

Quantity Processing in Object Counting Task Based on Event-Related Potentials

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Abstract: In the preliminary event-dependent potentials study, our team found that the neural mechanism of Chinese singular and plural picture naming is different, and explained that the differences might lie in the different numbers of quantitative processing. However, previous studies have lacked separate neural processing of objects in singular-plural pictures. This study intends to explore the neural differences in quantity processing in singular and plural pictures by using an object counting task and combining Event-related potential (ERP). It is expected to prove that the neural differences of naming Chinese single and plural pictures found in our previous ERP research are neural processing differences of different quantities, further demonstrating that the quantity processing in Chinese singular and plural picture naming is automatic. The experimental results showed no significant differences in object counting accuracy ($P=0.139$) and reaction time ($P=0.231$) between the singular and plural groups. However, there was a noticeable difference in ERPs between the two groups ($P<0.05$) and statistical analysis showed that the P1 effect of the parieto-occipital lobe was greater in plural pictures than in singular pictures (140-180ms) and the P2 effect of the parieto-occipital lobe was more significant in singular pictures than in plural pictures (200-320ms). There are differences in the quantity processing of healthy adults in object counting tasks. These differences are similar to the neural differences in Chinese singular-plural picture naming, indicating that the quantity is automatically processed in this process.

Keywords: Singular, Plural, Quantity Processing, Object Counting, Event-Dependent Potentials (ERP)

1. Introduction

Numerical competence, the ability to represent, identify, and process a number of objects and events [1], is an essential component of higher-order cognition and exists widely in the animal kingdom [2]. Many characteristics of the external world will be automatically processed along the pathway of quantity processing. It is crucial to master the quantitative cognitive ability to help humanity better understand the world and deal with daily life.

Numerical magnitude is an abstract property of a set, which can be presented in symbolic or non-symbolic form, representing the same quantitative meaning ("8", "eight", ".....") [3]. It is generally accepted that humans have an innate approximation system for handling numerical magnitudes,

which can distinguish the number of elements in a set [4-6]. Accumulating studies suggest that very young infants (even newborns) have mastered the ability to process non-symbolic numerical magnitudes before they acquire language, and they can distinguish between a single object and multiple collections of objects [5, 7] or simple dot patterns [8, 9].

However, this processing is an approximate processing system that may not be very accurate [10] and can be influenced by the ratio between the two numerical values [11, 12]. Similar numerical processing capability has been found in animal experiments with different species [13, 14]. For example, Brannon and Terrace [15] trained two macaques to learn the numbers 1 to 4 in ascending order, and the experiment showed that the monkeys were able to respond to the numbers 1 to 9 (including the novel numbers 5-9) in

ascending order. Further studies have shown that the quantity processing of early humans also involved arithmetic operations [16]. After repeated experiments on visual preference tasks based on strict control of continuous variables, researchers found that early humans had a fundamental concept of numbers, preferred to see the exact number of objects, and spent more time on the results of numerical calculation errors [5, 9]. Some studies even showed that controlling the repetition of a task-irrelevant number, fMRI data showed that subjects' quantity processing brain regions could still be activated even if the subjects were unaware of seeing the number symbol [17, 18]. Therefore, the essential quantity-processing ability is innate. When facing objects with different amounts of information, people not only activate sensory perception mode but also carry out the neural processing of counting or calculating unconsciously.

In 1993, Dehaene S and Changeux JP proposed the classical neural processing model for non-symbolic quantity processing-- "quantity detection model", specifying how visual objects are counted [19]. First, the information about the size and position of objects will be input into and represented on the retina. Second, a fixed population of neurons form a topological mapping corresponding to the objects' position to normalize the objects' size and position. Finally, the quantity detector summarizes the output of the position mapping, forming a neural mapping which is highly related to the quantity. In 2004, Verguts and Fias further proposed the "backpropagation network model" to improve this theory; that is, the position of objects was presented in the input layer, and the corresponding numerosity was required as output, and they applied it to the symbolic numerical processing [20]. Both above two computational models focus on the two numerical representation models of summation coding and spatial coding.

Two kinds of coding sequence occur: summation coding is a prerequisite for the execution of the spatial coding, which continues the properties of the summation neurons (like accumulators). It is assumed that the neuronal activity will increase linearly with the increase of the number of neurons, while the spatial codes of the position neurons only make neuroelectric emissions for a specific number or a preferred number (like a band-pass filter) [2, 19, 20]. It was found that the choice of encoders may be influenced by the task paradigm [21, 22]. For example, summation coding may be preferred in size-comparison tasks [20, 23], while spatial coding may be preferred in dissimilarity-comparison tasks [22]. Therefore, we were curious about whether there would be automated quantitative processing when people see objects with different amounts of information in their daily lives and whether there would be differences in the neural processes of different amounts.

