

# Counting in everyday life: Discrimination and enumeration

Yun Nan<sup>a,b</sup>, Thomas R. Knösche<sup>a,b</sup>, Yue-Jia Luo<sup>a,c,\*</sup>

<sup>a</sup> Key Laboratory of Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing 100101, China

<sup>b</sup> MPI for Human Cognitive and Brain Sciences, Leipzig, Germany

<sup>c</sup> National Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing, China

Received 21 September 2004; received in revised form 27 October 2005; accepted 27 October 2005

Available online 19 December 2005

## Abstract

Enumerating the number of items in a set accurately and quickly is a basic mathematical skill. This ability is especially crucial in the more real-life situations, where relevant items have to be discriminated from irrelevant distracters. Although much work has been done on the brain mechanisms and neural correlates of the enumeration and/or discrimination process, no agreement has been reached yet. We used event-related potentials (ERPs) to show the time course of brain activity elicited by a task that involved both enumeration and discrimination at the same time. We found that even though the two processes run to some extent in parallel, discrimination seems to take place mainly in an earlier time window (from 100 ms after the stimulus onset) than enumeration (beyond 200 ms after the stimulus onset). Moreover, electrophysiological evidence based on the N2 and P3 components make it reasonable to argue for the existence of a dichotomy between *subitizing* (for sets of less than four items) and *counting* (for sets of four and more items). Source estimation suggests that *subitizing* and *counting*, though being distinct brain processes, do recruit similar brain areas.

© 2005 Elsevier Ltd. All rights reserved.

**Keywords:** Subitizing; Counting; Event-related potential (ERP)

## 1. Introduction

The ability to quantify is of great importance in our daily life. It is generally assumed that there are two kinds of quantification processes: *subitizing* for sets of less than four objects, and *counting* for larger sets. The term “*subitizing*” was first introduced by Kaufman, Lord, Reese, and Volkman (1949), and refers to the fast and accurate perception of the numerosity of small sets.

Psychological studies on enumeration have typically measured reaction times (RT) and error rates. The results obtained from these behavioral experiments typically show an “elbow” effect, i.e. the enumeration time increases slowly from one to three or four items (50–80 ms/item) and then starts to increase sharply and linearly (by about 200 ms/item) (Akin & Chase, 1978; Mandler & Shebo, 1982; Simon, Peterson, Patel, & Sathian, 1998; Trick & Pylyshyn, 1993), leading to the hypothesis that *subitizing* and *counting* are two distinct processes. However, after having analyzed a large set of behavioral enumer-

ation data with refined statistical tests, Balakrishnan and Ashby (1991, 1992) found no statistical evidence of discontinuity in the reaction times between *subitizing* and *counting*. Their analysis showed that the “mental effort” (measured in terms of RTs) required for enumeration increased with each additional item in the display, both within and beyond the *subitizing* range.

However, the controversial debate over a possible dichotomy between *subitizing* and *counting* is not restricted to behavioral measurements. The explorations of the detailed mechanisms underlying these two processes have also yielded inconsistent results. While *counting* is widely believed to be a process involving visual–spatial serial localization (Dehaene, 1997), the nature of *subitizing* remains controversial.

Mandler and Shebo (1982) postulated that *subitizing* may consist of the recognition of a familiar pattern and therefore rely on a separate mechanism that is not involved in *counting*. For instance, the dots in the *subitizing* range displays always form a familiar shape: a line from two dots, a triangle from three dots, and a quadrilateral from four dots. A different explanation is offered by Cowan (2001), who suggested that the fact that *subitizing* only works for small sets might be reflective of a capacity-limited short-term memory system. Similarly, Trick

\* Corresponding author.

E-mail address: luoyj@bnu.edu.cn (Y.-J. Luo).

and Pylyshyn (1993) proposed that *subitizing* is based on a limited capacity pre-attentive visual process that is capable of individuating a maximum of four items in parallel, while *counting* requires serial shifts of spatial attention. It has been shown that *counting* is influenced by the spatial arrangement of objects (facilitated by perceptual groupability of items and by the geometry of the array) while *subitizing* is not (Atkinson, Francis, & Campbell, 1976; Mandler & Shebo, 1982; van Oeffelen & Vos, 1983). These studies suggest that the employment of spatial attention might be crucial to *counting*, while *subitizing* recruits no spatial attention-related processes.

