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Research report

The effect of numerical distance and stimulus probability on ERP components elicited by numerical incongruencies in mental addition

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Abstract

In two experiments, we investigated the effect of the numerical distance of incongruous results from correct results and stimulus probability on the N270/N400 event-related brain potential components. In Experiment 1, 12 subjects saw two one-digit addends and a possible solution and signaled if the proposed result (falling in the range of 3–17) was true or false. Incorrect results could deviate by ± 2 or by ± 9 from the correct answer. The probability of correct results was 50%. Twelve subjects carried out a similar task in Experiment 2 without giving behavioral responses. The probability of incorrect results was 20%, 50% or 80% in different conditions. Both raw potentials and incorrect minus correct difference potentials were analyzed.

A fronto-central N3 and a centro-parietal dN3 (incorrect–correct difference) were present for incongruous results in both experiments. The amplitude of the dN3 was not sensitive to numerical distance, but the latency of the dN3 was longer when numerical distance was larger. The overall amplitude of the N3 and of the dN3 was not sensitive to the probability manipulation. However, there was a parietally localized effect of probability on N3 amplitude.

The dN3 in mental addition is most probably identical to the arithmetic N400 effect reported earlier in mental multiplication. The distance effect in latency may be a correlate of the discrimination of correct vs. incorrect results. A parietally localized probability effect (right greater than left) was found in the N3 amplitude. The dN3 was insensitive to the probability manipulation. In accord with its insensitivity to stimulus probability, the dN3 seems to be more related to the N400 than to the N2b. Posterior attentional processes sensitive to the allocation of attentional resources may have contributed to the topography of the dN3. The N3 is more related to the detection of expectation violation, while the P3 reflects the ease of identifying stimulus categories.

Keywords: Mental arithmetic; Numerical distance effect; Numerical incongruency; Probability; N270; N2b; N400; N3; P300; LPC

1. Introduction

Recently, event-related brain potential (ERP) correlates of numerical judgements have been identified. In the usual experimental paradigm, subjects solve simple arithmetical problems and make judgements about the correctness of proposed solutions. Hits elicit a P3 component, while correct rejections result in a delayed and enhanced P3. For correct rejections, a negative component in the raw ERPs labeled N270 has been shown [35]; furthermore, an N400 and an LPC (a positivity following the N400) effect in the <incorrect minus correct> difference potentials have been identified [12,22,23] (hereafter, we refer to these three studies together as the Rösler group studies).

Wang et al. [36,37,39] elicited the N270 in response to incongruous results using a mixture of addition, subtraction, multiplication and division tasks. The Rösler group used multiplication tasks. Neither the N270 nor the N400 effect is specific to number processing as both were elicited in

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various tasks using diverse types of stimuli (for a recent review on N400, see Ref. [14]). In two experiments, we tested the properties of the N270 and/or the N400 effect in response to numerical incongruencies in simple addition tasks.

Simple multiplication and addition problems are mainly solved by retrieval of results from verbal memory where operands and results are supposed to be represented in an interconnected association network [10,20]. Strong evidence for the retrieval hypothesis and for the similar representation of simple multiplication and addition facts is that solution times for multiplication and addition problems containing the same operands are approximately equal [25,30,20]. Furthermore, priming studies have shown that decision times for incorrect addition solutions are slower if the proposed results are correct under multiplication than when the result is not related to the operands this way ([38], e.g., 4+5=20). This suggests that multiplication and addition "tables" are interrelated somehow. Accordingly, we expected to find similar ERP correlates for judging the correctness of addition problems as for judging multiplication outcomes. The properties of ERPs to incorrect results should (partly) be correlates of violating expectations about information represented in activated nodes of a network storing arithmetic facts.

The amplitude of the N400 ERP component correlates with the extent of semantic priming [15]. In single-digit multiplication tasks, Niedeggen and Rösler [22] found that the amplitude of a negative component peaking around 400 ms was more negative to erroneous outcomes having no associative relationship with correct results (unrelated errors which deviated ±1 from the correct result; e.g., 3×6=19) than to related (e.g., 3×6=24) multiplication errors. Wang et al. [35] did not investigate the effect of semantic variables on ERPs.

Another semantic effect in arithmetic tasks is the so-called numerical distance effect. In number comparison tasks, the latency of magnitude comparison is an inverse function of the distance between the numerosities to be compared, independent of the presentation format of the stimuli [2,9,21]. The distance effect can also be elicited when judging the correctness of addition results. In this case, response latencies are longer when the distance between the proposed and correct results is smaller than when it is larger [27]. The effect is independent of the physical characteristics of the stimuli and depends only on conceptual similarity in number meaning, and it affects the subjects' performance even if the numerical distance is irrelevant in the given task [5,11]. The distance effect is thought to reflect the spreading activation of analogue magnitude representations along the hypothetical "mental number line" [6]. We used the ERP distance effect to test for semantic effects on ERPs elicited by incongruencies in addition tasks.

In number comparison tasks (e.g., subjects have to decide if numbers 1, 4, 6 or 9 are smaller or larger than 5), the numerical distance is correlated with the amplitude of parietal ERPs between 120–250 ms independent of the surface format of stimulus presentation [4,26,32]. The (ERP) distance effect is thought to be a correlate of the

Table 1
Main differences between the Niedeggen et al. studies, Wang et al. [35] and this study

Parameter	Study				
	Niedeggen et al. [23]	Niedeggen and Rösler [22]	Jost et al. [12]	Wang et al. [35]	This study
Reference electrode (1)	Nose tip	Nose tip	Nose tip	Linked earlobes	Linked earlobes
Stimulus length (ms)	350/500	max. 1500 ms	max. 1500 ms	300	1000–1500
ISI (ms) (2)	250/–300 vs. 0	350	250	400	0–500
SOA (ms)	500	500/200	600	700	2500/1000
Arithmetic task(s)	×	×	×	×,+,/,–	+
Problem size (3)	6–72	6–72	6–72	0–9	3–17; words
Arithmetic problems (4)	2×56 possible	2×56	2×56	Random	Random
Percent of correct results	50	50	50	50	20–50–80
RT (ms) (5)	a. 671, 683, 776; b. 553, 589, 645	?, 525–570	(a) 517, 560; (b) 606, 627	753, 810	1. 456, 522, 567
Latency of N2/N4 (ms)	Difference N4 360–400	Difference N4 app. 360	Difference N4 320–360	Raw N270 267	dN3 292–348
Effect on the N400/dN3	(2) Relatedness	Relatedness distance	Number size	Not tested	(1) Distance (3) Probability
Subjects	12/20	16	20	14	12/12/8
Trials per subject	112	600	224	100	240–300