Many previous studies on the processing mechanism of non-symbolic quantities were explored in an abstract form (same number of dots). But in fact, quantitative relations are ubiquitous in daily life: we can say one apple or three apples. Moreover, concrete objects such as shoes, pants, and bananas often exist in the plural form.

At the same time, our previous study found that the neural processing in Chinese naming of singular and plural pictures is different. We proposed that there are two neural processing processes in Chinese picture naming: lexical generation and implicit quantitative processing. The neural difference in Chinese singular and plural picture naming reflected the difference in quantity processing [24]. Nevertheless, our study needs to be completed and detailed enough, lacking ERP research on the separate quantity processing in singular and plural pictures for comparative verification. Therefore, based on the previous experiments, this study set up a singular-plural counting task of the same type of pictures to explore the differences in the quantity processing of singular and plural pictures to supplement this part of the evidence.

2. Materials and Methods

2.1. Experimental Subjects

In this study, twenty healthy college students (10 males and 10 females; age range: 24-30 years, average age \pm SD: 26.6 \pm 1.7 years) were recruited from Jinan University, Guangzhou, China, as paid participants. All subjects were native Chinese speakers with right-handed and normal or corrected normal vision, without neurological history, reading or learning disabilities, or color blindness. All subjects signed the written informed consent after understanding the purpose and procedures of the experiment, and the Medical Ethics Committee of the First Affiliated Hospital of Jinan University approved the design scheme of this study.

2.2. Stimulation Materials

They are consistent with the previous research materials [24].

2.3. Experimental Procedures

Participants were asked to wear Ag-AgCl electrode caps, sit approximately 120 cm away from a 23-inch computer monitor, and use the MindXP software to complete this experiment in a room with weak sound and dim light. Their eyes should be at the same level as the center of the screen to avoid excessive eye movement.

The experiment started with the "+" displayed in the center of the screen for 500 ms, and the color picture (stimulus presentation) and the dark gray background (stimulus interval) were presented alternately. All the participants were asked to complete the counting task at the last speed after the stimulus disappeared (if the number of objects was 1, press the left mouse button; if the number was 3, press the right button). Before the experiment, the participants will complete a pre-experiment designed by the other 5 pictures to familiarize themselves with the experimental procedure. They will be asked to practice repeatedly until the accuracy of key pressing reaches more than 95%.

The experiment included 132 trials consisting of two identical blocks. One block took about 1.35 minutes to play 66 pictures, with a minute break between blocks. The experiment took 3.79 minutes to complete. The unified

presentation time of color pictures is 600ms, and the stimulus interval was randomly selected between 500-1000ms to reduce distractions caused by long stimulus presentations or intervals (as *Figure 1*). At the same time, the experiment used a Latin square design; grouping singular and plural pictures of 10 subjects was exactly the opposite of the other 10 subjects [25]. In this process, the ERP device will automatically record the EEG data as well as the keystroke specifics (including whether the keystroke was correct and when the reaction was made).

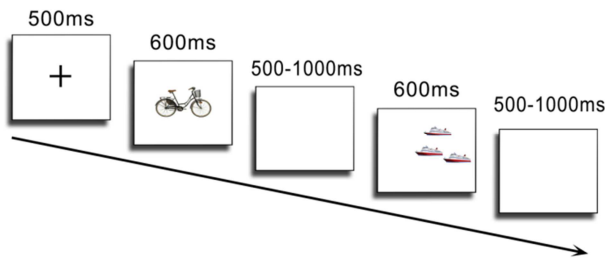


Figure 1. Experimental flow chart.

All trials in the experiment followed the order described in the figure. The "+" picture appeared to indicate the immediate start of the naming task. Then the colored pictures (stimulus presentation) were presented alternately with a dark gray background (stimulus interval). Task requirements: Subjects pressed the left mouse button (1 object) or the right mouse button (3 objects) at the last speed after the picture stimulus disappeared.

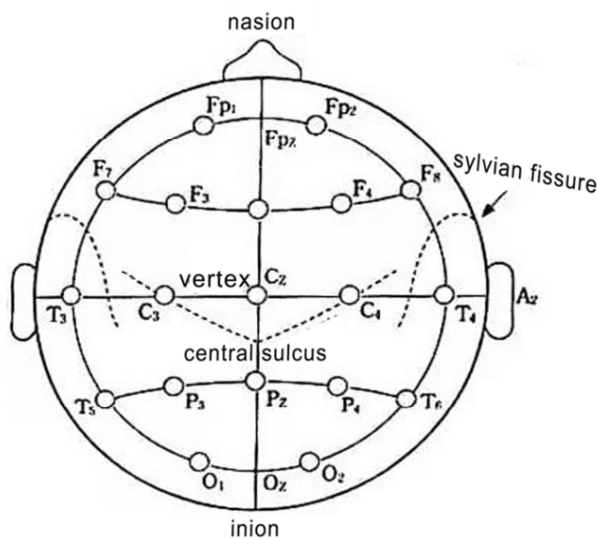


Figure 2. The international 10-20 EEG recording system.