Some support for the notion of separate processes for *subitizing* and *counting* concerning the involvement of spatial serial processing comes from studies with patients. For example, Dehaene and Cohen (1994) measured reaction times and error rates with a numerosity naming task in five simultanagnosic patients, who suffered from severe difficulties in serial *counting*. These patients made close to 100% errors in quantifying sets comprising more than three items, but they were excellent at quantifying sets of one, two, and sometimes three items. The authors suggest that *subitizing* might be not based on serial processing but rather on a parallel algorithm dedicated to small numerosities. Likewise, in an investigation on patients with visuospatial neglect (Vuilleumier & Rafal, 1999), a dissociation between localizing and enumeration processes was observed. The results are taken as evidence that *subitizing* might not recruit spatial encoding mechanisms but instead relies on parallel visual processing that still operate in the neglected field.

However, the parallel processing model of *subitizing* is still problematic, for it cannot easily accommodate the fact that RTs increase even in *subitizing* range. In contrast, the fast preverbal *counting* mechanism proposed by Gallistel and Gelman (1992) could well account for this decrease of performance within the *subitizing* range, as these authors postulated, *subitizing* is just a fast *counting* mechanism whose accuracy decreases as the number of items increases. Upon encountering larger numbers of items, subjects switch to a more accurate but slower serial “verbal” process, referred to as *counting*.

Additional support for a dissociation between *subitizing* and *counting* comes from the identification of a special group of cells in the parietal–occipital cortex of the cat, which were selectively responsive to small quantities, regardless of whether the quantities were presented in the visual, auditory, or tactile modalities (Thompson, Mayers, Robertson, & Patterson, 1970). Number-responsive neurons were also found in monkey parietal cortex (Sawamura, Shima, & Tanji, 2002).

Recently, several brain imaging studies using functional Magnetic Resonance Imaging (fMRI) or Positron Emission Tomography (PET) have investigated the issue of enumeration. Using PET, Sathian et al. (1999) reported that *subitizing* activated foci in the occipital extrastriate cortex, while *counting* activated a widespread network of brain regions, including multiple areas involved in shifting visual attention—large regions of the superior parietal cortex bilaterally and a focus in the right inferior frontal cortex. The authors interpreted the results to support the notion of two separable processes mediating pre-attentive vision and shifts of visual attention. However, Piazza,

Mechelli, Butterworth, and Price (2002) presented a PET study to challenge the idea of the two processes being implemented in separable neural systems. Their results showed a common network for *subitizing* and *counting* that comprises extrastriate middle occipital and intraparietal areas. Direct comparison between *subitizing* and *counting* showed that *counting*, relative to *subitizing*, was correlated with increased activity in this occipitoparietal network, while *subitizing* did not show areas of increased activation as compared to *counting*.

In real life, a discrimination process almost always accompanies the enumeration, as we need to distinguish the relevant targets from irrelevant distracters. An enumeration process involving discrimination might differ from a pure enumeration process in that the additional discrimination task makes extra costs for visual working memory due to the competition between targets and distracters (Watson & Humphreys, 1999). There is a rich body of electrophysiological data on visual discrimination. Recent studies have demonstrated that the visual N1 component is modulated by the presence of a discrimination process (Hopf, Vogel, Woodman, Heinze, & Luck, 2002; Vogel & Luck, 2000). Similarly, the involvement of the N2 (or N2b) in discrimination tasks has been established (Kida, Nishihira, Hatta, & Wasaka, 2003; Potts, 2004; Potts & Tucker, 2001; Ruijter, de Ruiter, Snel, & Lorist 2000; Senkowski & Herrmann, 2002). The amplitude of the N2 component (N2b) seems to be positively correlated with the difficulty of the discrimination process. Smid, Jakob, and Heinze (1999) also reported an increased latency of the N2 component for more difficult color discrimination tasks. Eimer (1996) postulated that the N2 might be indicative of the attentional filtering processes during visual search tasks. Thus, the N2 may reflect the attentional selection of the task-relevant stimuli. Similarly, another component, the P3, has been discussed in visual discrimination studies. Originally, the P3 was established as an endogenous component reflecting the updating of the working memory stores (Donchin & Coles, 1988). Kida et al. (2003) suggest that the P3 amplitude is sensitive to the working memory load, the specific allocation of attentional resources to the stimulus processing, and the attentional orienting toward the relevant stimuli. Moreover, it has been found that more difficult discrimination processes elicited smaller P3s (Comerchero & Polich, 1999; Grillon, Courchesne, Ameli, Elmasian, & Braff, 1990; Hoffman, Houck, Macmillan, Simons, & Oatman, 1985; Palmer, Nasman, & Wilson, 1994; Polich, 1987, 1997; Vogel and Luck, 2000).

