An ERP study on shift of spatial attention resulting from number processing*

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Abstract Using the "stimulus-delay-target" experimental model, the brain mechanism of visual-spatial attention shift after number processing was conducted on 13 participants by using event-related potentials (ERP) technology. Results show that influence of the number processing on the spatial attention is indexed by the P3 component; parietal lobes at both sides may be the main neural substrate for number processing and spatial attention, and the numerical-spatial interaction mainly occurs in the response selection stage.

Keywords: **number processing, visual spatial attention, the mental number line, ERP.**

The emergence and development of mathematics has dramatically promoted science progress, in particular, of natural science. Mathematics is one of the most important fundamental sciences. Studies have been conducted on the distance effect[1], symbol effect[2,3], magnitude effect[4,5] and tie effect[6,7] of number processing as well as the relationship between number processing and different attentions[8,9]. In recent years, more importance has been attached by the scholars to correlational studies of number processing and spatial cognition processing.

The spatial-numerical association of response codes effect (SNARC) experiment performed by Deheane and his colleagues[10] was one of the classical experiments on the relationship between number and space. During the experiment, the participants were requested to judge the parity of presented numbers. It was found that no matter whether it was odd number or even number, the left-hand responses were faster for numerically small numbers, whereas right-hand responses were faster for large numbers. Further study performed by Bachtold and his team revealed that when numbers were represented as the scale of ruler, the standard SNARC effect could be observed, however, when numbers were represented as the scale of a watch or a clock, the reverse SNARC was found[11], i.e. left-hand responses were faster for numerically large numbers and right-hand responses were faster for small numbers. This shows that cultural background is a critical factor in respect of SNARC. In addition, in the experiment performed by Calabria, when the participants were requested to point out the middle point of a straight line formed by letter "X", all of them could give the correct answer. However, when the participants were requested to point out the middle point of a straight line formed by figure "9" or French word "neuf" (nine), the participants would always point at a place right away from the middle point. For a straight line formed by figure "2" and French word "deux" (two), the participants would always point at a place left away from the middle point[12]. This experiment clearly demonstrates that number processing has caused the automatic left or right deviation of attention. Fischer et al.[13] performed the behavioral experiment and demonstrated the automatic mutual influence between number processing and spatial attention to a great extent. The experiment showed that though the participants were not requested to make any response to the numbers, the presentation of numbers also has influence on the participants' spatial orientation attention processing in visual fields of both sides.

At present, numerical and spatial processing researches have been largely independent in the cognitive neuroscience. So it is very important to break down this division, to integrate related results about

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the interaction between number and space in behavioral researches, and to reveal the spatial-temporal characteristics and brain mechanisms of interaction between number and space. As it has high temporal resolution, ERP is superior in revealing the time process of brain mechanism in respect of mutual interaction of numbers and spatial cognition. Therefore, the present experiment will make use of ERP technology for further study. In Fischer's experiment, the randomly selected delayed time included 50 ms, 100 ms, 200 ms, 300 ms, 400 ms and 500 ms. Only when the delayed time was above 400 ms, could the interaction between digit magnitude and spatial attention orientation take place. Therefore, for the purpose of exploring the brain mechanism regarding the interaction between numbers and spatial cognition, the delayed time in the present experiment was set as 400—500 ms.

1 Method

1.1 Participants

The participants included 13 students (6 males, 7 females) from China Agricultural University, having an average age of 20.3 years. All subjects were right-handed and had normal or corrected-to-normal visual acuity. None of the volunteers reported any history of neurological or psychiatric diseases.

1.2 Stimulus

The experiment was conducted in a sound-proof room. The participants sat comfortably 76 cm away from the computer screen. The experimental materials included the white square frames, circles and Arabic ciphers on dark background displayed on the computer screen. The viewing angle of square frames was $1\times1^{\circ}$, the circles $0.8\times0.8^{\circ}$ and Arabic ciphers $0.4\times0.75^{\circ}$. The experimental procedure was programmed with E-PRME1.2.

