An event-related brain potential study of the arithmetic split effect

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Abstract

This study explores the split effect on arithmetical sequence processing using event-related brain potentials (ERPs). This effect has been reported in arithmetic problem verification tasks and refers to an increase in reaction time when an incorrect solution close to the correct one is presented. The use of different strategies has been suggested to account for this effect: a whole-calculation strategy for close incorrect solutions (small-split problems), and a plausibility-checking strategy for far or obviously incorrect solutions (large-split problems). In the present study, participants were asked to verify whether the last item of a numerical sequence was correct or not, according to the rule established by the preceding numbers. Subjects were presented with sequences of numbers, and the distance between the proposed and the correct ending was manipulated by presenting the correct ending, a small-split ending or a large-split ending. To avoid problems that violated the parity rule only even numbers were presented. Two ERP components were evident whenever the arithmetical sequence was broken: an early negativity peaking at about 270 ms and a subsequent late positivity component (LPC) peaking between 550 and 650 ms. The early negativity was larger at posterior sites. The late positivity had a centro-parietal scalp distribution, and its amplitude was sensitive to the numerical distance from the correct number: the greater the distance, the larger the positivity. The present results suggest that the centro-parietal LPC can be taken as an index of the split effect and may broaden our knowledge about arithmetical processing strategies.

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1. Introduction

Number processing and mathematical calculation is a field of research with a growing interest in cognitive neuroscience (for a recent review, see Campbell, 2005). Several phenomena have been described concerning the processing of numerical information, but one of the most robust phenomena is the effect of the manipulation of the numerical distance between the proposed and the correct solutions in a problem verification task. This is usually known as the split effect (Ashcraft and Battaglia, 1978; Ashcraft and Stazyk, 1981) and it is the core of this paper.

The split effect appears in verification tasks of simple mental calculation problems where incorrect solutions close or far from the correct solution are presented. Put in a nutshell, this effect consists of a slower and less accurate response when the proposed solution is a number close to the correct solution. The suggested explanation for the split effect is that two different strategies to solve arithmetical problems are used (Duverne and Lemaire, 2005; El Yagoubi et al., 2003, 2005). When the proposed solution is close to the correct solution, subjects may use an exhaustive verification strategy — the whole-calculation strategy — to achieve the exact calculation. However, when the proposed solution is a long way from the correct one, subjects may not need to obtain the exact calculation and may give their answer by using an easier and faster estimation strategy — the plausibility-checking strategy. Thus, one can speculate that when an incorrect solution near the correct one is presented in an arithmetical task (from now on, small-split solution), subjects need to calculate the problem to decide about the correctness of the proposed solution. By contrast, when an incorrect solution that is a long way from the correct one is presented (from now
on, far-split solution), subjects may not need to calculate the problem to give their answer of incorrectness.

Event-related potential (ERP) studies of brain activity have reported a late positive slow wave at parietal sites functionally related to mental arithmetical calculation (Iguchi and Hashimoto, 2000; Núñez-Peña et al., 2005, 2006; Pauli et al., 1994, 1996). This component can be useful to shed new light on the split effect and to find out whether this effect reflects the type of strategy used to solve arithmetical problems. If subjects need to calculate the problem when a small-split solution is presented in a verification task, the late positive slow wave is expected to be elicited, because exact calculation is necessary. However, this late positive slow wave should not be elicited by large-split solutions, because the problem can be solved by a plausibility-checking strategy.

Previous studies with ERPs have reported a number of findings regarding the effects of violations of arithmetical rules in verification tasks (Niedeggen and Rösler, 1999; Núñez-Peña and Honrubia-Serrano, 2004; Szücs and Csépe, 2004, 2005). Niedeggen and Rösler (1999) presented simple multiplication problems and asked participants to judge their correctness. Incorrect solutions elicited a negativity peaking at about 400 ms followed by a posteriorly distributed late positive component (LPC). In the incorrect solutions, the distance from the correct number was manipulated and the results showed that the amplitude of the late positivity increased monotonically with the size of the numerical distance between the incorrect and correct solutions. These authors related this positive deflection to the P3b component, which is assumed to indicate the amount of surprise or context updating (Donchin and Coles, 1988). Similar results to those of Niedeggen and Rösler (1999) have been reported by Szücs and Csépe (2004, 2005) when participants verified simple additions. These authors also reported a late positive component elicited by incorrect solutions. Although they manipulated the numerical distance from the correct solutions, no modulation of the amplitude of the late positive component was found. Szücs and Csépe (2004, 2005) also reported a negative component in response to incorrect arithmetical results, but in this case it was earlier (at about 270 ms post-stimulus) than that reported by Niedeggen and Rösler (1999).