Here, stimulus means the result of the required arithmetic operation. Ordinal numbers in cells refer to experiment numbers. Remarks are as follows. (1) Using the same paradigm as in Experiment 1 on two subjects, we checked how putting the reference electrode on the nose tip (Rösler group studies) instead of on the earlobes (Wang et al. and our study) affected ERPs. ERPs remained unaffected when referencing to the tip of the nose instead of using the linked earlobes. (2) An ISI of −300 ms means that stimuli overlapped with the previous ones. (3) The range of numbers which were used as the end results of the required arithmetic operation(s). (4) Niedeggen et al. [23] used all the possible one-digit multiplication problems twice. Ties and operands 0 and 1 were excluded. (5) Niedeggen et al. ([23]; Experiment 2): Rows—correct result, unrelated false result, related false result; (a) ISI=−300 ms; (b) ISI=0 ms. Niedeggen and Rösler [22]—RTs to hits were not communicated; incorrect results. Jost et al. [12]—correct vs. incorrect, (a) small problem size and (b) large problem size. Wang et al.—correct and incorrect result. This study—Experiment 1, correct result, condition DL and DS.

activation of semantic magnitude representations residing in the bilateral horizontal intraparietal sulci [7].

In an initial experiment, we aimed at replicating an N270 component (in raw ERPs) and an N400 effect (in <incorrect minus correct> difference ERPs) to incongruous addition results. Furthermore, we also investigated whether the numerical distance of the incongruous results from the correct results had an effect on the appearing negativities. In a second experiment, we tested if the incongruency-related negativity behaves similarly to the N2b when changing the proportion of correct and incorrect outcomes. To be able to compare our results both with the Rösler group and with the Wang et al. studies, both grand average raw ERPs and grand average difference potentials were analyzed. The core methodology was the same in all published papers and in our experiments. Nevertheless, it is important to note that there are substantial differences between the parameters used in the studies. Table 1 summarizes the most important relevant parameters. We will refer to these when discussing the results.

2. Experiment 1

In this experiment, we expected to find an N270/N400 incongruency effect (ICE) to incorrect results relative to correct results in mental addition. We also expected to find a graded effect of numerical distance on the amplitude of the N400 effect.

2.1. Method

2.1.1. Participants

In both experiments reported in this paper, subjects participated either as a course requirement or for payment. All subjects were right-handed, healthy native Hungarian university students. They had normal or corrected to normal vision and gave written informed consent. Each subject participated in only one of the studies described in this article. Twelve subjects (Six females; age 20.4 years; range 18–26 years) participated in Experiment 1.

2.1.2. Stimuli and procedure

Stimuli were Arabic digits between 1 and 17. Stimuli were presented in the center of a 19-inch computer monitor in black on light green background. All trials began with a fixation cross shown for 1000 ms followed by the first stimulus (S1) visible for 2000 ms. Five hundred ms later, the second stimulus (S2) appeared and remained on the screen for 1200 ms. The S1 consisted of two one-digit numbers (1–9) presented one above the other. The subjects' task was to mentally add up the two numbers and indicate by a button press with the left or right index finger if the digit appearing as S2 equaled to the result of addition or not. Response hands were counterbalanced. S2 was the correct result in 50% of the cases. When S2 was incorrect, it could deviate by ± 2 (condition small difference [DS]) or ± 9 (condition large difference [DL]) from the correct result (condition correct [C]) by equal chance. The number of positive and negative deviations was equal. S2 was followed by a yellow triangle visible for 2 s. During this time, subjects were allowed to blink. Via a button press by their right thumb, they could request a 15-s-long break if needed. Stimuli were delivered in eight series each containing 30 trials (trials per subject 120 correct, 60 small and 60 large distance; altogether 1440 and 720/720 trials). One practice block preceded the experiment. Addition problems were generated randomly. Ties (e.g., 3+3) were excluded. To avoid repetition, priming effects problems consisting of the same operands in either position could not be repeated in two consecutive trials.

2.1.3. Recording and data analysis

Electric brain activity was recorded by a NeuroScan hardware/software system at 18 electrodes placed individually, according to the international 10–20 system at F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, Oz and O2 locations. Ocular artifacts were monitored by electrodes placed below and above the eyes and outside of both canthi. Linked ears served as reference, and the middle of the forehead served as ground. Impedance was kept below 5 kΩ. Digital recording was performed with a sampling rate of 250 Hz. An online filter set to 0.15–30 Hz was used. All epochs exceeding ± 60 μV on any of the electrodes were rejected. Epochs extended from 300 ms prestimulus time to 900 ms poststimulus. The baseline correction was related to the averaged interval between -100 and 0 ms. The data were processed by the NeuroScan Edit program and by Matlab 6. Topographic maps were created by the ICA Matlab toolbox (The Salk Institute, CA). Only behavioral responses and ERPs to S2s receiving a correct response (hits and correct rejections) were analyzed. RTs were calculated relative to the onset of S2.

Peak latencies were measured as the most negative or most positive data points in intervals designated in the results section. Peak amplitudes were calculated as the mean of the data points peak ± 2 points (20 ms). The terms latency and amplitude refer to peak latency and peak amplitude unless otherwise indicated. The effect of numerical distance from the correct result on RTs, error rates, peak amplitudes and peak latencies was tested by repeated measures analyses of variance (ANOVA). Factors were distance (DS vs. DL), hemisphere (left, midline, right), location (frontal, central, parietal), proximity (proximal electrodes next to midline, e.g., C3 and C4; distal electrodes further away from midline, e.g., T3 and T4.) and electrode. To decrease the probability of Type I error Greenhaus–Geisser ε (epsilon) corrected p values were computed for ERP data when necessary [34]. The topography of the difference potentials was assessed similarly as in the Rösler group studies [18,33]; that is, after calculating the difference, curves amplitude values in each condition were standardized across electrodes. All but midline and occipital electrodes were included in the topographical analyses when otherwise not indicated. Both original potentials and Z scores were analyzed in the topographical analyses.