2.4. Electrophysiological Recordings

The EEG recording system was provided by the Nanfang Hospital, Southern Medical University, with a 19-channel EEG amplifier (Symtop Instrument®) that records continuously at a sampling rate of 1,000 Hz with a filtered passband of 0.5-100Hz. The international 10-20 EEG recording system (FP1, FP2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fz, Cz and Pz) uses two marker lines,

along with the linked earlobe, as a reference (as *Figure 2*). The impedance between the EEG scalp and the electrode was kept below 10k Ω .

3. Data Analyses

3.1. Behavioral Analyses

Calculate the average accuracy and reaction times (RTs) of keystrokes. The keystrokes errors include the preemptive answer, timeout, invalidity, or misjudgment of quantity. Then, SPSS 26.0 software was used to conduct two-tailed paired t-test on the accuracy and reaction time of the singular and plural groups, respectively.

3.2. Event-Related Potentials Analyses

This study used MindWave-sorting and SPM software developed by our lab to analyze ERPs [26-28]. MindWave-sorting software was used for preprocessing of the EEG data, including automatic correction of the original EEG data and extraction of ERPs. First, an artifacts threshold of $\pm 70\mu V$ is set using MindWave-sorting software to detect disturbances caused by eyes, muscles, or other activities. Next, the EEG signals are automatically corrected for artifacts by principal component analysis [29, 30]. Then, two ERPs (singular and plural ERPs) were obtained in 19 channels by segmenting the time from -100ms to 600ms after the start of stimulation and baseline correction (using the average amplitude of 100ms interval before stimulation). After that, the total average waveforms of the singular and plural ERPs of 20 subjects were obtained by SPM software. The two ERPs were statistically compared using a two-tailed paired t-test, and the results of 19-channel repeated measurements were corrected through the false discovery rate (FDR) [31, 32]. Finally, the difference between the two ERPs was represented as a topographic map using interpolation methods associated with generalized cortical imaging techniques [33]. The topographic map took 0.05 as the threshold for statistically significant differences; and set a fixed time window of 20 ms for the graphs without overlapping data.

4. Results

4.1. Behavioral Data

All participants completed the experiment at one time, and no one was excluded. The accuracy of keystrokes was high for all people, the average percentage was about $97.05 \pm 2.03\%$, and the average reaction time was $319.28 \pm 45.62\text{ms}$ (the fluctuation range is within 3 standard deviations). The specific behavioral statistics of the two groups are shown in Table 1. The types of keystroke errors and their percentage (%) are reported in Table 2. After paired t-test, it was also found that there was no significant difference between the two groups in terms of accuracy ($P=0.139$) and RTs ($P=0.231$).

Table 1. Behavioral results (mean \pm SD) (N=20).

Behavioral performance	Singular Picture counting	Plural picture counting	<i>t</i>	<i>p</i>
Accuracy rate (%)	97.58 \pm 1.93	96.52 \pm 2.09	1.543	0.139
Reaction time (ms)	322.30 \pm 49.63	316.25 \pm 43.56	1.238	0.231

Table 2. Error trial classifications (mean \pm SD) (N=20).

