Title

Numerical distance effect in the N240 component in a number-matching task

Journal

Neuroreport, 17(10)

ISSN

0959-4965

Authors

Zhou, Xinlin
Chen, Chuansheng
Dong, Qi
et al.

Publication Date

2006-07-17

DOI

10.1097/01.wnr.0000221840.12632.9f

Numerical distance effect in the N240 component in a number-matching task

Xinlin Zhou[a], Chuansheng Chen[b], Qi Dong[a], Hongchuan Zhang[a], Chunhui Chen[a], Sibing Qiao[a],
Hui Zhao[a], Ting Jiang[a] and Yi Guo[a]

[a]State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing, China and [b]Department of Psychology and Social Behavior, University of California, Irvine, California, USA

Correspondence and requests for reprints to Dr Qi Dong, State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing 100875, China
Tel: 8610 58807615; fax: 8610 58806154; e-mail: dongqi@bnu.edu.cn

Sponsorship: This study was supported by the National 973 Project (2003CB716803) of China and the National Pandeng Project (95) of China.

Received 15 March 2006; revised 29 March 2006; accepted 31 March 2006

The event-related potential technique was used to investigate the time course and scalp-potential topography for the numerical distance effect in a number-matching task. Twenty undergraduates judged whether a number matched or did not match another number presented 1.5 s earlier. Compared with number pairs with a 'small' numerical distance (distance=1), number pairs with a 'large' numerical distance (greater than 2) showed a longer latency and a greater positive amplitude in the N240 component. This numerical distance effect was limited to fronto-central electrodes. These results were discussed in terms of the neural bases of the numerical distance effect during the automatic processing of numbers. *NeuroReport* 17:991–994 © 2006 Lippincott Williams & Wilkins.

Keywords: event-related potentials, numerical cognition, numerical distance effect

Introduction

The numerical distance effect was discovered by Moyer and Landauer in 1967 when they found that people responded more slowly when comparing number pairs that were closer to each other (e.g. 5 vs. 6, with a 'small' numerical distance of 1) than when comparing those that were farther away from each other (e.g. 1 vs. 9, with a 'large' distance of 8) [1]. Since then, numerous studies have confirmed this robust effect with different sizes of the number pairs (single-digit or double-digit number pairs) and different cognitive tasks such as comparisons (which of the two numbers is bigger?), identity judgment (are the two numbers the same?) [2], and Stroop-like tasks [which number is bigger in physical (or numerical) size? 3 or 2?] [3].

Different explanations have been proposed to account for the numerical distance effect [4]. For example, according to the analogue models [1,5], numbers are posited on an analogue mental number line and the number pairs with a small numerical distance between them would have overlapping neural activation and thus be more difficult to discriminate than those with a large distance. As the magnitude information of a number is embedded in its location on the analogue mental number line, the existence of numerical distance effect has been considered as reflecting the processing of numbers' magnitude information. Consequently, researchers have used the numerical distance effect to investigate neural bases of the processing of numbers' semantics or magnitude [6,7,8,9].

Functional magnetic resonance imaging studies have shown that, compared with number pairs with a 'large' numerical distance, those with a 'small' numerical distance typically elicited greater activation in the inferior parietal lobe [7,8,9]. Event-related potentials (ERPs) studies also demonstrated that the level of potential deflection over the parietal electrodes (between 120 and 250 ms poststimulus) varied as a function of numerical distance [5,8,9]. On the basis of such findings, the parietal lobe, especially the bilateral intraparietal sulcus, has been assumed to be the brain region responsible for the processing of numbers' magnitude information [10].

Distance effect has also been found in the N400 component in two studies [11,12]. These studies used a verification task in which participants were asked to solve an arithmetic problem and then make a judgment on whether their answer matched a presented solution. Compared with the trials with the correct solutions, those with incorrect solutions consistently elicited a greater negativity with a peak latency around 400 ms poststimulus. More interesting and relevant to the current study, within the trials with incorrect solutions, the arithmetic N400 component was modulated by the numerical distance between the solution and the correct answer. Specifically, the amplitude of N400 component was greater for 'large' distance solutions (e.g. $5 \times 8=16$, in which the presented solution '16' was very different from the correct answer '40') than for 'small' distance solutions (e.g. $5 \times 8=32$, which was closer to 40). This numerical distance effect in the N400 component, however, was limited to trials in which the incorrect solutions were related to one of the operands (e.g. $5 \times 8=16$, 24, 32). In other words, Niedeggen and Rosler [11] did not find the numerical distance effect for trials whose presented solutions were not related to one of the operands (e.g. $5 \times 8=18$, 26, and 34).