In a recent study (Núñez-Peña and Honrubia-Serrano, 2004), we have reported a similar positive component using numerical sequences. Sequences of seven numbers were presented, and participants were asked to judge the correctness of the last number in the sequence. For the incorrect endings, the numerical distance was manipulated in such a way that the target could deviate by ±1 or ±25 from the correct ending. Incorrect numbers elicited an early negativity, peaking at about 270 ms, followed by a late positive component. The late positivity had a latency between 500 and 600 ms post-stimulus and a centro-parietal scalp distribution. Moreover, its amplitude was sensitive to numerical distance, being largest when the number presented was furthest from the correct one. On the basis of these results, we suggested that this positivity was functionally similar to the syntactic P600 component (Frisch et al., 2002; Kaan et al., 2000; Kaan and Swaab, 2003a,b; Osterhout et al., 1994), and so similar neurophysiological processes may be required for processing numerical sequences and linguistic syntactic structures.

Summarizing, in all previous studies a pattern of a negative component followed by an LPC has been described whenever an incorrect solution to an arithmetical problem is presented. The modulation of the positive component as a function of the distance between correct and incorrect solutions has been explained in different ways, but it may also be explained in terms of the type of arithmetical problem solving strategy that subjects used to verify the problem. It has been suggested elsewhere (Iguchi and Hashimoto, 2000; Núñez-Peña et al., 2005, 2006; Pauli et al., 1994, 1996) that a parietally distributed positive slow wave can be taken as a direct electrophysiological correlate of the exact calculation. Therefore, the positive slow wave elicited by small-split problems might be due to the use of a whole-calculation strategy, whereas the sharp late positive wave elicited by large-split problems might result by the use of a plausibility-checking strategy. Although the late positive slow wave reported in these studies (Niedeggen and Rösler, 1999; Núñez-Peña and Honrubia-Serrano, 2004) could be taken as an index of the use of an exact calculation strategy to verify small-split problems, this conclusion could be invalidated by the fact that the split effect might have been disturbed in these studies by another effect that is well established in the literature: the odd–even effect. The odd–even effect consists of the faster rejection in verification tasks of an incorrect proposed result if its parity differs from the parity of the expected correct result. This effect has been described both in additions — i.e., $4 + 6 = 12$ — (Krueger and Hallford, 1984; Vandorpe et al., 2005) and multiplications — i.e., $4 \times 6 = 25$ is rejected faster than $4 \times 6 = 26$ — (Krueger, 1986; Lemaire and Fayol, 1995; Masse and Lemaire, 2001). The explanation of this effect is that subjects use a parity rule such as “a sum must be odd if an odd number of its addends are odd, otherwise it must be even” and “a product must be even if either one or both of its multipliers is even, otherwise it must be odd” (Vandorpe et al., 2005). The fact is that if a small-split solution that violates the parity rule is presented in a verification task, participants may not need to calculate the problem to give their answer of incorrectness (i.e., $4 + 6 = 11$), because they can solve the problem by means of the parity-checking strategy. As a consequence, a whole-calculation strategy would not be used to achieve the exact calculation although the distance between the correct and the proposed solution was small. As we have previously mentioned, some studies that have investigated the split effect on the ERPs while subjects verify arithmetical problems have not accounted for the possibility that the split effect could have been disturbed by the odd–even effect. Therefore, the ERP pattern observed in small-split problems would not be attributed to the fact that subjects used an exhaustive calculation strategy in these studies.

1.1. The present study

The purpose of the present study was to investigate the split effect on arithmetical sequence processing with ERPs. To
prevent subjects from using the parity-checking strategy — in other words, to isolate the split effect from the odd–even effect — only even numbers were used. Participants were presented with sequences of five even Arabic numbers that could be finished by a number that completed the sequence correctly (e.g. 6–10–14–18–22) or by a number that violated the sequence (e.g. 6–10–14–18–24). The size of the violations varied: the incorrect number could deviate by ±2 (from now on, this will be referred to as the small-split ending) or +26 from the correct ending (referred to as the large-split ending).