To conclude, the aforementioned literature concerning the enumeration process suggest that: (a) the behavioral distinction between *subitizing* and *counting* is not reliable; (b) spatial attention is involved in the *counting* process; (c) brain imaging studies (PET and fMRI) yield non-consistent results concerning *subitizing* and *counting*, which might be due to the coarse temporal resolution that those methods could offer.

This controversial body of evidence on enumeration, especially the existence and nature of a possible *subitizing*–*counting* dichotomy as well as the possible interaction between the enumeration and discrimination processes, calls for more studies, preferably with alternative techniques with higher temporal resolution, such as event-related potentials (ERPs). As far as we

know, there have been rather few ERP studies investigating the brain electrophysiological correlate of enumeration processes (Bruder et al., 1998; Iguchi & Hashimoto, 2000). As a result, there is no well-established ERP marker for the two enumeration processes yet. However, in the context of discrimination, a great number of studies using electroencephalography (EEG) have been conducted. Several well-known ERP components, such as the N1, N2, and P3, vary as a function of the difficulty of the discrimination process in different manners, in that the amplitudes of the N1 and N2 are positively correlated with the difficulty level of the discrimination, while the amplitude of the P3 negatively varies with the increase of the difficulty.

The present study was designed to test the dichotomy of *subitizing* and *counting* processes as well as the influence of discrimination onto the enumeration processes by means of behavioral measures and ERPs. Visual targets were presented together with distracters. By manipulating both the number of targets and the presence or absence of distracters, we aimed to approximate the brain response for enumeration processes in real-life situations. Taking into account the number of distracters should contribute to the understanding of the detailed nature of this discrimination effect and its possible interaction with the enumeration, and hence also to the treatment of the question of whether there is indeed a fast and specialized *subitizing* process for small sets of items.

As predicted by previous studies, we expected that *subitizing* might produce better performance (reflected in RTs and/or error rates) as compared to *counting* in general (possibly with an “elbow” effect, supporting a qualitative distinction between the two processes), while the presence of the distracters might affect the *counting* process to a larger degree than *subitizing*, which thus may contribute to the notion that discrimination competes with *counting* (but not with *subitizing*) in recruiting spatial attention. Electrophysiologically, the amplitude of N1 was expected to be positively modulated by the increase of the items. The dichotomy of *subitizing* and *counting*, if it could be demonstrated in ERPs, was more likely to be seen in the N2 time window, since the N2 was found by previous studies to be reflective of visual attention. On top of that, the N2 component might also depict the modulation of discrimination process, in that the presence of distracters might enlarge the amplitude. Likewise, the P3 component was highly expected to reflect the distracter effect as well. Thus, more distracters were predicted to be related to smaller P3 amplitude both in *subitizing* and *counting* ranges.

## 2. Methods

### 2.1. Subjects

Fourteen paid subjects (seven males and seven females) between 18 and 23 years old (mean age 21.2 years) participated in the experiment. 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. Informed written consents were obtained from all participants prior to the study. The experimental protocol was approved by the Local Ethics Committee (Chinese Academy of Sciences).

### 2.2. Stimuli

White rectangles ( $0.4\text{ cm} \times 0.8\text{ cm}$ , visual angle  $0.23^\circ \times 0.46^\circ$ ) and white circles (diameter  $0.5\text{ cm}$ , visual angle  $0.29^\circ$ ) were presented on a black background. The rectangles were defined as targets and required the subjects' enumeration responses. The circles were defined as distracters and the subjects were instructed to ignore them. The stimuli were displayed on a computer monitor (Samsung CRT Monitors 17 in.) screen (visual angle  $6.88^\circ \times 6.88^\circ$ ). Atkinson, Campbell, and Francis (1976) have shown that the limit number at which quantification becomes slow and erroneous drops from 4 to 2 if the angular distance between dots in a linear array drops below  $0.05^\circ$  of visual angle (still an easily resolved separation). Our stimuli were therefore presented to the subjects with the minimum distance of visual angle of  $0.5^\circ$ . The specific locations of rectangles and circles in each display were randomized. The number of targets varied between 1 and 6, and the number of distracters was either zero, equal to the number of targets, or twice the number of targets. Thus, there were a total of 18 ( $6 \times 3$ ) possible combinations of targets and distracters. Nine hundred and sixty trials were distributed equally over 4 blocks with 240 trials per block and with 53 or 54 trials per condition.