The present study aims to extend this line of research by using a simpler task (i.e. a number-matching task) to tap time course and scalp-potential topography of the distance effect in automatic processing of numbers. Previous ERP studies have examined the numerical distance effect in tasks involving intentional processing of numbers: that is, participants were asked to intentionally process the magnitude information of the numbers in order to do simple arithmetic or to compare the magnitude information of the numbers. The current study investigated neural bases of 'automatic' processing of the magnitude information by asking participants to perform numerical identity judgment, for which no intentional processing of the magnitude information was required (i.e. participants could rely purely on physical same–different judgment to perform this identity task). Given that previous chronometric studies showed the numerical distance effect under the condition of automatic processing of numbers in identity judgment tasks [2] and Stroop-like tasks [3], we expected to find ERP differences associated with numerical distance.

Methods

Participants

Twenty undergraduates (10 men and 10 women) from Beijing Normal University were recruited as participants. The average age was 22.0 years, ranging from 18.5 to 22.3 years. All participants were right-handed with normal or corrected-to-normal eyesight. They had not participated in similar experiments on number cognition during the past half a year. They gave written informed consent for the experiment.

Materials

Single-digit numbers (1–9) were used. They were paired into 60 number pairs, half of which were 'small' distance pairs (distance=1, e.g. 2 and 3) and the other half 'large' distance pairs (distance >2, e.g. 2 and 7) (see Appendix A). The small-distance and large-distance number pairs had the same distribution of odd and even numbers and these numbers averaged to be of the same size as a whole. In addition, the nine matched number pairs (e.g. 4 and 4) were repeated $2 \sim 4$ times to create 60 trials for the matched condition.

Procedure

Participants were seated in a dimly lit, sound-attenuated room, facing a screen 105 cm away. All stimuli were presented visually in white against black background at the center of the screen. For each trial, a fixation sign '◇' (3×4 cm in size) was first presented for a duration of 200 ms, followed by a blank screen for 500 ms. Then an Arabic digit number ($2 \times 3\,\mathrm{cm}^2$ in size) was presented for 150 ms, followed by a blank screen for 1350 ms. After the blank screen, the second Arabic digit number of the same physical size as the first one was presented. Participants were asked to judge whether the second number was the same as the first number by pressing a key. Half of the participants responded for 'Yes' with their right hand and for 'No' with their left hand, and the other half in the opposite way. After the response, there was a blank for 2000 ms before the next trial began. Instructions to the participants emphasized both speed and accuracy.

Each of the 60 nonmatched number pairs was used twice in this study. A total of 120 nonmatched trials and 120 matched trials existed. These trials were grouped into four blocks of 6 min each. A rest of 2 min exists between blocks. Within the block, number pairs were randomly presented with the constraint that consecutive trials should not involve the same digit.

Before the formal experiment, there were 20 practice trials with a random selection of 20 number pairs. During the practice stage, the participants would be given feedback if they committed too many response errors, took too long to respond, or made significant head movement.

Event-related potential recording and analysis

Scalp voltages were recorded using a SCAN system (Neuro Inc., EL Paso, Texas, USA) with a 64-channel Quick-cap. Linked ears served as reference, and the middle of the forehead served as ground. Two channels were placed at the outer canthi of both eyes to record the horizontal electrooculogram, another two channels above and below the left eye for vertical electrooculogram. Electroencephalogram (EEG) was amplified on-line with a high-pass frequency filter of 0.05 Hz and a low-pass frequency filter of 100 Hz. The sampling rate was 1000 Hz. The impedance of all electrodes was kept below 5 kΩ.