Based on the literature reviewed above, our first prediction is that the distance between the proposed and the exact solution will influence subjects’ performance. Specifically, small-split endings are expected to elicit less accurate responses than both correct and large-split endings, replicating the standard split effect. Second, we hypothesized differences in the ERPs depending on the size of the split. A sharp late positive component is expected to be elicited by large-split problems and a late positive slow wave is expected to be elicited by small-split endings. The amplitude modulation of this LPC might suggest that different strategies are used to solve small- and large-split problems: a late positive slow wave has been related to mental arithmetic calculation and calculation strategies are considered to be necessary to verify small-split problems. Finally, a negative component preceding the positive component is expected to be elicited by both small- and large-split endings, as reported in previous studies.

2. Methods

2.1. Participants

Sixteen healthy volunteers were tested in this study (ten women; age 20–38 years, mean = 25.06, standard deviation = 5.52; fifteen right-handed). All were university students and had normal or corrected-to-normal visual acuity. Because of a large number of artifacts, the data from three participants were excluded from the ERP data analysis. Thirteen subjects (nine women; age 20–38 years, mean = 24.30, standard deviation = 4.89; twelve right-handed) took part in ERP experiment. Subjects had no history of neurological or psychiatric disorders, and gave written informed consent to participate after the nature of the study had been explained to them.

2.2. Stimuli

The stimuli were sequences of five even Arabic numbers, which were constructed in the following way: even numbers were selected to begin sequences, and the same constant quantity1 was consecutively added. Thus, forty-eight sequences were generated. The sequences ended in a number that was: a) a number that continued the sequence according to the same rule — correct ending; b) an incorrect number that deviated by ±26 from the correct one — large-split ending; and c) an incorrect number that deviated by ±2 from the correct one — small-split ending. For example, in the sequence 6–10–14–18, the correct ending was 22, the large-split ending was 48, and the small-split ending was 24.

The experiment was controlled by the STIM 2.0 program (NeuroScan Inc., Herndon, Va). Numbers were presented in white against a black background, and subtended a visual angle of 1.76° vertically and 1.10° (for one digit stimuli) or 2.42° (for two digits stimuli) horizontally.

2.3. Procedure

Each experimental session lasted approximately 2 h and 30 min, including preparation. Participants were seated in an electrically-shielded, sound-attenuating room at a distance of 130 cm from the screen, whose center was at eye level. The session began with a training block consisting of the presentation of some trials similar to those used in the recording session. To ensure that subjects understood the task to be performed, the training period finished when one of the following learning criteria was reached: a) the participant had answered correctly the first 10 consecutive trials; or b) the participant correctly answered 90% of trials. Feedback was given whenever a participant’s response was wrong. There was a 30 s break after every 20 trials.

When the training period was over, the recording period started. Each trial consisted of a sequence of five Arabic numbers that were successively presented on the screen. Numbers remained on the screen for 1000 ms and the inter-stimulus interval (ISI) was 1500 ms. After the presentation of the last number of the sequence, an asterisk was shown for 500 ms. The inter-trial interval was 1500 ms. Subjects were asked to judge whether the last number in the sequence was correct or incorrect by pressing the corresponding STIMPAD keys, with the same finger of each hand (responding fingers were counterbalanced across subjects). They were required to wait until an asterisk cue before responding. The asterisk also informed the subjects that the sequence had finished. Subjects were instructed to relax and to keep their eyes on the screen. They were also advised to blink during the presence of the asterisks or the break messages in order to reduce the probability of eye movements in the critical epochs. A message indicating a 30 s break appeared on the screen after 12 trials and there was a 5 min break in the middle of the recording session. In contrast with the training session, during the recording session no feedback was given in the case of incorrect responses.

All participants were tested on 432 trials, 144 for each type of stimulus. Twelve blocks of 36 trials were presented to every participant. A block included twelve trials of each type of stimulus (correct, small-split and large-split ending) presented pseudorandomly so that no more than three correct or three incorrect trials could appear consecutively.