2.2. Results

2.2.1. Behavioral results

RTs were longer in condition DS (mean ±SD 567.0±66.6 ms) than in condition DL (522.8±67.9 ms; distance $F(1,11)=30.37$; $p<0.0002$); that is, there was a numerical distance effect. RTs were shorter to correct (456.8±64.4 ms) than to incorrect results ($F(2,22)=23.91$; $p<0.0001$; Scheffé tests, both correct vs. condition DS and correct vs. condition DL, $p<0.001$). The proportion of correct responses was 95.2%, 94.4% and 96.0% to hits and in condition DS and DL, respectively.

2.2.2. Event-related potentials

After artifact rejection, the number of epochs accepted for averaging were 1110 (mean 77.1%; range 74–95%), 562 (78.1%; 69–96%) and 567 (78.8%; 68–97%) in conditions C, DS and DL, respectively. ERP components were easily identifiable in all subjects. Grand average ERPs and incorrect minus correct difference potentials are shown in Fig. 1. Hits elicited a P2 wave followed by a small negativity at 230 ms and a P3 between 200–600 ms. A P2, an increased negativity (N3), as well as a delayed P3 component, appeared to correct rejections relative to hits. In the <incorrect minus correct> difference potentials, a difference N3 (dN3) and a LPC appeared at 300 and 450 ms, subsequently.

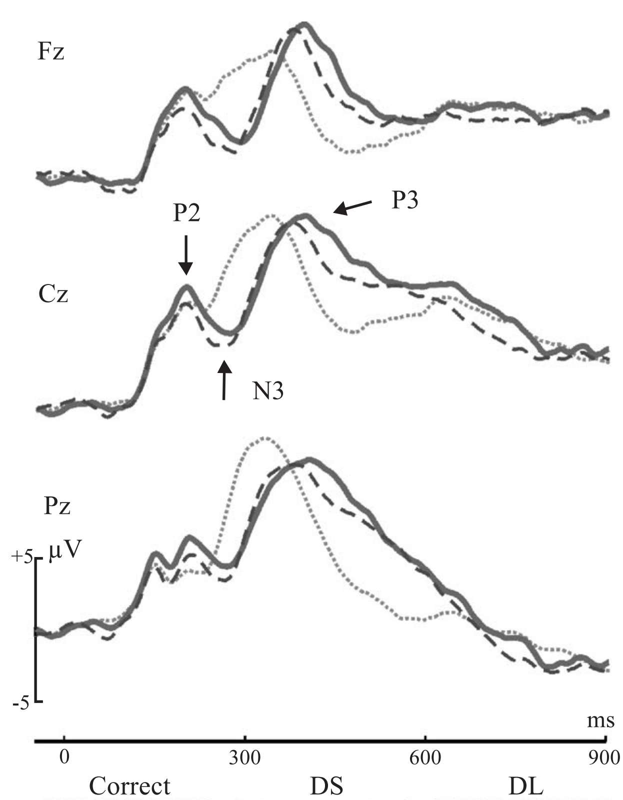

Fig. 1. Raw grand average ERPs to S2 in Experiment 1. Components P2, N3 and P3 are labeled.

2.2.2.1. Raw ERPs.

The latency of the fronto-central P2 was determined between 160 and 260 ms. The latency of the P2 did not differ according to conditions. Its amplitude was more positive in condition DS (6.29 µV) than in condition DL (5.05 µV; $F(1,11)=10.67$; $p=0.007$). The first effect of distance could be seen at 160 ms. The mean amplitude of the 160–260 ms interval was more positive in condition DS (4.62 µV) than in DL (3.27 µV; $F(1,11)=12.67$; $p=0.004$).

The amplitude and the peak latency of the N3 were measured in the 230–320 ms range on frontal, central and parietal electrodes where this component could be well discriminated. Peak amplitudes and latencies of the N3 and those of the dN3 are described in Table 2. The mean amplitudes measured in the N3 time window were more negative to correct rejections than to hits ($F(2,22)=32.30$; $\varepsilon=1$; $p<0.0001$). The latency of the N3 was 12 ms longer in condition DS than in DL ($F(1,11)=14.17$; $p=0.0032$). The amplitude of the N3 was more positive in condition DS than in DL ($F(1,11)=9.85$; $p=0.01$).

The amplitude and peak latency of the P3 was measured between 300 and 500 ms. The latency of the P3 was shorter to correct than to incorrect results ($F(2,22)=50.68$; $\varepsilon=0.949$; $p<0.0001$). The latency of the P3 was somewhat longer in condition DS than in DL ($F(1,11)=3.74$; $p<0.08$). This latency difference was significant over the fronto-central electrodes (DS 410 ms; DL 390 ms; $F(1,11)=7.248$; $p<0.022$). The peak amplitude of the P3 varied neither by correctness nor by numerical distance ($p<0.21$).

2.2.2.2. Difference potentials.

Difference potentials are shown in Fig. 2A. The topography of the dN3 is shown in standardized (Z score transformed) maps in Fig. 3A. The ICE and the DE were investigated by analyzing incorrect minus correct difference potentials. The dN3 (240–340 ms) peaked at centro-parietal electrode sites. The latency of the dN3 was 301 ms in condition DS and 292 ms in condition DL ($F(1,11)=8.90$; $p=0.012$). There were no effects on the amplitude of the dN3.

The topography of the dN3 was tested in each condition by location×proximity×hemisphere (left vs. right) ANOVAs in both conditions. Amplitudes were more negative proximally than distally (DS $F(1,11)=17.08$; $p=0.0016$; DL $F(1,11)=18.47$; $p=0.0012$) and more negative at central and parietal than at frontal sites in condition DL (location $F(2,22)=4.80$; $\varepsilon=0.539$; $p=0.0016$) and marginally in condition DS ($F(2,22)=3.49$; $\varepsilon=0.0482$; $p=0.062$). Topographic differences between conditions were tested by ANOVAs including additional “distance” factors run both on raw potentials and on Z scores. No between conditions topographical differences were found.

Table 2
Peak latencies and peak amplitudes (peak ±8 ms) of the raw N3 and the dN3 components

Study	Condition	Correct	Incorrect		Incorrect–correct	
		Latency (ms)	Latency (ms)	Amplitude (μV)	Latency (ms)	Amplitude (μV)
Experiment 1	DS	230 (8.3)	276 (13.8)	3.95 (2.8)	301 (15.3)	−6.10 (2.30)
	DL	230 (8.3)	264 (12.5)	2.74 (2.8)	292 (21.3)	−6.44 (2.49)
Experiment 2	IC20	272 (20.4)	289 (14.3)	1.67 (2.98)	298 (13.4)	−4.63 (2.36)
	IC50	271 (16.2)	303 (10.1)	1.45 (1.08)	328 (17.9)	−4.75 (2.13)
	IC80	267 (13.3)	275 (13.8)	3.01 (1.96)	348 (23.8)	−4.23 (1.00)

Standard errors are shown in parentheses. Average values for all electrodes are shown.