The same sequence of stimulus trials was used for all participants. Each stimulus appeared successively on the computer display in a pseudo-random order in which the same pattern of the targets and/or distracters was not delivered in succession. Immediately after the presentation of a small centrally located cross for 1000 ms, the stimulus appeared and was presented for 300 ms. The subjects were allowed to respond within a 1-s time window after stimulus presentation. The intertrial interval was randomized between 250 and 350 ms.

### 2.3. Paradigm

The subjects sat on a comfortable reclining chair in an electrically shielded room. A computer display was placed 1.0 m away from the subjects' eyes. During each trial, after the presentation of the stimulus display, subjects were asked to perform a parity judgment task in which they had first to enumerate the number of targets and then to judge the parity of the final count by pressing the corresponding key. The assignment of odd and even response to the left- and right-hand response keys was balanced across subjects. Subjects were instructed to perform the task silently and to avoid both eye and body movements. Before the real experimental session, there was a brief training session. The instructions to the subjects emphasized both the accuracy and speed of the response.

### 2.4. ERP recording and measurements

The present study was carried out on a NeuroScan ERP workstation. All subjects were fitted with an elastic cap with 64 tin electrodes (Neuromedical Supplies). The impedances were kept below 5 k $\Omega$ . Vertical and horizontal electrooculograms (EOG) were recorded. Two reference electrodes were put at left and right mastoids. The signals were filtered using a 0.05–70 Hz bandpass. The sampling rate was 500 Hz. The total length of an ERP epoch was 1200 ms including a pre-stimulus baseline of 200 ms. Trials with artifacts ( $>\pm 100\text{ }\mu\text{V}$ ) were identified and rejected off-line. Visual inspection was carried out after the rejection to assure the data quality.

### 2.5. Data analysis

The ERPs were averaged for each of the 18 conditions (6 targets numbers  $\times$  3 distracters numbers) separately. Only artifact-free trials with a correct behavioral response entered the averaging process. Visual inspection was used to define the electrodes which best represented certain effects. In accordance with the general average topographic pattern (see Fig. 2), the following 10 electrode sites were selected for statistical analysis of the P3: central (C3/4, Cz), frontal (F3/4, Fz), parietal (Pz), and occipital (PO5/6, POz). The same procedures were carried out for N1 and N2, resulting in the parietal (Pz) and occipital (PO5/6, POz) electrodes for N1, and the central (C3/4, Cz) electrodes for N2, respectively. The peak amplitude of N1 from the parietal and occipital sites, the mean amplitude for N2 (within a time window of 200–400 ms after stimulus onset) from the central sites (since for the *subitizing* without distracter condition, there is no proper N2 peak in some channels, refer to Fig. 2), and the peak amplitude of

P3 from all 10 sites were subjected to a repeated-measures analysis of variance (ANOVA). The peak amplitudes were determined for each electrode separately within a time window of 100–250 ms for the N1 and 350–600 ms for the P3.

ANOVAs were performed on both behavioral (RT and error rates) and electrophysiological data (the amplitudes of N1, N2, and P3 components). The following within-subject factors were considered: target number (6 levels, 1–6), distracter number (3 levels—none, the same as the targets, and twice the number of targets), and electrode sites (only for ERP, 10 levels for P3, 4 levels for N1, and 3 levels for N2). Based on estimated marginal means, pairwise comparisons were carried out for multiple mean comparisons, which were adjusted by the least significant difference. Furthermore, in order to gain precise insight into the relationship between discrimination and each of the enumeration processes (*subitizing* and *counting*), the target numbers were grouped in two subsets: *subitizing* with target number from 1 to 3, and *counting* with target number from 4 to 6. Another set of ANOVAs was calculated with the factor *target number* replaced by *enumeration process* with two levels (*subitizing* and *counting*) for those dependent variables, for which a dichotomy between these groups could be actually verified on the basis of pairwise comparisons between all different target number levels. The *p* values of all main and interaction effects were corrected using the Greenhouse–Geisser method for repeated-measures effects.