Offline, trials were rejected for incorrect responses. A direct current correction was applied, and then ocular artifact was corrected with NeuroScan EDIT (Neuro Inc., EL Paso, Texas, USA, Version 4.3). The continuous EEG data were segmented into epochs starting from 100 ms before the onset of the second number and continuing until 800 ms after the onset of the second number. The 100 ms prestimulus served as the baseline. Epochs exceeding the range of -100 to $100\,\mu\mathrm{V}$ at any channel except horizontal electrooculogram and vertical electrooculogram were rejected as artifacts. The remaining trials were baseline corrected. The corrected data were averaged for each participant by conditions (i.e. those involving matched numbers, small-distance nonmatched numbers, and large-distance nonmatched numbers). A filter with a low pass of 30 Hz (12 DB/octave) was applied to the averaged results.

Statistical analysis

Sample-by-sample nonparametric statistics (with the Wilcoxon test) were performed on the ERP data to detect significant differences between experimental conditions. Following Pinel *et al.*'s [9] procedure, differences between two experimental conditions were considered to be significant only when 30 or more consecutive EEG samples on at least five adjacent electrodes consistently showed a significant sample-level effect (at $P<0.05$). The voltages over representative electrodes were then averaged and entered into repeated measures analysis of variance (ANOVA) to test for the numerical distance effect. The scalp electrodes were grouped in terms of their location in the anterior-to-posterior direction or caudality (frontal, central, and parietal) and laterality (left, medium, and right): F3, F5, F7; F1, FZ, F2; F4, F6, F8; C3, C5, T7; C1, CZ, C2; C4, C6, T8; P3, P5, P7; P1, PZ, P2; P4, P6, P8. Scalp topographies for numerical distance effect were visualized by EEGLAB (http://sccn.ucsd.edu/eeglab/).

Results

The mean response time and standard errors for the three conditions were 367 ms (SE=15) for the matched condition, 416 ms (SE=16) for the small-distance nonmatched condition, and 417 ms (SE=17) for the large-distance nonmatched conditions. ANOVA with the condition as the within-subject factor showed a significant main effect of the condition, F(2,38)=4.14, MSe=0.14, $P<0.05$. Pairwise comparisons with Bonferroni adjustment showed that reaction times (RTs) were longer during the trials with both types of nonmatched numbers than during those with matched numbers. ANOVA on error rates revealed no main effect of the experimental conditions. The mean error rates were 3.5% (SE=0.5) for the matched condition, 4.6% (SE=0.5) for the small-distance condition, and 4.5% (SE=0.5) for the large-distance condition.

The grand mean potentials over representative electrodes FZ, CZ, and PZ are shown in Fig. 1. The typical waveform included N100, P160, N240 components and a late positive component (LPC). The peak amplitude and latency on the three components (P160: 120–200, N240: 200–280; LPC: 320–400) were entered into three-factor matched measures ANOVA with anterio-posterior direction (frontal and central), laterality (left, medium, and right), and numerical distance (small-distance and large-distance) as within-subject factors. The only significant effect was that the peak latency of N240 potentials for the small-distance condition appeared earlier (232 ms) than that for large-distance condition (241 ms) at the fronto-central electrodes, F(1,19)=13.10, MSe=1202.86, $P<0.005$.

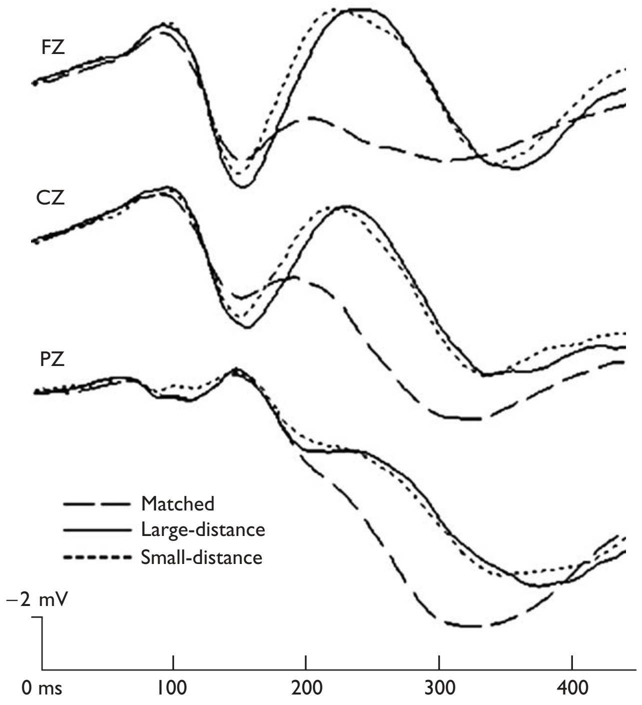

Fig. 1 The grand mean potentials elicited by matched, large-distance and small-distance number pairs.