2.4. Electrophysiological recording

EEG was recorded with the SynAmps/SCAN 4.3 hardware and software (NeuroScan, Inc., Herndon, Va) from 31 tin electrodes mounted in a commercial electro-cap (Electro-Cap

\[x_{i+1} = x_i + c,\]

where \(c\) is a constant that could take the values \(-2, -4, -6, 2, 4, 6\).
International, Eaton, OH). Nineteen electrodes were positioned according to the 10–20 International System: three electrodes were placed over midline sites at Fz, Cz, and Pz locations, along with 8 lateral pairs of electrodes over standard sites on frontal (FP1/FP2, F7/F8, F3/F4), central (C3/C4), temporal (T3/T4, T5/T6), parietal (P3/P4), and occipital (O1/O2) positions. Two electrodes were placed at Fpz and Oz, and ten electrodes were placed halfway between the following additional locations: fronto-central (FC1/FC2), fronto-temporal (FT3/FT4), centro-parietal (CP1/CP2), temporoo-parietal (TP3/TP4), and mastoids (L1/L2). The common reference electrode for EEG and EOG measurements was placed on the tip of the nose. EEG channels were continuously digitized at a rate of 500 Hz by a SynAmp™ amplifier (5083 model, NeuroScan, Inc., Herndon, Va). A band pass filter was set from 0.05 to 30 Hz, and electrode impedance was always kept below 5 kΩ. For monitoring eye movement and blinks, Fp1, Fp2, Fpz (for the vertical EOG), and an electrode placed at the external canthus of the right eye (for the horizontal EOG) were used.

2.5. Data analysis

2.5.1. Behavioral data

The percentage of correct responses was analyzed with a repeated-measures ANOVA, taking ending type (correct, small-split and large-split) as within-subjects factor (the Greenhouse-Geisser correction for sphericity departures was applied when appropriate). The F value, the uncorrected degrees of freedom, the probability level following correction, and the ε value are reported. Whenever a main effect reached significance, pairwise comparisons were conducted using t tests, and the Bonferroni adjustment was used to control for the increase in type I error. Tests of simple effects were calculated in the presence of a significant interaction. In this report, differences were considered significant at p < .05 for overall ANOVA.

2.5.2. EEG analysis

Analysis of the electrophysiological responses was carried out on the fifth number of the sequence. Firstly, epochs for every subject in each type of ending were averaged relative to a pre-stimulus baseline that was made up of the 100 ms of activity preceding the epoch of interest. Secondly, trials with artifacts (voltage exceeded ±50 μV in any channel) and those with response errors were excluded from the ERP average. The mean number of epochs included in each ERP average varied between 105 and 114 for the various types of stimuli used, and the minimum number of epochs included in any individual average was 49. Finally, ERPs were quantified as mean amplitude measures in the 250–300 and 550–650 ms latency windows following the onset of the fifth number of the sequence, which was the stimulus of interest. The first window covers the early negativity effect and the second window the late positivity effect.

A 3 × 3 × 5 repeated-measures ANOVA was performed on the ERP amplitudes at 15 electrodes (F7, F3, Fz, F4, F8, T3, C3,
Cz, C4, T4, T5, P3, Pz, P4, T6) taking as factors, ending type (correct, small-split and large-split), frontality (frontal, central, and parietal) and laterality (five levels from left to right — L1, L2, L3, L4, and L5). ERP scalp distribution analysis was performed on normalized amplitudes according to the across-subject average vector length (McCarthy and Wood, 1985; Picton et al., 2000). Statistical analyses were performed in the same way described to behavioral data. Topographic maps were plotted using the EEProbe 3.1 program (ANT Software BV, Enschede, The Netherlands).

3. Results

3.1. Behavioral data

The main purposes of the correct/incorrect judgment task were to ensure that participants were paying attention to the sequences during the measurement of ERPs, and to record accuracy data, which would allow us to establish to what extent split effect was present in our data. Reaction times were not recorded in this experiment because subjects were asked to respond only after an asterisk mark appeared on the screen, in order to avoid a contamination of the ERP by response-related activity.