In order to obtain an idea of the spatial localization of the P3 component, the grand average ERP of both the *subitizing* and *counting* ranges (one to three target items and four to six target items, respectively) were subjected to source analysis. A single dipole was fitted to a small time window around the peak latency of the P3 range (350–600 ms) using the ASA software (A.N.T. Software B.V., Enschede, The Netherlands). To account for the volume conductor effects, the boundary element method was used with a Talairach scaled standard head model. The resulting dipole location was then overlaid onto a standardized MR-Image.

### 3. Results

#### 3.1. Behavioral results

Table 1 shows the results from the two-way ANOVAs for reaction times and error rates. The RTs generally increased with both target and distracter numbers. For all target numbers, RTs were lowest with no distracters present. Introducing distracters considerably increased the RTs, while a further increase of distracter number (i.e. double the number of targets) made a much smaller difference (Fig. 1a). Pairwise follow-up tests showed that all levels of target number could be significantly distinguished from each other in all the different distracter conditions ( $p < 0.05$  for all the different target number pairs). Hence, the RTs did not support any dichotomy across different target numbers. This opposes previous findings reporting reaction time changes from the *subitizing* range to the *counting* range (Akin & Chase, 1978; Mandler & Shebo, 1982; Simon et al., 1998; Trick & Pylyshyn, 1993), but it is in line with other studies, which found no dichotomy for the reaction time between *subitizing* and *counting* (Balakrishnan and Ashby, 1991, 1992).

Pairwise comparisons of error rates between different target number levels yielded no evidence of a dichotomy between a

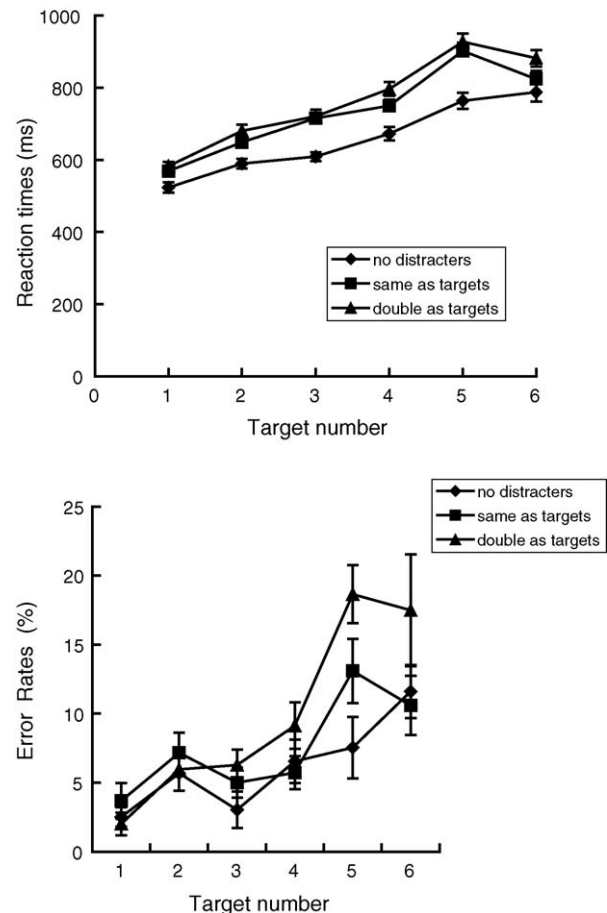


Fig. 1. The mean reaction times (a) and error rates (b) for all the 14 subjects in all target and distracter number levels as a function of target number. The error bars stand for the standard error of the mean.

subitizing and a counting range for different distracter conditions either. However, there seemed to be a tendency that, from distracter number level 2 (as many distracters as targets) to distracter number level 3 (twice as targets), error rates appeared to rise faster while target number increased (Fig. 1b). Pairwise comparisons for the difference in error rates between distracter number levels 2 and 3 revealed the following significant pairwise differences: 1–4, 2–4, 3–4, 1–5, 2–5, 3–5, 1–6, 2–6, and 3–6 ( $p < 0.05$ ). That means, all comparisons crossing the boundary between 3 and 4 were significant, all others were not. Thus, there seems to be a dichotomy for the different distracter effects between smaller target numbers (from 1 to 3) and larger target numbers (from 4 to 5).