1.3 Procedure

Firstly a white point was fixated in centered between two square frames (each had 5° eccentricity) for 500 ms. Then one of the four digits (1, 2, 8, 9) was presented in the middle of the screen for 300 ms. After the digit was removed, a delay (400—500 ms) elapsed, followed by a circle occurred in the left or right square frames. Subjects had to press the space bar with the right hand or left hand when they saw the circle, which appeared in the two visual fields randomly. In 20% trials no circle were presented, at the moment subjects could not press any key (Fig.1).

In the course of formal experiment, each number was displayed for 150 times, and following the same number, the white circle showed itself in left and right visual field for 60 times respectively. For the remained 30 times, no white circle was displayed. The entire experiment had 600 turns. The participants could have a rest of several minutes after completing each 120-turn test. The experiment was expected to be completed within half an hour.

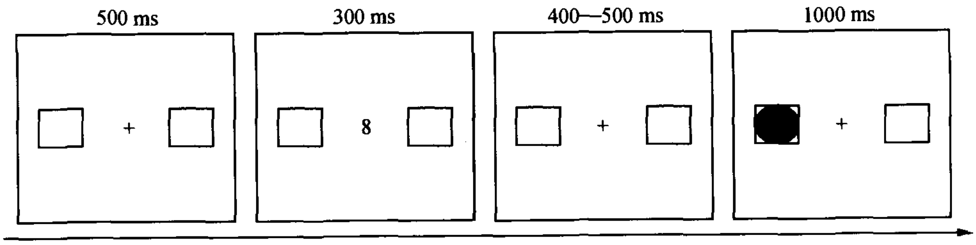

Fig. 1. Experimental procedure.

1.4 ERP recording

All subjects were fitted in an elastic cap with 64 tin electrodes (NeuroScan EEG Recording System). The impedances were kept below 5 kΩ. The vertical and horizontal electrooculagram (EOG) were recorded. The signals were amplified using a 0.05—100 Hz bandpass and recorded continuously at a sampling rate of 500 Hz/channel. Trials with artifacts ($>\pm 80$ μV) were rejected off-line.

1.5 ERP data analysis and statistics

The total length of the ERP epoch was 700 ms including a pre-targets baseline of 100 ms. Overlap and average EEG of the targets in left and right visual fields according to number magnitude, and the overlapping times ranged from 105 to 115 times with an average of 110 times. According to the purpose and the wave features of the grand averages, the following 12 sites were chosen for statistical analysis: left hemisphere (F7, T7, C3, P1, P5, PO5) and right hemisphere (F8, T8, C4, P2, P6, PO6).

For the latencies and amplitudes of the ERPs components, four-way repeated-measured analyses of variance (ANOVA) were conducted. The ERPs components were measured at 50—120 ms (P1), 120—220 ms (N1), and 230—450 ms (P3). The factors were number (2 levels: small and large), targets display visual field (2 levels: left and right), hemisphere laterality (2 levels: left and right) and electrodes (6 levels: F7/F8, T7/T8, C3/C4, P1/P2, P5/P6, PO5/PO6). The p-values of all main and interaction effects were corrected using the Greenhouse—Geisser method for repeated-measures effects.

2 Results

2.1 Behavioral data

The behavioral data were analyzed by two-way repeated-measured analyses of variance (ANOVA), result revealed that there was no main effect for the number and visual field, but there was a significant interaction between number and visual field, $F(1, 12) = 19.28$, $p < 0.01$. We found in simple effect test that after processing small numbers, subjects' responses to the targets presented in the left visual field were quicker than right $F(1,12) = 6.72$, $p < 0.05$; while after processing large numbers, subjects responded to the targets presented in the right visual field more quickly than left $F(1, 12) = 5.25$, $p < 0.05$. Correct rate was above 98.5% in all cases.