ANOVA results showed a significant effect of ending type, $F(2,30)=16.82, p<.001, \varepsilon=.615$. Paired contrasts were carried out to determine more specifically which ending types differed from one another. Small-split endings were responded less accurately than correct endings, $F(1,15)=12.03, p=.003$, and than large-split endings, $F(1,15)=24.90, p<.001$. There were no significant differences in performance accuracy between correct and large-split endings. Means and standard errors (in parentheses) of percentage of correct response were 92.4 (.01), 95.3 (.02) and 82 (.04) for correct, large-split and small-split endings, respectively.

3.2. Event-related brain potentials

The grand average ERPs for the three ending types are shown in Fig. 1. Visual inspection of these ERPs reveals different waveforms for the three ending types. When a large-split ending was presented, the presence of an early negativity, peaking between 250 and 300 ms, was noted, followed by a sharp positive wave, peaking between 500 and 600 ms. This positive shift increased from frontal to posterior sites with an equal distribution over the two cerebral hemispheres. The effect was largest over centro-parietal sites (voltage maps indicating the distribution of the effects are shown in Fig. 2). A similar

![Fig. 2. A) The spatial distribution of the early negativity effect (the voltage difference between 250 and 300 ms) over all electrodes at the scalp surface. Left: Voltage differences between small-split and correct endings. Right: Voltage differences between large-split and correct endings. B) The spatial distribution of the late positivity effect (the voltage difference between 550 and 650 ms) over all electrodes at the scalp surface. Left: Voltage differences between small-split and correct endings. Right: Voltage differences between large-split and correct endings.](image-url)
ERP pattern can be seen in small-split endings, but, in this case, the early negativity was followed by a late positive slow wave, smaller than that elicited by large-split endings, and present only at posterior sites (difference waves obtained after subtracting small-split and correct endings, and large-split and correct endings are plot in Fig. 3). Again, inspection of the grand-averages and voltage maps showed no hemispheric asymmetries in the size of this late positivity. Finally, correct endings elicited a 250 ms negative peak of smaller amplitude than that elicited by incorrect endings, followed by a sharp positive wave peaking around 300 ms.

3.2.1. Early negativity effect

The ANOVA performed on the 250–300 ms window with normalized data showed statistically significant effects for Ending × Laterality \( [F(4,48)=5.78, p=0.002, \varepsilon=0.39] \), and for Ending × Frontality × Laterality, \( [F(16,192)=14.23, p<0.001, \varepsilon=0.33] \). In order to analyze the higher order interaction (Ending × Frontality × Laterality), separate ANOVAs were carried out for the five levels of laterality. Results showed that the Ending effect was statistically significant for all the five levels of laterality (\( F \) values ranged from 17.67 to 38.92; all \( p \)-values<.001), but the Ending × Frontality interaction was only significant at the left laterality L1 \( [F(4,48)=5.92, p<0.001, \varepsilon=0.51] \).

A more detailed analysis of the ending effect was performed by means of paired comparisons conducted for the three types of ending at frontal, central and parietal sites, and at all levels of laterality. Table 1 shows the analysis at frontal, central and parietal sites. It can be seen that a larger negativity was elicited whenever an incorrect ending was presented. Both incorrect endings — small- and large-split endings — were different from the correct endings (\( p \)-values<.001); however, no reliable differences were found between the two incorrect endings. Furthermore, the mean differences in Table 1 show that the differences in voltage increase from frontal to parietal sites. The results for paired contrasts for all levels of laterality showed that again, there was a widespread negativity effect: the difference between correct and both incorrect endings reached significance at all five levels of laterality (all of the \( F \) values ranged from \(-1.97 \) to \(-3.27\); all \( p \)-values<.001).

Because the Ending × Frontality interaction reached statistical significance at the left laterality L1, ANOVAs taking Ending as within-subjects factor were conducted at F7, T3 and T5, as those were the electrodes in laterality L1. The results showed that the ending effect was only present at T3 \( [F(2,24)=16.77, p<.001, \varepsilon=0.863] \), and T5 \( [F(2,24)=23.79, p<.001, \varepsilon=0.851] \). Ending type had no effect on ERP amplitude at F7 (\( p \)-value>.05).

Overall, an early negativity effect was elicited by the incorrect endings and this was unaffected by the distance between incorrect and correct solution. This negativity effect was larger over central and posterior sites.