The mean amplitude of the difference potential was more negative in condition DL than in DS between 160 and 260 ms (DL −0.63 μV; DS +0.81 μV $F(1,11)=9.18$; $p=0.011$) and between 400 and 500 ms, including the peak of the LPC (DL 3.43 μV; DS 5.46 μV; $F(1,11)=6.83$; $p=0.024$). No DE was found in the mean amplitude of the 240–340 ms interval when the dN3 peaked ($p=0.5$). The difference in LPC latency did not reach significance.

The topography of the difference potentials was investigated between 160 and 260 and between 4 and 500 ms. The topography of the LPC is shown in Fig. 4A. Between 160 and 260 ms, amplitudes were more negative over the right than over the left hemisphere in both conditions (DS −1 μV; $F(1,11)=34.99$; $p=0.0001$; DL −0.76 μV; $F(1,11)=7.39$; $p=0.0083$). However, no such systematic hemispheric difference was found between 400 and 500 ms. There was no effect of distance on the topography between 160 and 260 nor between 400 and 500 ms.

2.3. Discussion

2.3.1. Incongruency effect

In the raw ERPs, incorrect results elicited an enhanced P2 and an N3, as well as a delayed P3 relative to correct results. The N3 appeared at approximately 270 ms, and it was most expressed at fronto-central sites. The N3 seems to be identical to the N270 reported by Wang et al. [35]. However, we call the component N3 to maintain consistency throughout the manuscript, as this negativity appeared in the latency range of 270–330 ms in Experiments 1 and 2.

In the difference potentials, a dN3 and an LPC appeared. The topography of the dN3 was very similar to the formerly reported arithmetic N400 effect. The dN3 appeared somewhat earlier than the arithmetic N400 effect reported by the Rösler group. The incongruency-related negativity found by the Rösler group appeared in the raw ERPs at about 270–335 ms, while the N400 effect in difference potentials peaked between 320 and 390 ms in their studies (Frank Rösler, personal communication, 2003). A further similarity with the Rösler group studies is that in the Niedeggen and Rösler and Niedeggen et al. studies ([22,23] Fig. 5 and Fig. 3, respectively), the largest effect of the semantic manipulation did not appear around the peak of the negativity, but it became the most prominent after the peak of the negativity. We found a similar distance effect.

The very similar timing in both raw ERPs and in difference potentials, as well as the similar distribution of effects, suggest that we have replicated the arithmetic incongruency-related ERPs found in the Rösler group studies for addition. However, there remain two main discrepancies between the results to be resolved.

A conspicuous difference is that the latency of the dN3 in Experiment 1 was on average much shorter than that reported in the Rösler group studies. There are a number of reasons for this. First, the problem size in our experiment was much smaller (1–17) than in the Rösler group experi-

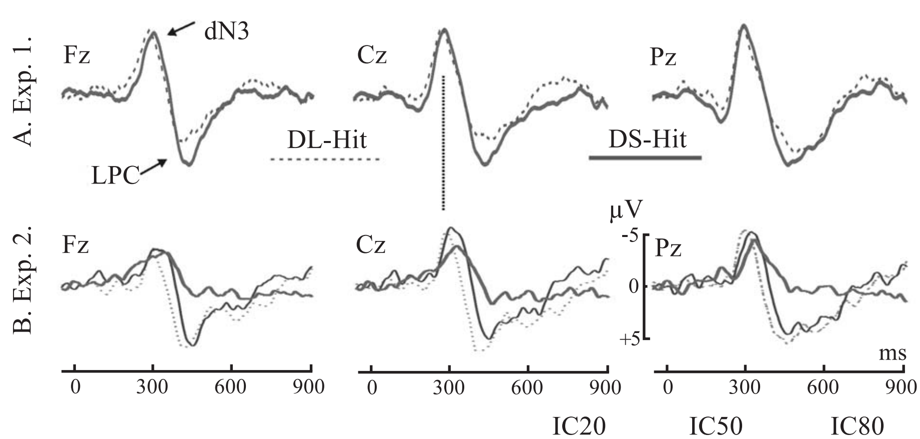

Fig. 2. Incorrect minus correct difference potentials in Experiments 1 and 2. Components dN3 and LPC are labeled. The dotted vertical line at Cz at 300 ms is inserted for comparison purposes only. Note that negative is up for this figure.

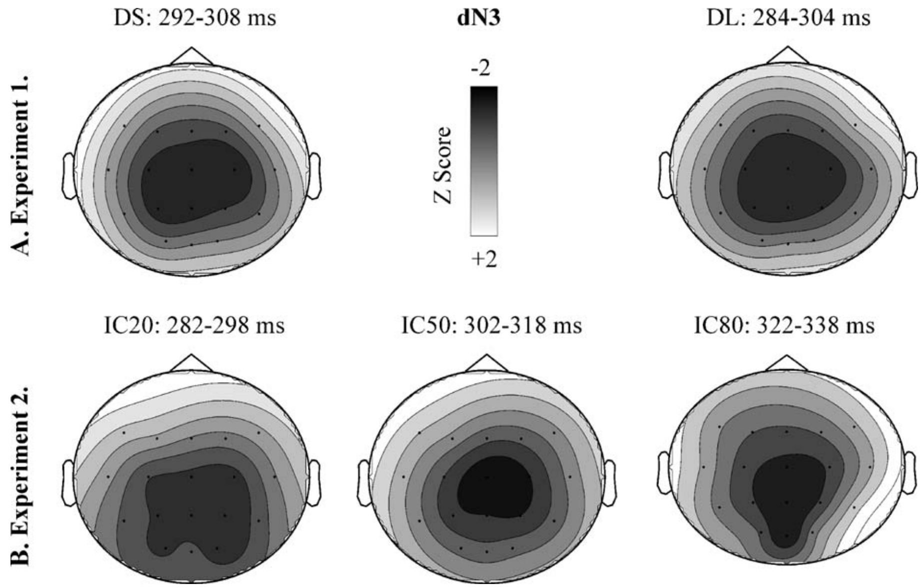

Fig. 3. The topography of the dN3 (at the peak±8 ms) in Experiments 1 and 2. Standardized amplitude maps.

ments (6–72). Jost et al. [12] found that the N400 effect peaked at 320 ms to small (between 6–20) problems and at 360 ms to large (42–72) problems. The small problem size in our experiment may have resulted in shorter latencies.

