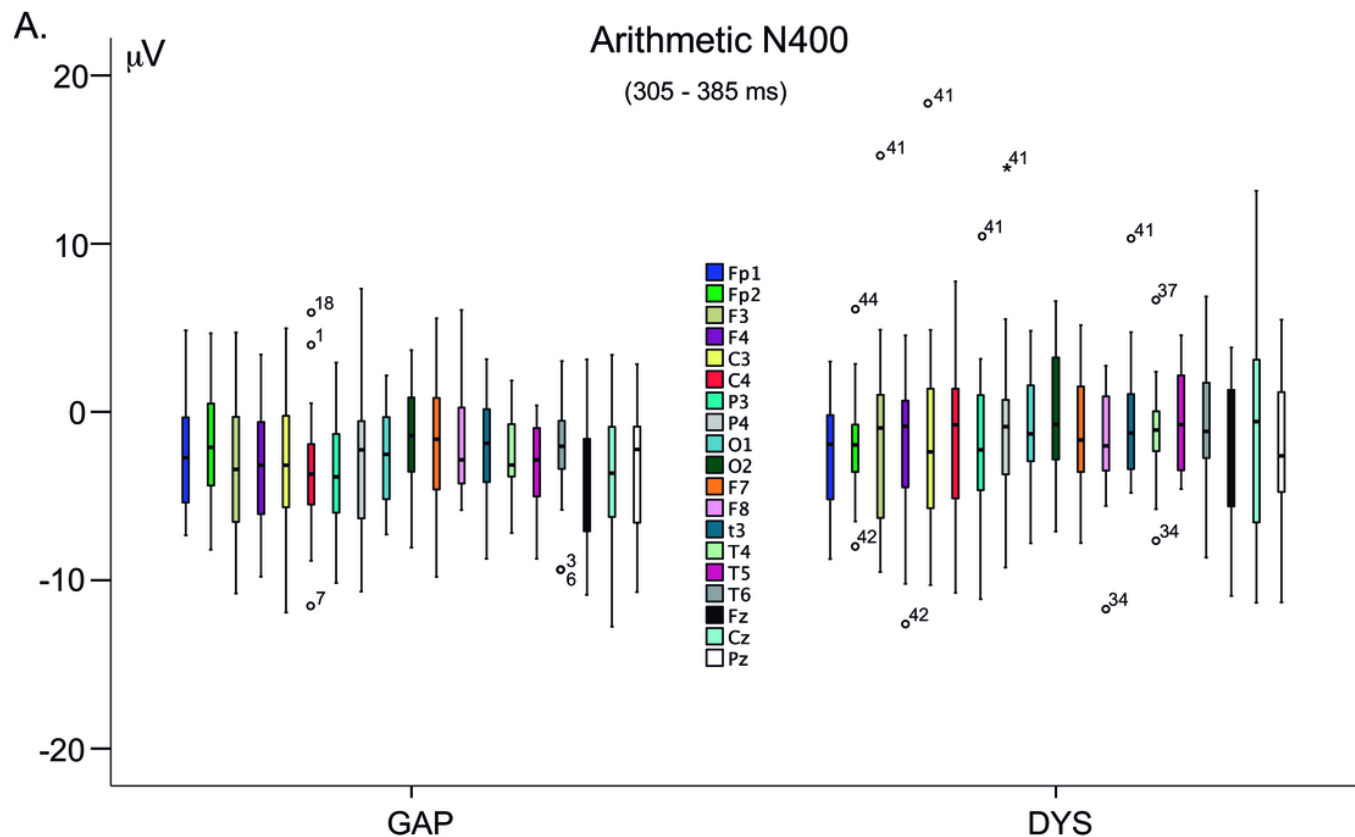



Figure 9

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 grey-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.