2.2 ERP data

2.2.1 P1 component

The main effect of the P1 amplitude laterality was significant, $F(1, 12) = 4.84$, $p < 0.05$, and presented as that of the left hemisphere (0.34 ± 0.20 μV) was larger than the right (-0.01 ± 0.20 μV). The main effect of recording points was also significant, $F(5,60) = 3.96$, $p < 0.05$, with the peak at point P1/P2 (0.78 ± 0.37 μV), which was larger than C3/C4 & PO5/PO6 ($p < 0.05$) and P5/P6 & T7/T8 ($p < 0.01$), but did not have significant difference from that of point F7/F8. The P1 latency showed significant interaction between targets display visual field and hemisphere laterality, $F(1, 12) = 12.57$, $p < 0.01$, which was mainly manifested when the right hemisphere recorded targets was presented in left side (89 ± 3.0 ms), and P1 latency was earlier than that presented in the right side (97 ± 4.4 ms), $F(1,12) = 4.92$, $p < 0.05$); while when the left hemisphere recorded targets was presented in right side (87 ± 3.6 ms), P1 latency was earlier than that presented in the left side (100 ± 3.2 ms), $F(1, 12) = 3.55$, $p < 0.05$.

2.2.2 N1 component

The main effect of the N1 amplitude targets display visual field was significant $F(1,12) = 6.03$, $p < 0.05$, that the left visual field (-1.38 ± 0.16 μV) was significantly smaller than the right (-2.03 ± 0.22 μV). The main effect of recording points was also significant, $F(5,60) = 6.13$, $p < 0.01$, with the peak at point P5/P6 (-2.67 ± 0.36 μV), which was larger than T7/T8 & PO5/PO6 ($p < 0.05$) and F7/F8 & P1/P2 ($p < 0.01$), but was not significantly different from that of point C3/C4. There was also a significant interaction between targets display visual field and hemisphere laterality, $F(1, 12) = 33.78$, $p < 0.001$, which was manifested when the left hemisphere recorded targets was presented in right visual field (-3.06 ± 0.48 μV), N1 amplitude was bigger than that presented in the left (-0.34 ± 0.21 μV), $F(1,12) = 8.31$, $p < 0.01$; while when the right hemisphere recorded targets were presented in the left visual field (-2.42 ± 0.31 μV), N1 amplitude was bigger than that presented in the right (-0.99 ± 0.17 μV), $F(1,12) = 4.73$, $p < 0.05$. The main effect of recording points for the N1 latency was also significant, $F(5,60) = 8.31$, $p < 0.01$, the shortest latency at point F7/F8 (142 ± 3.1 ms), which was shorter than T7/T8 ($p < 0.01$) and P5/P6 & PO5/PO6 ($p < 0.001$), but did not have significant difference from that of point C3/C4 & P1/P2.

2.2.3 P3 component

The main effect of P3 amplitude recording points was significant $F(5,60) = 11.93$, $p < 0.001$, with the peak at point C3/C4 (8.93 ± 1.12 μV), which was larger than PO5/PO6, F7/F8, T7/T8 and P5/P6 ($p < 0.001$), but did not have significant difference from that of point P1/P2. There was a significant interaction between number and visual field, $F(1,12) = 8.34$, $p < 0.05$. It showed that after processing small numbers, the targets presented in the left visual field elicited smaller P3 amplitude than that in the right $F(1,12) = 6.52$, $p < 0.05$; while after processing large numbers, the targets presented in the right visual field elicited smaller P3 amplitude than that in the left $F(1, 12) = 16.44$, $p < 0.001$. The main effect of recording points for the P3 latency was also significant, $F(5, 60) = 10.45$, $p < 0.001$, the shortest latency at point F7/F8 (278 ± 9.0 ms), which was significantly shorter than P1/P2 & C3/C4 ($p < 0.05$) and T7/T8, PO5/PO6, P5/P6 ($p < 0.001$) (Fig. 2).