Second, in our experiment, the SOA was 2500 ms. Formerly, the latency of the N400 effect was reported approximately 500 ms when the SOA was 200 ms, while the effect peaked at 420 ms when the SOA was 500 ms [23]. Therefore, the long SOA in our experiment could also contribute to the earlier peaking of the N400 effect. Third, the average distance of the incorrect results from the correct results in our experiment was smaller than in the Rösler group experiments. The observed latency difference could plausibly be attributed to the above factors.

A further crucial question is why numerical distance did not have an effect on the amplitude of the dN3. In the baseline-to-peak measures of the raw ERPs, we obtained such an effect. However, the apparent raw N3 amplitude change was a consequence of a broad amplitude deflection between conditions DS and DL in the 160–550 ms time interval. This was reflected in the fact that no effect of semantic distance on the amplitude of the dN3 was found.

Niedeggen and Rösler [22] targeted the effects of associative strength (table relatedness). They found that the amplitude of the N400 effect was more negative to table-unrelated than to table-related errors. Here, we solely manipulated the numerical distance from the correct results. A semantic manipulation in mental addition similar to that

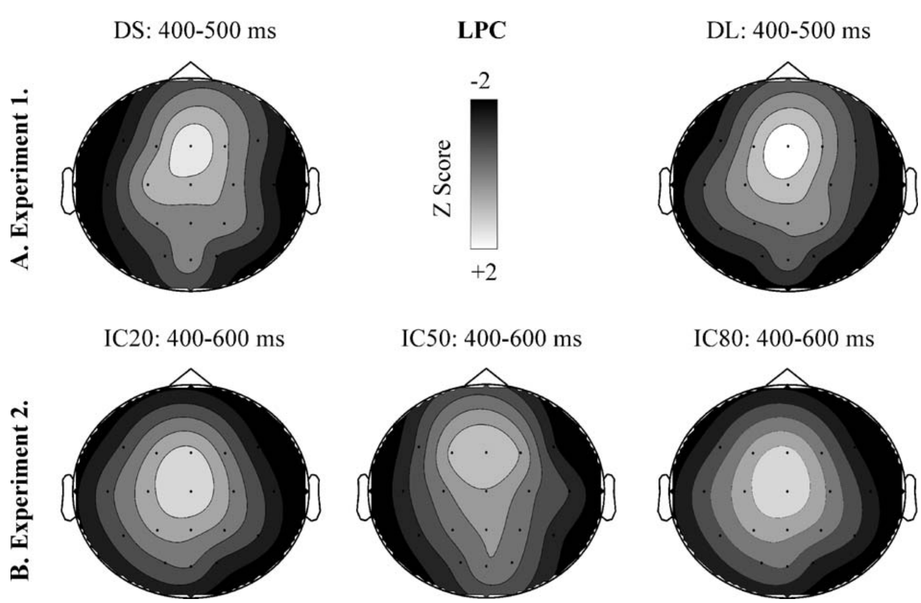

Fig. 4. The topography of the LPC in the given intervals in Experiments 1 and 2. Standardized amplitude maps.

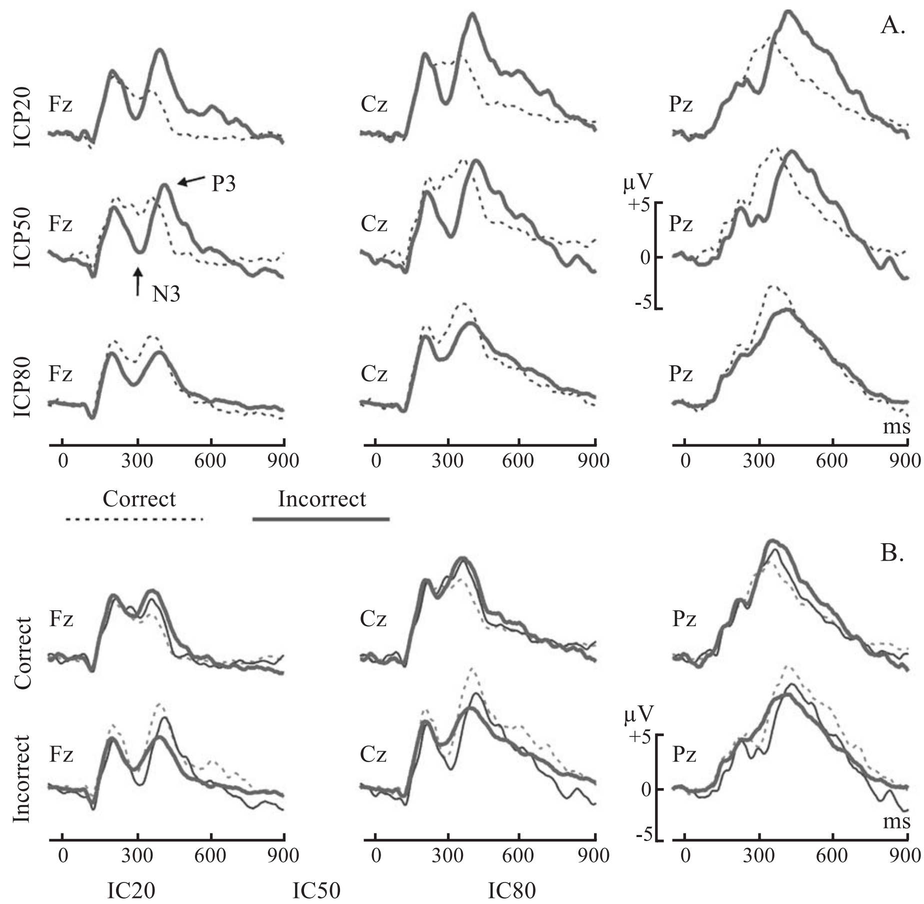

Fig. 5. Raw grand average ERPs grouped by probability (A) and correctness (B) in Experiment 2. Components N3 and P3 are labeled.

used in the Niedeggen and Rösler [22] study would have been to form incorrect addition problems like 4+5=20 vs. 4+5=21. However, in such an experiment, the distance of incorrect results from correct results would be much larger in addition than in multiplication.