3.2.2. Late positivity effect

In order to study the late positivity effect, the normalized mean amplitude in the 550–650 ms latency window was analyzed using ANOVAs. The interaction Ending × Frontality was statistically significant \( [F(4,48)=5.69, p=0.009, \varepsilon=0.52] \). Because we were particularly interested in the differences in scalp distribution between the three types of endings, pairwise comparisons were conducted for the three conditions at frontal, central and parietal sites.

Table 1 shows the pairwise contrasts for the three types of endings at frontal, central and parietal sites. Results showed...
significant differences between large-split and correct endings, and between large- and small-split endings at all levels of frontality (p-values < .001 at frontal, central, and parietal sites). It can be seen that large-split endings elicited more positive voltages than both the correct and the small-split endings. Although this late positivity effect was widespread, the ERP differences between large-split and correct endings were larger over parietal sites (5.9 μV) than over central (4.8 μV) and frontal sites (3.4 μV). These differences can be seen in the voltage map in Fig. 2B (right column). The results showed that the small-split endings elicited a larger positivity than the correct endings only over parietal sites (p = .01). This posteriorly distributed effect for the small-split endings can also be observed in the voltage map in Fig. 2B (left column). In summary, the late positivity effect was more pronounced at posterior than at other sites, as shown in the statistical analysis and in the voltage maps. This effect was present both in large-split endings and in small-split endings over posterior sites, although it was largest for large-split endings.

To sum up, the results indicate that incorrect endings elicit a late positivity effect. This positive shift increased from frontal to parietal sites, and was larger over centro-parietal sites. No hemispheric asymmetries in the size of this component were observed. Moreover, the amplitude of this positive component was modulated by the size of the split, being larger in the large-split endings than in the small-split endings. The split effect was present at centro-parietal sites.

4. Discussion

The experiment reported here used ERPs to examine the split effect on arithmetical sequence processing. Three predictions were made. First, we expected that the size of the split would influence participants’ accuracy, causing them to respond less accurately to small-split endings than to correct and large-split endings. Second, the size of the split also would influence the amplitude of a posteriorly distributed late positive component: a late positive slow wave was expected to be elicited by small-split endings and a larger and sharper positive wave was expected to be elicited by large-split endings. Third, we predicted that a negative component preceding this late positive component would be elicited by both incorrect endings.

The first prediction addressed the question of how the distance between the proposed and the correct solution to an arithmetical problem would influence participants’ accuracy. Previous studies have shown that when subjects are presented with an incorrect solution to an arithmetical problem, they perform slower and less accurately if the number presented is close to the correct solution than if the number is very different (Ashcraft and Battaglia, 1978; Ashcraft and Stazyk, 1981). In the present experiment, the split effect was indeed found on accuracy as suggested by previous research. Small-split endings elicited less accurate responses than correct and large-split endings. Nonetheless, the difference in accuracy is rather unusual (small-split endings yielding an accuracy rate of more than 10% below those of correct and large-split endings — namely 82% relative to 92.4 and 95.3%, respectively). Generally, in healthy participants differences between small- and large-split trials are most obvious on response latencies and not so much on accuracies. One possible interpretation of the present result might be that participants tend to double check the small-split endings, and upon being confronted with a limitation of response latency (a relatively short inter-trial-interval of 1500 ms), the likelihood of errors could increase dramatically. This explanation is plausible considering the high working memory demand upon solving these problems: it has to be reminded that one trial consisted of five stimuli that have to be held in working memory in order to solve the task successfully.

The second prediction deals with the question of whether there is a neurophysiological evidence for the split effect. The present results show that arithmetical incorrectness has an impact on processing and induces a clear neurophysiological response in the form of an LPC effect. As predicted, an amplitude modulation of an LPC was associated to the split-effect. Small-split endings elicited a late positive slow wave that was largest over parietal sites, distributed equally over both hemispheres. This positive shift might suggest that the exact calculation is needed to decide on the incorrectness of these problems. Previous results (Iguchi and Hashimoto, 2000; Núñez-Peña et al., 2005, 2006; Pauli et al., 1994, 1996) have shown that a late positive slow wave may be functionally related to mental arithmetical calculation. This late positive slow wave has been suggested to constitute a brain signature of calculation, so the fact that in the present experiment small-split problems elicited a late positive slow wave might suggest the idea that subjects used a whole-calculation strategy to solve these problems.