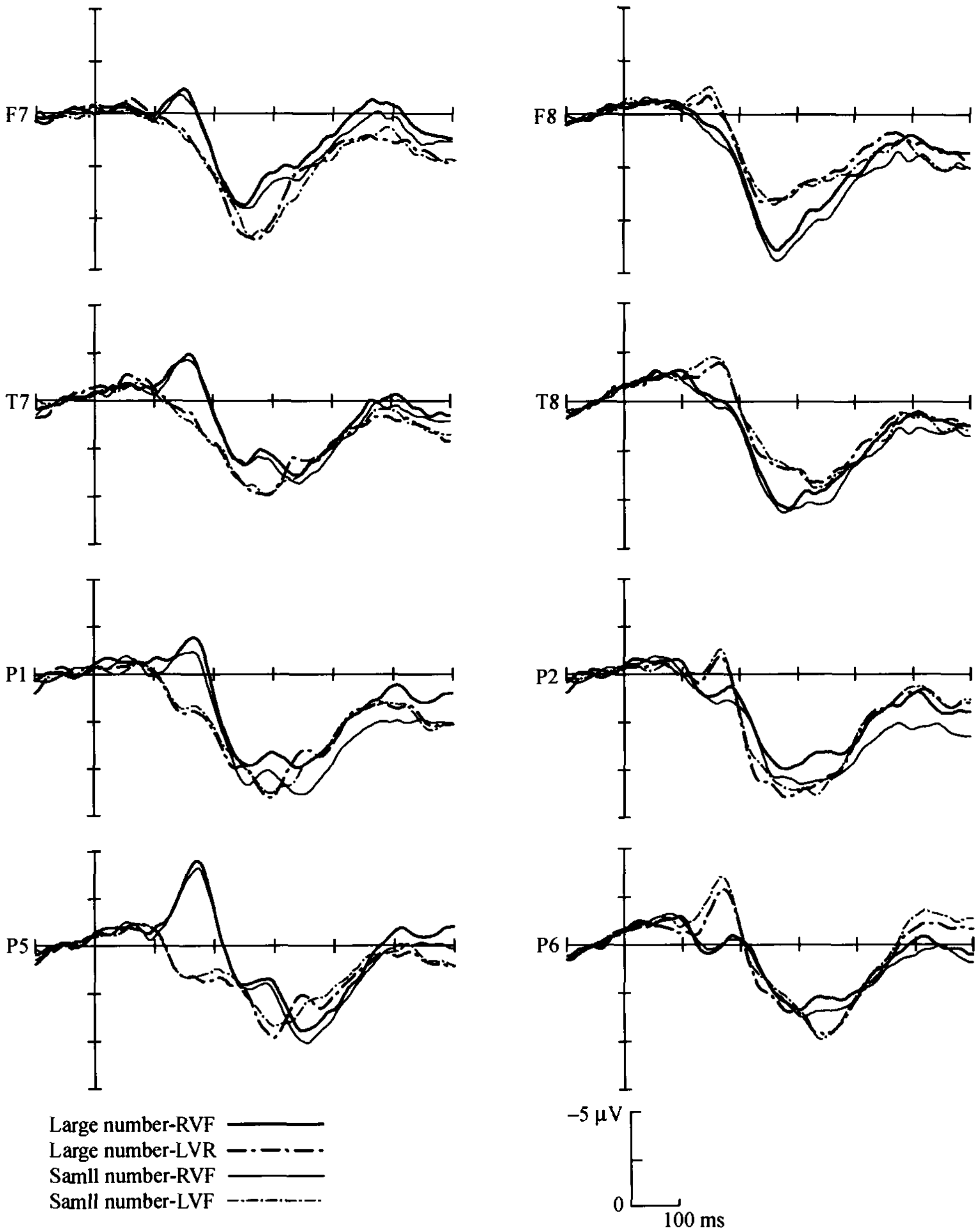

Fig. 2. Grand-average ERPs waveform to large/small numbers and in left/right visual field.

3 Discussion

The experimental behavioral data are corresponding with Fischer's experiment and the experiment demonstrates that the automatic processing on numbers (small and large) can lead to the deviation of spatial attention orientation. The processing of large numbers is more likely to cause the visual-spatial attention to the right than the processing of small numbers. However, the processing of small numbers is more likely to cause the visual-spatial attention to the left than the processing of large numbers. This is similar to SNRC effect and can be explained with "mental number line", i.e. the numbers are mentally represented as a digital line which is similar to the abscissa number axis in numeric symbol system, with the coincident relation of "the left corresponding to small numbers and the right to large numbers"[10].