The lack of an amplitude effect in our experiment may mean that the dN3/N400 amplitude modulation characterizes only the violation of associative connections. The amplitude modulation may not be sensitive to nonassociative violations. Another, less likely, possibility is that our distance effect was not a strong enough violation to result in an amplitude modulation.

2.3.2. Distance effect

The distance effect was manifested in three dependent variables. (1) Incorrect results deviating ±2 units from correct results elicited more positive ERPs in the P2 and in the N3 interval, as well as in the descending part of P3 than results deviating ±9 units. The amplitude of the P2 and the P3 was closer to hits in condition DL than in DS. (2) The latency of the N3 and the dN3 was about 10 ms longer, and the latency of the P3 was 15 ms longer (20 ms fronto centrally) in condition DS than in DL. (3) RTs were 44.2 ms longer in condition DS than in condition DL.

Our data show that the evaluation of number meaning probably begins at about 200 ms as indexed by the distance effect in the amplitude of the P2. This observation is completely in-line with former ERP results (the earliest distance effects were measured at 124–234; 174–230; about 184 ms [4,26,32], subsequently). By the time the N3 appeared, the semantic information must have already been retrieved, as the mismatch signal embodied in the N3 is probably based on the end result of the discrimination process.

Contrary to previous observations [4,26,32], the distance effect was not restricted to the parietal electrodes, but it was seen over nearly all frontal, central and parietal electrodes. In former experiments, subjects had to compare a numerosity (defined either by dot arrays or Arabic digits) to a reference quantity, and they had to decide which of them was smaller or larger. The extent of deviation from the reference value was accompanied by a change in the amplitude of ERPs over parietal electrode sites. In our experiment, subjects had to compare the proposed result to the correct result, and they had to decide if the proposed result was correct or not. The larger the deviation of the proposed results from the correct results, the more negative was amplitude of the ERPs.

In our experiment, the validity of proposed results was checked (compared to a calculated reference number). Subjects strongly expected to see the correct results. The violation of expectations might have contributed to the appearance of the extensive distance effect. The effects of numerical distance and violating expectations possibly intermix in the ERP distance effect appearing when judging on the correctness of addition results.

However, subjects were not required to tell the difference from the reference quantity in former experiments nor in the current study. Therefore, the amount of deviation from the reference quantity was irrelevant to task execution; that is, the distance effect is probably a manifestation of automatic evaluation of number meaning in all cases.

Although, as noted earlier, distance did not have an effect on the amplitude of the dN3, the latency of the N3/dN3 was approximately 10 ms longer in condition DS than in DL in both raw ERPs and difference potentials. An explanation may be that the latency DE, similar to the behavioral DE, reflects the distance-dependent differential speed of discrimination of correct vs. incorrect activation patterns on the so-called mental number line [7]. This account relies on the finding that numbers are coded "analogously" as fuzzy activation patterns of band-pass filter-like neuronal structures [7,24].

However, a problem of the experimental design we used is that incorrect results sometimes deviated by ± 2 and sometimes by ± 9 from the correct results. Therefore, validations were contaminated by a parity check [17]. Parity checks might have facilitated the rejection of incorrect results when they were formed by adding ± 9 to the correct number (resulting in opposite parity), relative to creating them by adding ± 2 (resulting in a same parity number). Unfortunately, the direction of this parity effect coincides with that of the DE. This might also be a (partial) explanation of the observed latency DE.

A lateralization difference is clearly seen between 160 and 260 ms in the amplitude distribution difference between conditions DS and DL. This finding is in-line with former results showing hemispheric asymmetries in number comparison tasks [3,4]. The topography of the LPC was different from the topography found formerly [19,20]. We will discuss this later in the General discussion.

3. Experiment 2

In Experiment 1, an arithmetic ICE was elicited in mental addition. In a second experiment, we asked a more basic question about arithmetic incongruency detection. In Experiment 2, we tested whether stimulus probability affects the amplitude of the N3/dN3.

The N270 in raw ERPs could be elicited by conflicting stimuli in many tasks. The N270 appears when the location of two visual stimuli does not match [39] or even when the gender of the speaker does not match the shown face of the speaker [37]. Wang et al. [35] put forward the idea that the N270 appears on stimulus mismatch and hypothesized that the N270 is a distinct entity and not related to the N2b.

However, both the N2b and N270 have a similar fronto-central distribution pattern. The N2b and the following P3 appear in categorization tasks requiring stimulus discrimination. The amplitude of the N270 is more negative to task-relevant than to task-irrelevant stimuli [35]. The amplitude of the N2b changes similarly and is more negative to rare stimuli than to frequent ones [28].

In Experiment 2, we tested whether the amplitude of the arithmetic N3/dN3 becomes more negative if the probability of incorrect stimuli increases. To our knowledge, the N400 amplitude has not been reported to be reliably correlated with stimulus probability. If the probability manipulation does not have an "N2b-like" effect, we can assume that the dN3 is more related to the N400 than to the N2b.

Furthermore, as the negativities related to arithmetic incongruence have usually been elicited in experimental setups requiring behavioral responses, we decided to test the component in a situation where subjects did not have to give behavioral responses. As errors are relatively few (typically ranging between 1% and 8%) in simple arithmetical tasks, averaging together ERPs recorded to covert erroneous and correct responses does not have a large effect on the component structure. To use an experimental setup more similar to the Wang et al. [35] study, the presentation of the addends was changed from simultaneous to successive.

3.1. Method

3.1.1. Participants

Eighteen subjects participated in the experiment (three sessions per each subject), but due to artifacts and missing conditions, only 12 subjects' data (six females, age 18–26 years; mean 21 years) were analyzed. Subjects participated on different days in different conditions.

3.1.2. Stimuli and procedure

Details not mentioned here were the same as in Experiment 1. Stimuli were delivered in 10 series each containing 30 trials. The stimuli used were Arabic digits between 1 and 17 appearing consecutively in the center of a computer monitor. All stimuli appeared for 1000 ms. The structure of each trial was the following: fixation cross, first stimulus (S1), plus sign, second stimulus (S2), equal sign and proposed result (S3). The subjects' task was to add up S1 and S2 as fast as possible upon the appearance of S2 and to decide silently if S3 was the correct result of the addition or not (correctness factor). Subjects gave no behavioral response. There were three conditions. In CIC20 [condition incorrect probability 20%], S3 was incorrect in 20% (720 trials for all subjects), in 50% (1800 trials) in CIC50 and in 80% (2880 trials) in CIC80 (probability factor). In this experiment, incorrect results were generated randomly using the available range of numbers. The order of conditions was counterbalanced. One male–female pair was assigned to each possible order of conditions. To maintain subjects' concentration in the silent task, they were told that they participated in a simple intelligence test. Between series, subjects were continuously reminded of the importance of concentrating and judging correctly. Subject's overt attention was continuously monitored via video monitors. The ERP recording and analysis were performed as in Experiment 1. When otherwise not indicated, effects were tested by using ANOVAs with factors of probability×correctness×electrode in case of raw ERPs, probability×electrode in case of difference curves and probability×location (frontal, central, occipital)×proximity (proximal, distal)×hemisphere (left, right) in case of topographical analyses. Midline and occipital electrodes were excluded from topographical analyses. In this experiment, only ERPs to S3s are reported.