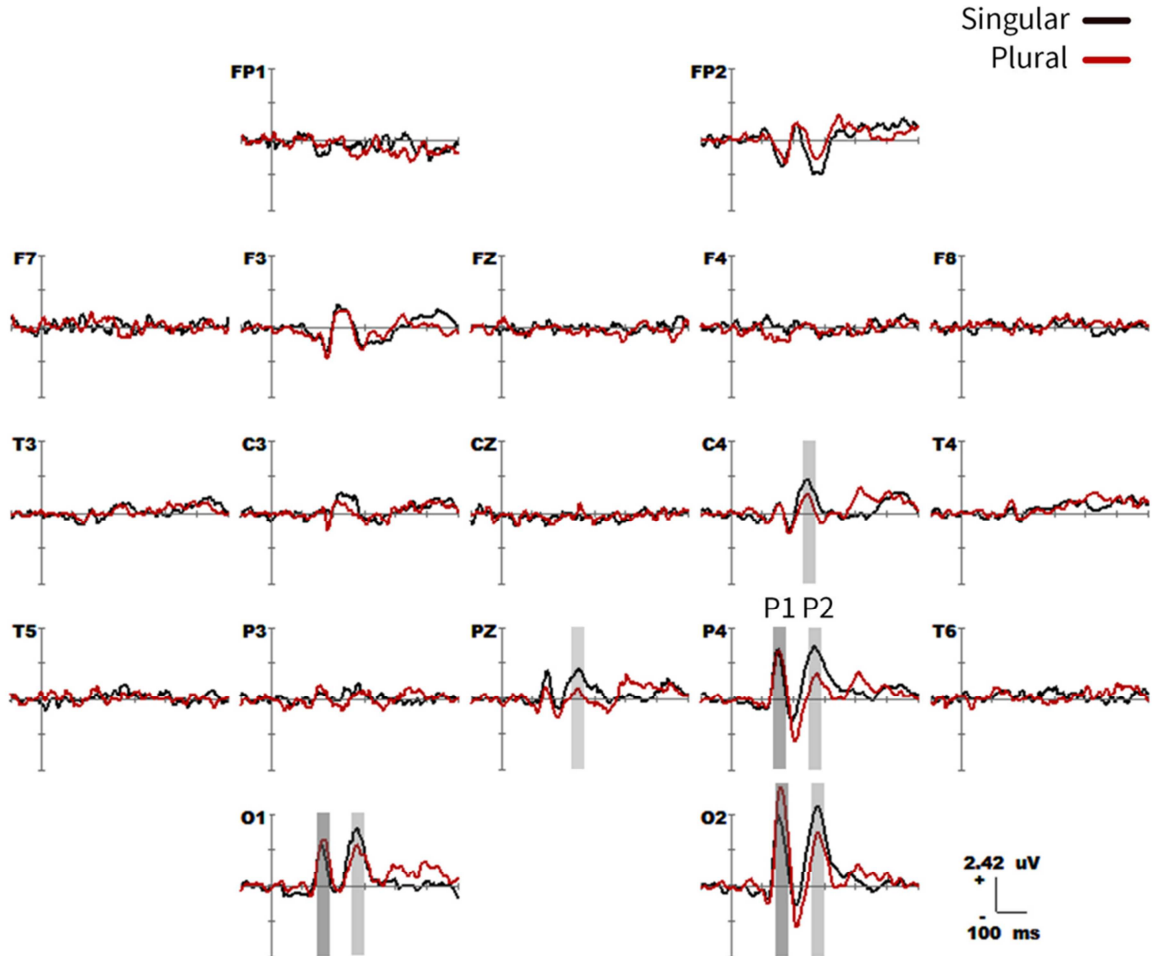
Error trial classification	Singular picture counting	Plural picture counting
preemptive answer (%)	1.06 \pm 0.84	1.44 \pm 0.75
Timeout (%)	0.38 \pm 0.66	0.53 \pm 0.72
Keystroke error (%)	1.14 \pm 0.94	1.52 \pm 1.27

4.2. Waveform and Component Analysis

In the experiment, the total average ERPs waveform and its difference between the singular-plural counting tasks ranged from 0 to 400ms (as Figure 3). And the ERPs waveforms of the two groups also showed significant differences between the two phases.

In the first phase (P1), the average amplitude at the O1, O2, and P4 electrodes in the parieto-occipital lobe within 140-180ms was greater in the plural pictures than in the singular pictures. In the second phase (P2), the average amplitude at the O1, O2, Pz, P4 and C4 electrodes in the parieto-occipital lobe within 200-320ms was greater in the singular pictures than in the plural pictures.

The results of previous literature on quantitative processing ERPs suggest that quantitative processing is completed within approximately 400ms [34, 35]. We think that the waveform difference after 400ms in this experiment may be related to the psychological expectation of performing the keystroke task, which is not the object of this experiment. The difference in waveform amplitude between the two ERPs at typical electrodes is detailed in Table 3, with a fixed time window of 20 ms. The maximum P1 effect is 2.42uV at the 160ms of the O2 electrode, the amplitude of the corresponding plural picture is 4.63uV, and the amplitude of the singular picture is 2.21uV. The maximum P2 effect is 1.88uV at the 260ms of O2 electrode, the amplitude of the corresponding singular picture is 5.34uV, and that of the plural picture is 3.46uV.

**Figure 3.** Average waveform diagram.

Overall average waveform (-100~600 ms) of ERPs on 19 electrodes for singular (black line) vs plural (red line) picture object counting task in 20 subjects. The baseline of ERPs is the average amplitude of the waveform within 100ms before stimulus presentations.

Table 3. Significant waveform effects for differences in ERPs of singular and plural object counting tasks ($N=20$).