As for large-split endings, the largest and sharpest LPC was elicited. This result is consistent with previous studies. First, Niedeggen and Rösler (1999) and our own group (Núñez-Peña and Honrubia-Serrano, 2004) reported an LPC modulation in arithmetical problem verification tasks depending on the numerical distance between the proposed and the presented solution: the greater the distance, the larger the amplitude. Second, El Yagoubi et al. (2003, 2005) reported a modulation on an LPC in an inequality verification task that was interpreted as an index of the different strategies that subjects used to verify complex inequalities: a whole-calculation strategy for small distance problems and a plausibility-checking strategy for large distance problems. Although there are some differences in the scalp distribution of the LPC reported by El Yagoubi et al. — larger at frontal than at parietal sites and left-lateralized — and the LPC reported in the present study — parietally distributed and without hemispheric asymmetries —, this discrepancy may be explained. First, neuropsychological and neurophysiological studies have indicated that both the prefrontal and the parietal cortices are involved in arithmetical tasks (see for example, Menon et al., 2000; Stanescu-Cosson et al., 2000; Zago and Tzourio-Mazoyer, 2002). The involvement of the parietal cortex in number processing has been reported in data from brain-lesioned patients, and by using positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) (for a review see Dehaene et al., 2003); it has been proposed that the parietal lobe contributes to the representation of numerical quantity (Dehaene and Cohen, 1995). Second, the experimental
tasks were different. In the present study, a problem verification task was used, consisting of verifying if the last number of a sequence was correct or not. By contrast, El Yagoubi et al. used an inequality verification task that consisted of deciding if the addition of two numbers was smaller or larger than 100.

It is tempting to speculate that the LPC elicited by arithmetical violations in a verification task reflects the application of arithmetical rules in working memory, especially because parietal regions are believed to be involved in arithmetical processing. However, a more accurate characterization of the LPC reported in the present experiment will have to await future investigation, because there are arguments that suggest that these findings are not limited to this particular cognitive domain. First, we have suggested elsewhere (Núñez-Peña and Honrubia-Serrano, 2004) that the modulation of the amplitude of this late positive component might be a response to the difficulty of integrating the incoming element to the previous structure, because some studies have shown a comparable LPC amplitude modulation in grammatical (Frisch et al., 2002; Kaan et al., 2000; Kaan and Swaab, 2003a,b; Osterhout et al., 1994) and musical structure processing (Patel, 2003; Patel et al., 1998). The more difficult it is to integrate an element into the previous structure, the larger the amplitude of this component. Consequently, this ERP component might be a brain response related to the ability to repair structural incongruities in sequences governed by rules. Second, the LPC reported in the present experiment is also similar to the well-known P3b, whose amplitude has been suggested to vary as a function of memory load, with smaller amplitudes associated with increased memory load. When a small-split ending is presented, a whole-calculation strategy would be expected to involve a greater memory load than a plausibility-checking strategy. Summarizing, the question as to whether the LPC reported in the present experiment is a specific computational index or a reflection of a more general mechanism is unresolved. To clarify this question an additional experiment should be performed in order to assess the distinctiveness of brain responses to anomalies that involve calculation and to anomalies that do not involve calculation. Although there is no firm evidence for the arithmetical specificity of the LPC effect reported in the present experiment, we considered that the LPC can be a useful dependent variable in mathematical research needs to be carried out in order to further our knowledge of the issue.

The main conclusions of the present study are as follows. First, we demonstrated a significant LPC effect in response to the size of the split in violations of arithmetical rules. This LPC effect might indicate that two different strategies are used to verify arithmetical problems: a whole-calculation strategy for small-split solutions and a plausibility-checking strategy for large-split solutions. Second, in addition to the LPC effect, there was another observation of interest: the presence of an early negativity, maximum over parietal sites, in arithmetical violations. Although this finding raises the possibility that this negative component is related to the discrepancy between the estimation of the following number prepared by the subject and the presented number, further research needs to be carried out in order to further our knowledge of the issue.

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