GAP
DYS H WM
DYS L WM

A. Fp1
B. Fp2
C. F3
Q. Fz
D. F4
K. F7
L. F8
E. C3
R. Cz
F. C4
M. T3
N. T4
G. P3
S. Pz
H. P3
O. T5
P. T6
I. O1
J. μV8 O2

-200
-4
600 800 ms

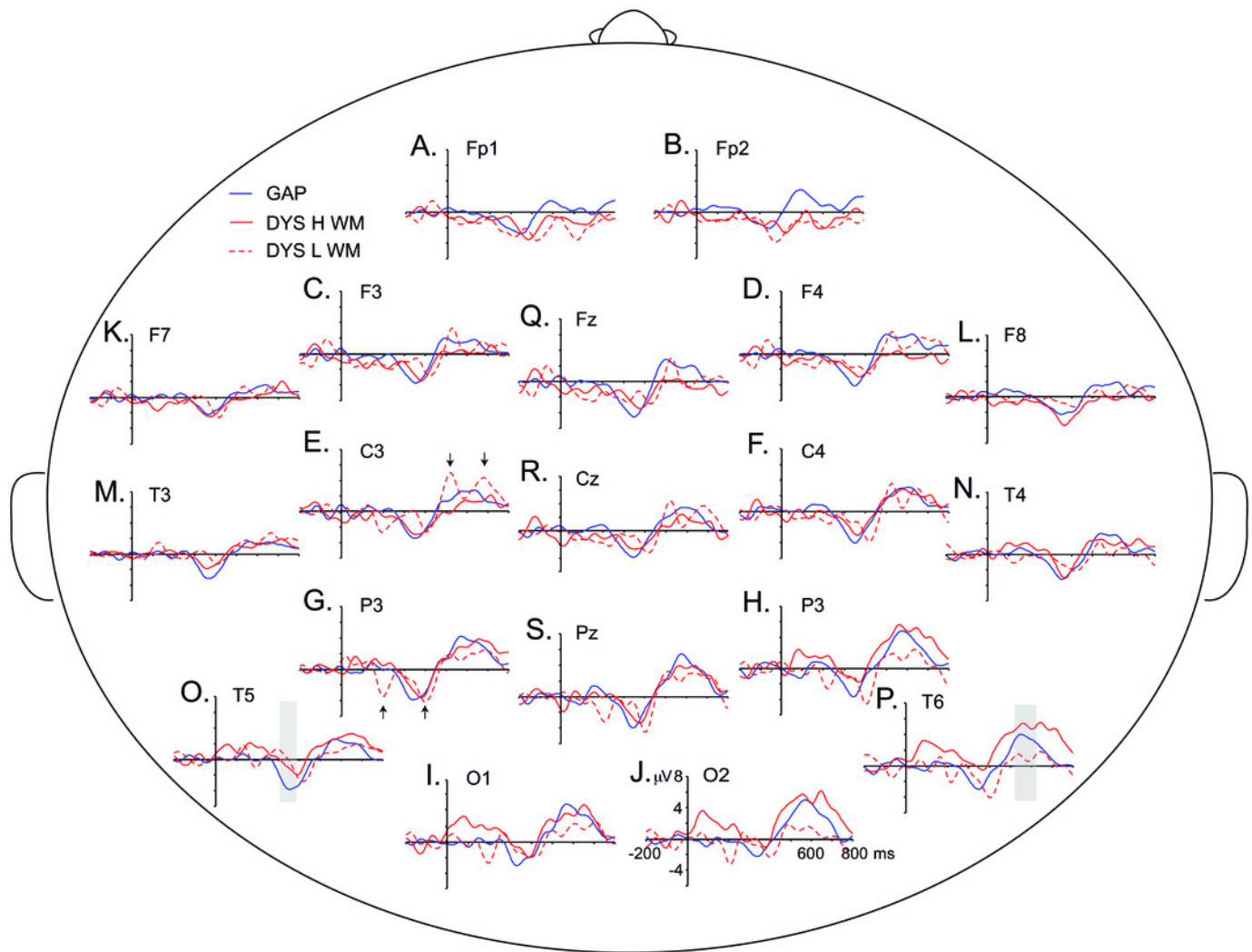



Figure 10

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 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 effects 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).

A.

LPC

(510 - 630 ms)

B.

C.

D.

LPC

(680 - 700 ms)

E.