Effect	P1 (O2)		P1 (O2)		P1 (P4)		P2 (O2)		P2 (Pz)	
	Stat.	p/VO	Stat.	p/VO	Stat.	p/VO	Stat.	p/VO	Stat.	p/VO
t/p	-2.49	0.022	-3.68	0.002	-2.19	0.043	3.27	0.004	2.71	0.017
Cohen's d/VO	-1.142	140	-1.688	160	-1.005	160	1.500	200	1.243	200
	P2 (P4)		P2 (C4)		P2 (O2)		P2 (Pz)		P2 (P3)	
t/p	3.31	0.004	3.06	0.007	3.48	0.003	2.52	0.025	2.24	0.047
Cohen's d/VO	1.519	200	1.404	200	1.597	220	1.156	220	1.028	220
	P2 (P4)		P2 (C4)		P2 (O1)		P2 (O2)		P2 (Pz)	
t/p	3.53	0.002	2.73	0.015	2.4	0.034	3.71	0.001	3.16	0.006
Cohen's d/VO	1.620	220	1.253	220	1.101	240	1.702	240	1.450	240
	P2 (P4)		P2 (C4)		P2 (O1)		P2 (O2)		P2 (Pz)	
t/p	3.51	0.002	2.74	0.015	2.26	0.049	3.32	0.004	2.44	0.031
Cohen's d/VO	1.610	240	1.257	240	1.037	260	1.523	260	1.120	260
	P2 (P4)		P2 (T6)		P2 (C4)		P2 (O2)		P2 (Pz)	
t/p	2.88	0.010	2.46	0.028	2.83	0.012	2.87	0.011	2.89	0.010
Cohen's d/VO	1.321	260	1.129	260	1.298	260	1.317	280	1.326	280
	P2 (P4)		P2 (C4)		P2 (O2)		P2 (Pz)		P2 (P4)	
t/p	3.24	0.004	2.37	0.034	2.54	0.022	2.6	0.019	2.9	0.009
Cohen's d/VO	1.487	280	1.087	280	1.165	300	1.193	300	1.331	300
	P2 (O2)									
t/p	2.72	0.014								
Cohen's d/VO	1.248	320								

Note: VO, time window. The time window is set to 20ms.

4.3. Spatiotemporal Pattern: SPM (t)

Figure 4 showed the topographic map of SPM (t) (0-600 ms) derived from the two-tailed paired t-test. The bright blue and red positions of the color code respectively correspond to the threshold of $p = 0.05$: $t_{(1, 19)} = \pm 2.09$; The white dots on the topographic map represent the electrode sites with significant differences. The difference in neural processing between the two groups in the counting task was initially shown in the

parieto-occipital lobe at 140-180 ms, and the average amplitude of singular pictures was smaller than that of plural pictures. And then, in the parieto-occipital lobe at 200-320ms, there was another significant difference in waveform amplitude between the two types of pictures. The difference was that the average amplitude of the plural pictures was smaller than that of the singular pictures. With the same waveform interpretation, we consider that the topographic differences after 400 ms are not related to the quantitative processing.

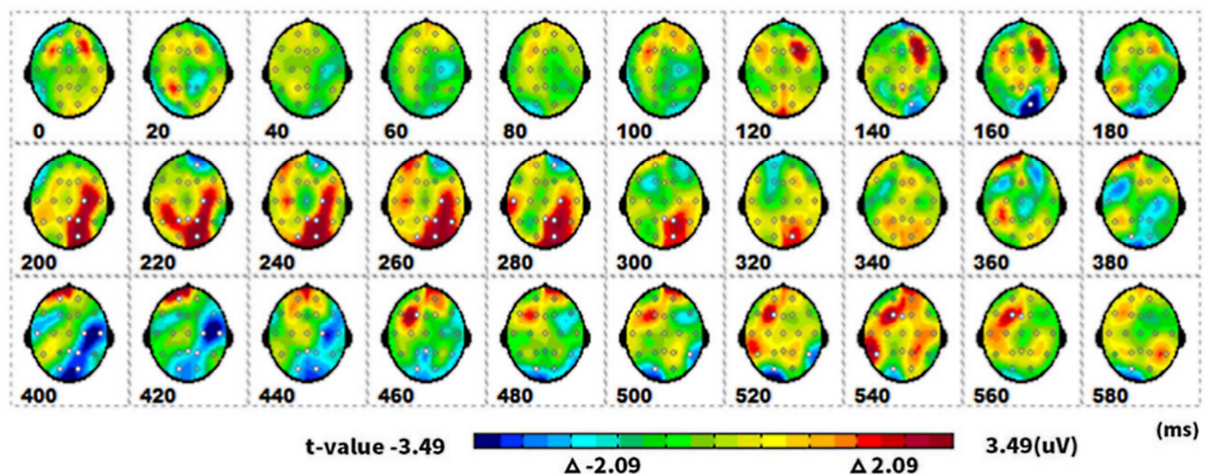


Figure 4. Spatiotemporal pattern diagram.

The ERPs of the singular-plural object counting task are tested by two-tailed paired t-test, and the spatiotemporal patterns of SPM (t) (0-600ms) are obtained by interpolation within the average t value. The time window is fixed at 20ms; the colour code's red and bright blue positions corresponded to the threshold of 0.05: $t(1,19) = \pm 2.09$. The white spots represent the electrode sites with significant differences.