3.2. Results

The following number of accepted epochs were averaged: CIC20, correct, 2260 (mean 78.4%; range 70–93%), incorrect, 577 (80.1%; 65–98%); CIC50, correct, 1607 (89.2%; 72–94%), incorrect, 1566 (87%; 74–92%); CIC80, correct, 649 (90.1%; 83–97%), incorrect, 2614 (90.8%; 84–96%). As shown in Fig. 5, in this experiment, ERPs to S3 were practically identical to those obtained to S2 in Experiment 1. Both correct and incorrect results elicited a P2 (peak 210 ms) component visible over all electrodes. In case of incorrect results, this was followed by a clear negativity peaking at about 300 ms (N3). A slight deflection to correct results could also be observed in CIC20 and CIC50, and it was very clear in condition CIC80. The P3 peaked at about 350 ms for correct and about 400 ms for incorrect results. A dN3 and an LPC were evident in the difference pontentials.

3.2.1. Raw ERPs

The peak amplitude of the P2 (150–250 ms) was more positive to correct than to incorrect results ($F(1,11)=8.18$; $p=0.0154$). The peak latency of the P3 (300–500 ms) was shorter to correct (365 ms) than to incorrect (412 ms) results ($F(1,11)=81.81$; $p<0.0001$). The latency of the P3 was longer in CIC50 (398 ms) than in CIC20 (380 ms) and in CIC80 (387 ms; $F(2,22)=5.07$; $\varepsilon=0.891$; $p=0.0194$). The latency of the P3 to correct results slightly increased as the proportion of correct results decreased (probability×correctcorrectness, $F(2,26)=2.92$; $\varepsilon=0.743$; $p=0.0747$). The peak amplitude of the P3 was larger to rare stimuli for both correct and incorrect results (probability×correctness interaction, $F(2,22)=9.01$; $\varepsilon=0.666$; $p=0.0058$). There were no main effects of correctness or probability.

An N3 (230–330 ms) with a latency of 290 ms was elicited by incorrect results relative to correct results (correctness in amplitude, $F(1,11)=30.13$; $p=0.0002$; fronto-central electrodes only, $F(1,11)=26.59$; $p=0.0003$). The latency of the N3 to incorrect results was longer in CIC50 than in CIC20 and CIC80 ($F(2,22)=11.82$; $\varepsilon=0.937$; $p=0.0005$). The amplitude of the N3 was not sensitive to the main effect of probability ($p=0.22$). However, there was a probability×location interaction ($F(4,44)=3.02$; $\varepsilon=0.720$; $p=0.045$). The amplitude of the N3 was 2 μV more positive in CIC80 than in the other conditions at the parietal electrodes. This effect was not present at the frontal electrodes. Electrodes C3, C4, P3 and P4 were entered into a probability×location×hemisphere ANOVA. The probability effect was the largest and most graded at right parietal electrodes (see Fig. 5.; triple interaction, $F(2,22)=3.42$; $\varepsilon=0.690$; $p=0.0481$). According to separate probability×hemisphere ANOVAs, the effect of probability was significant at parietal sites ($F(2,22)=3.83$; $\varepsilon=0.887$; $p=0.0436$) but only marginally at central sites ($p=0.0754$).

3.2.2. Difference potentials

Difference potentials are shown in Fig. 2B. The topography of the ICE in Experiment 2 is shown in Fig. 3B. There were no between condition differences in the amplitude of the dN3 measured between 240 and 400 ms ($p=0.87$). On the other hand, the latency of the dN3 increased with decreasing probability of correct results ($F(2,22)=25.91$; $\varepsilon=0.659$; $p<0.0001$). The topography of the LPC is shown in Fig. 4B. The mean amplitude of the LPC (400–600 ms) became more negative from CIC20 through CIC50 to CIC80 (3.35, 2.90 and 0.20 μV, subsequently, $F(2,22)=5.83$; $\varepsilon=0.784$; $p=0.0162$).

3.2.3. Topography

Z scores in the dN3 time window were first analyzed by a probability×electrode ANOVA. No effect of probability was found. Because of the visible occipital distribution differences, in a second analysis, occipital electrodes were involved as well. Electrodes F3, F4, C3, C4, P3, P4, O1 and O2 were involved in a probability×location×hemisphere ANOVA. The probability×location interaction was significant ($F(6,66)=3.67$; $\varepsilon=0.433$; $p=0.0281$). According to separate probability×hemisphere ANOVAs, the effect of probability on occipital electrodes was significant ($F(2,22)=3.97$; $\varepsilon=0.905$; $p=0.0387$). No effect of probability was found on the topography of LPC although a frontal shift in CIC50 relative to CIC20 and CIC80 is clear in Fig. 4B.

The topography of the dN3 and the LPC in the two conditions of Experiment 1 and in CIC50 of Experiment 2 was compared. *Z* scores were entered into common condition (between subjects factor)×location×hemisphere ANOVAs. No between conditions differences or interactions with condition was found.

3.2.4. Strategy change?

To check for signs of cognitive adaptation during task execution, we averaged ERPs in series 1–3, 4–7 and 8–10 in conditions IC20 and IC80, forming three blocks, and carried out a block×condition×correctness ANOVA. 189–271 trials were averaged when stimulus probability was 20%, and 805–1032 trials were averaged when stimulus probability was 80%. No block effect was detected. Contrary to the relatively few number of epochs averaged in the 20% cases, ERPs were clear, and the expected effect on P3 should have been robust and easy to detect.

