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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., $3 \times 6=19$) than to related (e.g., $3 \times 6=24$) 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.