5. Discussion

The stimulus time was chosen for the program setting because the Chinese picture naming process might contain quantitative information processing in our previous experiments, and this process would be completed within about 0-400ms. Therefore, in the object counting task, we appropriately shortened the picture presentation time to 600ms and shortened the interval time to reduce the distraction caused by the long stimulus presentation or interval time. Moreover, we also asked the subjects to press the keys after the picture stimulus disappeared. At the same time, the ERPs data were intercepted in the period of -100-600ms after the stimulus presentation, which only included the quantitative processing of EEG activities and excluded the confounding of task switching and button pressing execution.

Behavioral results showed no significant difference in the accuracy ($P=0.139$) and RTs ($P=0.231$) of counting tasks between the two groups. The accuracy of the two counting tasks was very high for all subjects, and their reaction time was relatively centralized, which suggested that the ERPs data of these 20 subjects could be combined. This was consistent with the previous literature: that was, 1 to 3 were small numbers, with relatively small differences in correctness and reaction time [36, 37]. As illustrated in the analysis of the results of the average waveforms, although the experiment intercepted 0-600 ms ERPs data, it mainly focused on the EEG from 0-400 ms. The ERPs results between 0-400ms showed that the differences between singular and plural quantity processing were mainly manifested in two stages: 140-180ms (P1 effect) and 200-320ms (P2 effect) in the parieto-occipital lobe; The characteristics of these two effects were respectively consistent with the neural processing features of summation coding and spatial coding, which were consistent with the results of ERPs about quantitative processing in previous literature [34, 38]. Previous literature showed that quantity processing mainly occurred in the parieto-occipital lobe, including summation and spatial coding. Summation coding is encoded first (N1 effect), which reflects the actual numerical value, about 150-200ms. The larger the value, the greater the ERP amplitude. Spatial coding (P2 effect) reflects the distance between the actual value and the psychological expectation value, which is about 200-300ms. The closer to the psychological expectation, the greater the ERP amplitude [38-40].

In this study, the first ERPs difference (P1 effect) of singular and plural processing was a positive wave in the parieto-occipital lobe at 140-180 ms. The amplitude of plural pictures was greater than that of singular pictures. The second

ERPs difference (P2 effect) was a positive wave of 200-320ms in the parieto-occipital lobe, with greater amplitude in singular than in plural pictures (singular pictures are more common in daily life, which are more consistent with psychological expectations). Because these two effects were consistent with the characteristics of summation coding and spatial coding in processing time, brain regions and waveform, the P1 and P2 effects should represent the difference between singular and plural quantity information processing. However, the polarity of the summation coding (P1) in this experiment is opposite to that of the previous arithmetic task ERPs (N1).

We considered that summation coding in this experiment may have been disturbed by the experimental materials. Because in the previous counting tasks, the stimulus materials often used different numbers of dots (non-symbolic values) or numbers (symbolic values), while in this experiment, we used color pictures of common objects in daily life. Even in the quantitative judgment task, the subjects will unconsciously extract the visual features of the objects after seeing the color pictures. Even if there is no word selection or naming, the object recognition/concept formation stage may have been completed. Therefore, the change of summation coding waveform may be affected by the concept of object.

The study found that quantity processing (0-350 ms) mainly completed two steps of summation coding and spatial coding after visual extraction, with the active brain regions mainly shifting to the parietal lobe. The P1 and P2 effects of ERPs in this study were very similar to the neural differences of Chinese singular and plural picture naming in our previous study regarding waveform shape, distribution of brain regions, and occurrence time course [24]. The results further supported the correctness of the previous research concluded that the neural differences between singular and plural picture naming lied in the differences in quantity processing or that there existed an automatic processing process of quantity information under the singular-plural picture naming task. According to the previous literature analysis, this was reasonable, and non-symbolic quantity processing was an innate ability [41]. We can complete the neural processing of singular and plural pictures without task requirements [42] or consciousness [17, 18]. As we all know, quantity is closely related to language. For example, symbolic values are a part of the language.

Moreover, the concept of quantity and the implementation of arithmetic involve semantic processing [43]. Summation coding of quantity processing can be used as the total number concept, and the time course of its electrical activity is very close to that of concept formation and lexical item selection in the process of lexical generation. If visual stimuli are given to different numbers of objects, it might help preschoolers or neurologically dysfunctional patients better to grasp the concept of quantity and lexical relations.