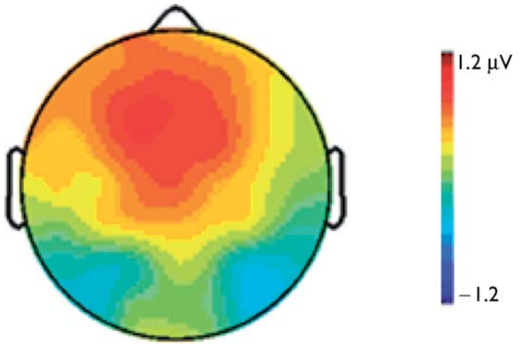

Fig. 2 Topography of difference potentials (large−small distance) in the interval 162–220 ms. The left of the picture corresponds to the left of the brain.

Sample-by-sample analyses showed a numerical distance effect in the interval of 162–220 ms, at the ascending part of N240 component. The mean amplitude in this interval was further analyzed with three-factor repeated-measures ANOVA with numerical distance (small and large distance), laterality (left, medial, and right), and anterior–posterior direction (frontal, central, and parietal) as within-subject factors. Results showed a significant main effect of numerical distance, F(1,19)=11.76, MSe=3.74, $P<0.005$, but no significant main effects for laterality and anterior–posterior direction. A significant interaction, however, exists between the numerical distance and the anterior–posterior direction, F(1,19)=6.41, MSe=2.51, $P<0.005$. Simple effect tests showed that large-distance number pairs elicited more positive mean potentials than did small-distance number pairs at the frontal and central part of brain, F(1,19)=18.74, MSe=2.95, $P<0.001$, F(1,19)=9.00, MSe=2.64, $P<0.01$. No numerical distance effects were found at the electrodes over posterior region. The topography for the mean difference waveforms of large-distance and small-distance number pairs is shown in Fig. 2.

Discussion

The goal of the present study was to investigate the time course and scalp-potential topography of the numerical distance effect during the automatic processing of numbers. Participants judged whether a number was identical to another number presented 1.5 s earlier. Compared with the matched numbers, the nonmatched numbers resulted in a greater N240 component with a maximum at the fronto-central electrodes. In terms of raw potentials, compared with small-distance number pairs, the large-distance nonmatched numbers elicited longer peak latency of N240 component and more positive mean amplitude at the ascending part of the N240 component in the interval 162–220 ms poststimulus. These numerical distance effects were limited to the fronto-central electrodes. The results extended previous research on ERP of numerical distance effect during intentional processing of numbers to such an effect during automatic processing. The distance effect at the neural level was evident even when the behavioral data did not show a distance effect in this study. In the following two paragraphs, we comment on two findings that were different from previous research.

First, our finding of numerical distance effect at fronto-central electrodes at first glance appears to be inconsistent with the previous research that located numerical distance effect for numerical comparison tasks at parietal electrodes [6,9,13] and located numerical distance effect for arithmetic solution verification tasks at a broader distribution, including frontal, central, and parietal electrodes [11]. The main plausible reason is that previous research involved intentional processing of the magnitude information of the numbers, whereas the task used in the current study tapped automatic processing. Calculation is typically involved in intentional processing of numbers and calculation tends to exploit more resources at the parietal lobe [10]. In Niedeggen and Rosler's [11] research, the interval between the presentation of the arithmetic problem and that of the proposed solution was only 350 ms. Participants generally could not finish solving the problems when they saw the proposed solutions. Thus, the verification process overlapped with the calculation. Even when the SOA was 2500 ms, participants may have had to repeat the calculation when they found that the proposed solution was not correct.