According to our experiment, P1 amplitude in left hemisphere is much larger than that in right hemisphere. This could be deemed as that the left hemisphere plays a more important role than the right hemisphere in the initial stage of numeric and spatial tasks. The main evidence which supports this conclusion comes from the report that the left hemisphere injured patients always have difficulty in numeric and spatial processing[13]. For N1 amplitude, when the target is presented on the right, the amplitude is significantly larger than that presented on the left. The reasons might be that all the participants are right-handed and the left hemisphere is the dominant hemisphere, which is superior in processing of the stimulus from the right visual field to that from the left[14]. In the experiment, for P1 latency of the left hemisphere, the latency is significantly earlier when the target is presented in the right visual field than that presented in the left field; for N1 amplitude of the left hemisphere, the amplitude produced by the target from the right side is larger than that from the left; whereas the pattern is reversed in the right hemisphere. It is because in physiology, the visual half field should be firstly projected in the opposite hemisphere and has short latency and high amplitude for evoked potentials. It is also proved that component P1 and N1 are exogenous and can be influenced by the physiological rule of conductivity.

The numeric and spatial interaction can happen in the stage of understanding of the stimulus, response selection and decision-making or implementation of response. It is not easy to correctly judge at which stage the interaction happens. For this purpose, the high precise time resolution of ERP can solve this problem. In this experiment, the number magnitude and orientation of presented targets for P1 and N1 amplitude and latency show no significant interaction, which can be explained by that the interaction between numeric and spatial attention orientation did not happen during the early physical understanding of the target. P3 is an endogenous component mainly related to mental factor and has relationship with attention, memory, thinking, probability of occurrence of stimulus, emotion and even decision-making[15]. Its amplitude can reflect the cognition activities such as the difficulty of task and the self-confidence degree of the participants. Higher amplitude represents a greater difficulty. In this experiment ERP data revealed that P3 amplitude produced by target in the left visual field after processing of small numbers was much smaller than that in the right one; P3 amplitude produced by target in the right visual field after processing of large numbers was much smaller than that in the left one. Behavioral data demonstrated that after processing small numbers, subjects response the targets presented in the left visual field quicker than right; while after processing large numbers, subjects response the targets presented in the right visual field quicker than left. So both behavioral and ERP data reflected that the processing of small numbers has reduced the difficulty of making response to the target from the left side and the processing of large numbers has reduced the difficulty of making response to the target from the right side. Meantime, it can also be reckoned from the latency of P3 that the numeric and spatial interaction mainly happens in the stage of response selection and decision-making, instead of the stage of response implementation. This proves from the electrophysiology that the processing of small or large numbers will influence the attention on spatial orientation.

The triple-code model of number processing proposes that numbers can be mentally represented in a visual system, a verbal system and a non-verbal quantity representation, which depend on different neural substrates[16]. Functional MRI (fMRI) has precisely localized the non-verbal quantity system, and the research indicates that numerical tasks typically involve a distributed network of areas, including the frontal cortex and the left and right parietal lobes[17]. fMRI experiment of arithmetical comparison task also indicates that the activation of the left and right intraparietal sulci (IPS) shows a close correlation with the distance effect. The activation signal in this region also shows an inverse relationship to the distance among the numbers being compared[18]. Through a meta-analysis to fMRI experiments of arithmetical tasks, such as comparison, calculation, approximation or even the mere detection of digits, it has been revealed that the bilateral horizontal segment of the IPS (HIPS) might have a particular role in the quantity representation[19]. In these experiments, the activation is spread to the dorsal side of parietal lobe, which is also related to the orientation of spatial attention. Therefore, in the activities related with number processing and spatial attention orientation, the activated lapped part in the brain is located at the parietal lobes of both sides. From the distribution of scalp on ERP grand average figure in this experiment, it can be seen that the main electrode points of waveform difference caused by the experiment also concentrates near the parietal lobe. This also shows to a certain extent that the neural area jointly activated by number processing and spatial attention is the parietal lobes of both sides, and is a mutual corroboration to the fMRI findings.

4 Conclusions

Influence of the number processing on the spatial attention is indexed by the P3 component. The P3 produced by target in the left visual field after processing of small numbers is much smaller than that in the right field. The P3 evoked by the target in the right visual field after processing of large numbers is much smaller than that in the left one. Parietal area at both hemisheres may be the main neural substrate for number processing and spatial attention, and the numerical-spatial interaction mainly occurs in the response selection stage.

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