3.3. Discussion

In Experiment 2, similar raw and difference ERPs appeared with approximately the same timing as in Experiment 1. The latency of the P2, N3, P3 and dN3 was somewhat longer in Experiment 2 than in Experiment 1. This can be attributed to the lack of explicit response requirements, which may have resulted in less motivation to evaluate the stimuli as fast as possible and give fast responses relative to Experiment 1. The effect of correctness, which can be considered as a sign of semantic evaluation of the stimuli, happened similarly early (at the P2 amplitude) in Experiment 2 as in Experiment 1 [4,26,32].

The topography of the dN3 in Experiment 1 did not differ from the topography of the dN3 in Experiment 2. Similar with Experiment 1, the topography of the dN3 was lateralized. The topography of the LPC in CIC50 was similar to the topography of the LPC found in conditions DS and DL in Experiment 1, where the joint probability of incorrect outcomes was 50%.

Various factors suggest that that the subjects were solving the task at approximately the same accuracy level as subjects in Experiment 1. These factors include the overall similarity of ERPs (including topography) in Experiment 1 and in Experiment 2; the very moderate increase in ERP latency; the early P2 effect; as well as our impression of the subjects based on continuous questioning about their performance in the course of Experiment 2. Had the accuracy level been considerably lower in Experiment 2 than in Experiment 1 (e.g., because subjects had not paid enough attention), ERP components would have been substantially "flattened" or otherwise distorted relative to Experiment 1. Taken together, explicit response requirements do not seem to play a serious role in determining the properties of the N3 component investigated by us, although of course, a latency difference was found.

The amplitude of the dN3 was not affected significantly by the probability manipulation. Therefore, we conclude that the dN3 is more related to the N400 effect than to the highly probability sensitive N2b [28].

Although the overall amplitude of the raw N3 remained insensitive to the probability manipulation, there was a lateralized (right greater than left) probability effect on the amplitude of the parietal N3. This coincides nicely with the fact that, usually, a larger involvement of the right than left parietal areas is found in number comparison tasks [3,4]. This is accepted as evidence for the larger involvement of the right than the left hemisphere in genuine number manipulations. Also, increasing calculation load leads to an increase in parietal activity [19]. There is a possibility that the altered activation of the parietal "number areas" due to the probability manipulation had a task-specific effect on the amplitude of the N3 in the addition task.

Alternatively, it cannot be excluded that (at least partly) interactions between the early rising part of the parietally peaking P3, and the genuine N3 contributed to the probability effect on the N3. However, this possibility cannot clearly explain the right greater than left nature of the present effect.

Regarding the N3/P3 dissociation, we have to note that the arithmetic judgement task contained an interesting dissociation. To judge on the correctness of the proposed result, subjects first had to retrieve [1] or compute [10,16] the result. As in normal adults, the computation of a single-digit addition is practically always correct, the representation of the correct result was refreshed in each trial. Thus, as this process was the same in all conditions independent of the probability manipulation, the activation level of the representation of the correct result was probably constant via conditions. On the other hand, the probability manipulation must have had an effect on the stimulus categorization processes.

It has long been known that the harder the evaluation of a stimulus, the longer is the latency of the P3 [13]. Furthermore, the lower the subjective expectancy (objective×subjective probability) of a stimulus, the larger the amplitude of the P3 [29,31]. Based on the different probability sensitivities in the present task, one can conclude that the N270 and the P3 accompany different stages of stimulus categorization. The N270 is relatively probability insensitive and appears not to be directly related to identifying response-relevant stimulus categories. However, it appears when expectations about response-relevant stimuli are violated (when relevant stimuli mismatch [35]). On the other hand, the amplitude and latency of P3 characterizes the ease of identifying the appropriate stimulus category.

An unexpected finding was that an occipital shift of the distribution of the dN3 could be seen in CIC20 and in CIC80 relative to CIC50 (Fig. 3B). An increased negativity of the amplitude of the occipital N2 around 200–300 ms has been described in the literature in response to increased discrimination load in visual search and in semantic content analysis [8]. This suggests to us that the discrimination load or the allocation of initial attentional resources increased in CIC20 and CIC80 relative to CIC50. In this case, the occipital shift in the topography of the dN3 could be explained by the influence of attention related posterior ERPs.

The latency of N3 and P3 was the longest in CIC50. The P3 usually correlates with reaction time, a common measure of overall task difficulty. The more intensive allocation of attentional resources in CIC20 and CIC80 could decrease P3 latencies in those conditions. The above differences may be distinguishable correlates of initial discrimination load (occipital part of dN3) and task difficulty (longer N3 and P3 amplitude and perhaps the frontal shift of LPC in CIC50).

The topography of the LPC was more anterior in our experiments than in former studies [12,22,23]. We cannot explain this firmly, but the observation may be related to the different nature of the arithmetic tasks used in this and in former studies.

An interesting question is whether some indication of changed cognitive processing can be detected in response to the altered probability of correct vs. incorrect stimuli. Specifically, we predicted that the P3 amplitude will differ by block as subjects adjust to the actual probability of incorrect responses. We could not find such an effect. This means that subjects had adapted themselves to the probability manipulation early in the task, as well as effectively. Alternatively, block effects could have cancelled out as a result of counterbalancing the order of conditions (due to different initial expectations of subjects assigned to different orders).

4. General discussion

In two experiments, subjects had to judge whether the solutions provided for simple additions were correct or not. In both experiments, erroneous solutions elicited a negativity peaking at about 264–303 ms in raw ERPs (N3) and between 301 and 348 ms in difference potentials (dN3). These components are most probably identical to those found earlier in raw ERPs (N270 [35]) and in difference potentials (N400 effect [12,22,23]).

The amplitude of the dN3 was not sensitive to the distance of incorrect solutions from the correct solutions. However, the latency of the dN3 decreased with increasing deviation from the correct solution and increased as the probability of incorrect solutions increased. The latency increase with distance may reflect either the discrimination speed of correct vs. incorrect results, or it may (partly) result from the confounding effect of facilitated rejection of incorrect results by a parity check.

There was a localized parietal probability effect in the N3 amplitude. We speculate that this might be an expression of the contribution of some task-specific, numerical-processing related parietal procedure to the amplitude of the raw N3.

The amplitude of the dN3 was not sensitive to varying the probability of incorrect results. Therefore, we conclude that the overall behavior of the dN3 is more similar to that of the N400 than to the N2b. Posterior attentional processes, sensitive to the allocation of attentional resources, contributed to the topography of the dN3. The N3 seems to be more related to the mere detection of expectation violation, while the P3 is more related to the ease of identifying stimulus categories.

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