Although we studied the neural process of quantity processing of singular and plural pictures and further verified the relationship between summation coding and lexical-semantic processing, it still has some limitations and

can be further studied. First, small and large numbers have different neural mechanisms. In this paper, all stimulus materials were small numbers. In the future, different numbers of stimulation materials can be selected to provide additional evidence for automatic quantitative processing (summation coding) in picture naming. Second, objects in the singular and plural pictures were randomly placed in this study. If the spatial position is changed in the future, more information about position coding could be obtained. Third, the stimulus materials chosen for this study were non-biological. Given the different neural processing of different types of objects, if we further classify the types (such as animals, fruits and tools) in the future, we can explore whether different types of images will produce different neural processing results. Fourth, the subjects of this study are healthy adults. In the future, we can focus on special disease groups, such as autism, aphasia and other groups, to provide more clues for clinical application.

6. Conclusion

There were no behavioral differences in the object counting task for singular-plural pictures, but the difference in ERPs was shown as the P1 effect of 140-180ms in the parieto-occipital lobe and P2 effect of 200-320ms in the parieto-occipital lobe. This neural processing difference is consistent with the neural difference in naming Chinese singular and plural pictures in our previous study, which further illustrates that the neural difference is the quantitative processing difference.

Data Availability Statement

The original data supporting the conclusions of this paper will be provided by the authors without undue reservation.

Ethical Statement

The study involving human participants was reviewed and approved by the Medical Ethics Committee of the First Affiliated Hospital of Jinan University (approval number: KY-2020-087). The patients/participants provided written informed consent for participation in this study.

Author Contributions

C-MS, L-YC and S-RS contributed to the conception and design of the study and performed the writing of this manuscript. L-YC, C-MS, Y-FY and Y-RS collected the recording data. Z-MC revised the main manuscript text and modified the article.

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Conflict of Interest

The authors declared that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- [1] Vandervort LR: A Brain for Numbers: The Biology of the Number Instinct by Andreas Nieder. *The Mathematical Intelligencer* 2021, 43 (1): 123-127.
- [2] Nieder A: The Adaptive Value of Numerical Competence. *Trends Ecol Evol* 2020, 35 (7): 605-617.
- [3] Holloway ID, Ansari D: Developmental specialization in the right intraparietal sulcus for the abstract representation of numerical magnitude. *J Cogn Neurosci* 2010, 22 (11): 2627-2637.
- [4] Butterworth B: The development of arithmetical abilities. *J Child Psychol Psychiatry* 2005, 46 (1).
- [5] McCrink K, Wynn K: Large-number addition and subtraction by 9-month-old infants. *Psychol Sci* 2004, 15 (11): 776-781.
- [6] Starkey P, Cooper RG: Perception of numbers by human infants. *Science* 1980, 210 (4473): 1033-1035.
- [7] Antell SE, Keating DP: Perception of numerical invariance in neonates. *Child Dev* 1983, 54 (3): 695-701.
- [8] Kurland J, Liu A, Stokes P: Effects of a Tablet-Based Home Practice Program With Telepractice on Treatment Outcomes in Chronic Aphasia. *J Speech Lang Hear R* 2018, 61 (5): 1140-1156.
- [9] Wynn K, Bloom P, Chiang W-C: Enumeration of collective entities by 5-month-old infants. *Cognition* 2002, 83 (3): B55-B62.
- [10] Bugden S, DeWind NK, Brannon EM. Using cognitive training studies to unravel the mechanisms by which the approximate number system supports symbolic math ability. *Curr Opin Behav Sci*. 2016; 10: 73-80.
- [11] Halberda J, Mazocco MMM, Feigenson L: Individual differences in non-verbal number acuity correlate with maths achievement. *Nature* 2008, 455 (7213): 665-668.
- [12] Xu F, Spelke ES: Large number discrimination in 6-month-old infants. *Cognition* 2000, 74 (1).
- [13] Diester I, Nieder A: Numerical values leave a semantic imprint on associated signs in monkeys. *J Cogn Neurosci* 2010, 22 (1): 174-183.
- [14] Stancher G, Rugani R, Regolin L, Vallortigara G: Numerical discrimination by frogs (*Bombina orientalis*). *Anim Cogn* 2015, 18 (1): 219-229.
- [15] Brannon EM, Terrace HS: Ordering of the numerosities 1 to 9 by monkeys. *Science* 1998, 282 (5389): 746-749.
- [16] Schneider M, Beeres K, Coban L, Merz S, Susan Schmidt S, Stricker J, De Smedt B: Associations of non-symbolic and symbolic numerical magnitude processing with mathematical competence: a meta-analysis. *Dev Sci* 2017, 20 (3).