Second, the onset of numerical distance effect in our number-matching task was about 160 ms poststimulus, which was similar to that found in Szucs and Csepe's [12] study. The present study, however, found a longer peak latency of N240 component for large-distance number pairs whereas Szucs and Csepe [12] found that the N400 component of large-distance solutions had a shorter peak latency. It is not clear why large-distance number pairs would have a slightly longer peak latency when numerical distance effect typically means a shorter latency for large-distance numbers. Perhaps this was due to the cutoff point of 2 as the division between small-distance and large-distance number pairs. Future research should examine when ERP data and behavioral data converge or diverge. Another explanation is that the shorter latency for large-distance solutions in Szucs and Csepe's [12] study could be due to a bigger difference between correct and incorrect solutions for large-distance trials than for small-distance trials. That is, for large-distance trials, the incorrect and correct solutions had different number of digits in their solutions (i.e. one is single digit, whereas the other is double digit, e.g. $3+4=16$ and $3+4=7$), whereas for small-distance trials, the incorrect and correct solutions had the same number of digits (i.e. both were either one or two-digit numbers, e.g., $3+4=9$ and $3+4=7$). In the present study, the large-distance and small-distance numbers were all single digit and matched in digit size, which eliminated the confounding factor of differential solution size.

In summary, we found a numerical distance effect marked by the N240 component in a number-matching task. The distance effect was found at the anterior and central electrodes, suggesting that automatic processing of number magnitude may be located here. Further studies with higher spatial resolution technique, for example, functional magnetic resonance imaging, are needed to investigate the brain organization for the numerical distance effect indexed by the N240 component.

APPENDIX A: LARGE-DISTANCE AND SMALL-DISTANCE NON-MATCHED NUMBER PAIRS

Number pairs			Number pairs		
1st	2nd		1st	2nd	
	Large-dist.	Small-dist.		Large-dist.	Small-dist.
1	4	2	5	8	6
1	6	2	6	1	5
1	8	2	6	3	5
2	5	1	6	1	7
2	9	1	6	9	7
2	5	3	7	2	6
2	7	3	7	4	6
3	6	2	7	2	8
3	8	4	7	4	8
4	7	3	8	3	7
4	9	3	8	3	9
4	9	5	8	5	9
5	2	4	9	2	8
5	8	4	9	4	8
5	2	6	9	6	8

Note: In the matched condition, the second number was the same as the first number.
dist, distance.

References

1. Moyer RS, Landauer TK. The time required for judgments of numerical inequality. *Nature* 1967; **215**:1519–1520.
2. Duncan EM, McFarland CE. Isolating the effect of symbolic distance and semantic congruity in comparative judgments: an additive-factors analysis. *Mem Cogn* 1980; **8**:612–622.
3. Girelli L, Lucangeli D, Butterworth B. The development of automaticity in accessing number magnitude. *J Exp Child Psychol* 2000; **76**:104–122.
4. Noël MP, Rousselle L, Mussolin C. Magnitude representation in children: its development and dysfunction. In: Campbell JID, editor. *Handbook of mathematical cognition*. New York: Psychology Press; 2005. pp. 179–195.
5. Dehaene S, Bossini S, Giraux P. The mental representation of parity and number magnitude. *J Exp Psychol Genet* 1993; **122**:371–396.
6. Dehaene S. The organization of brain activations in number comparison: event-related potentials and the additive-factors method. *J Cogn Neurosci* 1996; **8**:47–68.
7. Kadosh RC, Henik A, Rubinsten O, Harald Mohr H, Dori H, van de Ven V, *et al.* Are numbers special? The comparison systems of the human brain investigated by fMRI. *Neuropsychologia* 2005; **43**:1238–1248.
8. Kaufmann L, Koppelstaetter F, Delazer M, Siedentopf C, Rhomberg P, Golaszewski S, *et al.* Neural correlates of distance and congruity effects in a numerical Stroop task: an event-related fMRI study. *Neuroimage* 2005; **25**:888–898.
9. Pinel P, Dehaene S, Riviere D, LeBihan D. Modulation of parietal activation by semantic distance in a number comparison task. *Neuroimage* 2001; **14**:1013–1026.
10. Dehaene S, Piazza M, Pinel P and Cohen L. Three parietal circuits for number processing. *Cogn Neuropsychol* 2003; **20**:487–506.
11. Niedeggen M, Rosler F. N400 effects reflect activation spread during retrieval of arithmetic facts. *Psychol Sci* 1999; **10**:271–276.
12. Szucs D, Csepe V. The effect of numerical distance and stimulus probability on ERP components elicited by numerical incongruencies in mental addition. *Cogn Brain Res* 2005; **22**:289–300.
13. Temple E, Posner MI. Brain mechanisms of quantity are similar in 5-year-old children and adults. *Proc Natl Acad Sci USA* 1998; **95**:7836–7841.