- [17] Dehaene S, Naccache L, Le Clec'H G, Koechlin E, Mueller M, Dehaene-Lambertz G, van de Moortele PF, Le Bihan D: Imaging unconscious semantic priming. *Nature* 1998, 395 (6702): 597-600.
- [18] Naccache L, Dehaene S: The priming method: imaging unconscious repetition priming reveals an abstract representation of number in the parietal lobes. *Cereb Cortex* 2001, 11 (10): 966-974.
- [19] Dehaene S, Changeux JP: Development of elementary numerical abilities: a neuronal model. *J Cogn Neurosci* 1993, 5 (4): 390-407.
- [20] Verguts T, Fias W: Representation of number in animals and humans: a neural model. *J Cogn Neurosci* 2004, 16 (9): 1493-1504.
- [21] Parker AJ, Newsome WT: Sense and the single neuron: probing the physiology of perception. *Annu Rev Neurosci* 1998, 21: 227-277.
- [22] Salinas E: How behavioral constraints may determine optimal sensory representations. *PLoS Biol* 2006, 4 (12): e387.
- [23] Romo R, Brody CD, Hernández A, Lemus L: Neuronal correlates of parametric working memory in the prefrontal cortex. *Nature* 1999, 399 (6735): 470-473.
- [24] Cui L-Y, Cheng W-W, Shan S-R, Lv W, Sun C-M, Li R, Zhou S, Chen Z-M, Bao S-Y: Spontaneous quantitative processing in Chinese singular and plural picture naming: An event-related potentials analysis. *Frontiers In Neuroscience* 2022, 16: 898526.
- [25] Richardson JTE: The use of Latin-square designs in educational and psychological research. *Educational Research Review* 2018.
- [26] Cheng W, Huang Q, Chen Y, Dai W, Cui L, Shan S, Chen Z, Zhou S: Parsing the Neural Mechanisms of Short-Term and Long-Term Associations in the Flanker Tasks: An ERP Analysis. *Front Behav Neurosci* 2021, 15: 626907.
- [27] Zhou S, Xiong S, Cheng W, Wang Y: Flanker paradigm contains conflict and distraction factors with distinct neural mechanisms: an ERP analysis in a 2-1 mapping task. *Cogn Neurodyn* 2019, 13 (4): 341-356.
- [28] Zhou S, Zhou W, Chen X: Spatiotemporal analysis of ERP during chinese idiom comprehension. *Brain Topogr* 2004, 17 (1): 27-37.
- [29] Lins OG, Picton TW, Berg P, Scherg M: Ocular artifacts in EEG and event-related potentials. I: Scalp topography. *Brain Topogr* 1993, 6 (1): 51-63.
- [30] Lins OG, Picton TW, Berg P, Scherg M: Ocular artifacts in recording EEGs and event-related potentials. II: Source dipoles and source components. *Brain Topogr* 1993, 6 (1): 65-78.
- [31] Benjamini Y, Yekutieli D: The Control of the False Discovery Rate in Multiple Testing Under Dependency. *Ann Stat* 2001, 29.
- [32] Lage-Castellanos A, Martínez-Montes E, Hernández-Cabrera JA, Galán L: False discovery rate and permutation test: an evaluation in ERP data analysis. *Stat Med* 2010, 29 (1): 63-74.
- [33] Zhou S, Wei J, Luo Y, Yang W: New methods for three dimensional mapping of brain waves. *Brain Topogr* 1998, 11 (2): 103-110.
- [34] Ben-Shalom T, Berger A, Henik A: My brain knows numbers! - an ERP study of preschoolers' numerical knowledge. *Front Psychol* 2013, 4: 716.
- [35] Pinhas M, Buchman C, Lavro D, Mesika D, Tzelgov J, Berger A: The Neural Signatures of Processing Semantic End Values in Automatic Number Comparisons. *Front Hum Neurosci* 2015, 9: 645.
- [36] Jevons WS: The Power of Numerical Discrimination. *Nature* 1871, 3 (67): 281-282.
- [37] Piazza M, Giacomini E, Le Bihan D, Dehaene S: Single-trial classification of parallel pre-attentive and serial attentive processes using functional magnetic resonance imaging. *Proc Biol Sci* 2003, 270 (1521): 1237-1245.
- [38] Libertus ME, Woldorff MG, Brannon EM: Electrophysiological evidence for notation independence in numerical processing. *Behav Brain Funct* 2007, 3: 1.
- [39] Lyons IM, Ansari D: Foundations of children's numerical and mathematical skills: the roles of symbolic and nonsymbolic representations of numerical magnitude. *Adv Child Dev Behav* 2015, 48: 93-116.
- [40] Nieder A, Merten K: A labeled-line code for small and large numerosities in the monkey prefrontal cortex. *J Neurosci* 2007, 27 (22): 5986-5993.
- [41] Wynn K: Addition and subtraction by human infants. *Nature* 1992, 358 (6389): 749-750.
- [42] Roitman JD, Brannon EM, Platt ML: Monotonic coding of numerosity in macaque lateral intraparietal area. *PLoS Biol* 2007, 5 (8): e208.
- [43] Zhang H, Chen C, Zhou X: Neural correlates of numbers and mathematical terms. *Neuroimage* 2012, 60 (1): 230-240.