Interestingly, both error rates and reaction times show a “ceiling effect”, as demonstrated by Fig. 1a and b, indicating

Table 1

The results of two-way ANOVA (target number = 1–6) performed on the mean RTs and error rates of the subjects

	Reaction times	Error rates
Target number	$F(5, 65) = 117.496, p < 0.001$	$F(5, 65) = 12.359, p < 0.001$
Distracter number	$F(2, 26) = 117.661, p < 0.001$	$F(2, 26) = 15.464, p < 0.001$
Target $\times$ distracter number	$F(10, 130) = 9.395, p < 0.001$	$F(10, 130) = 5.010, p < 0.001$

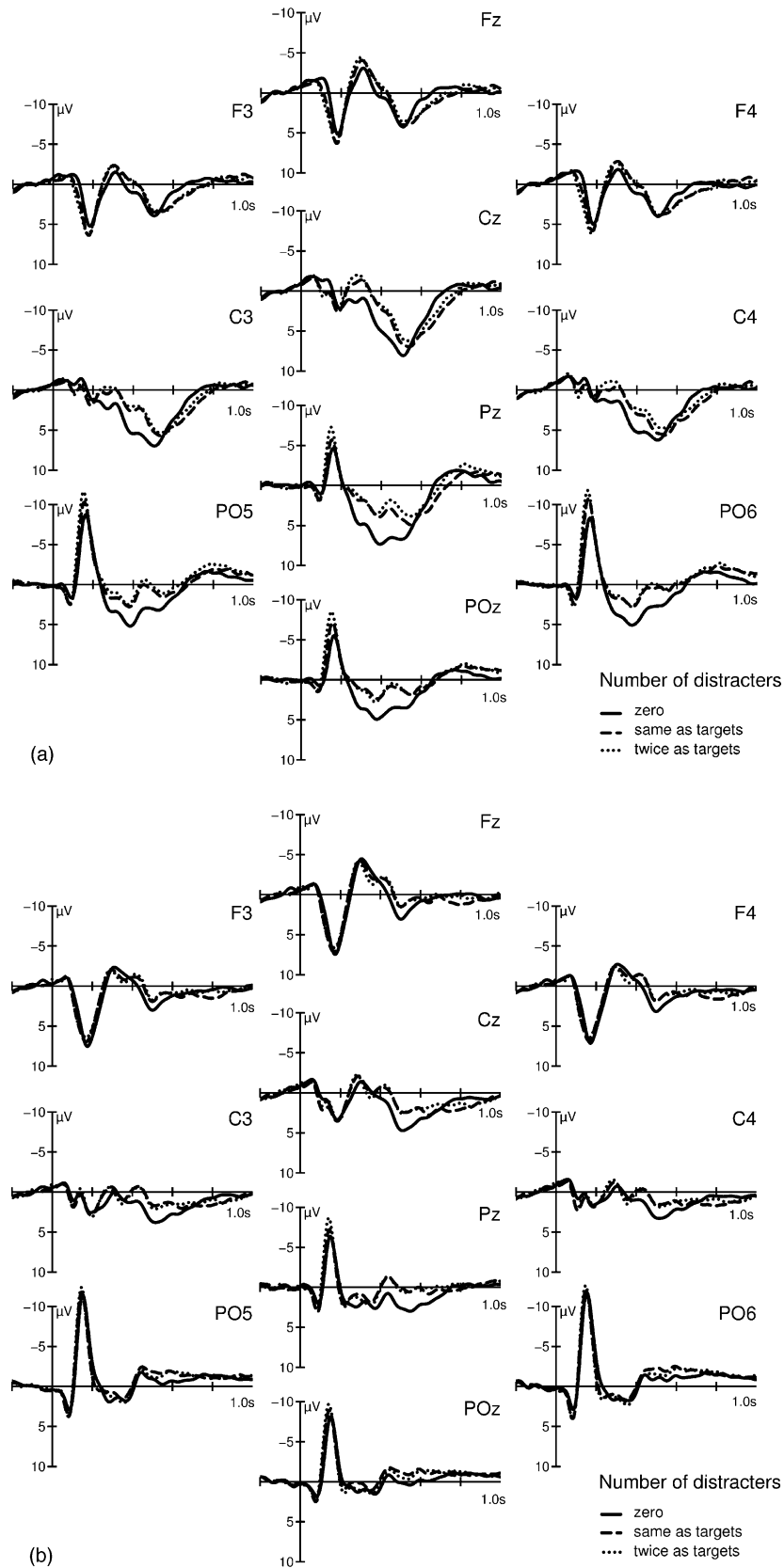


Fig. 2. Grand average ERPs for: (a) subitising range (one to three targets) and (b) counting range (more than three targets), both for different numbers of distractors.



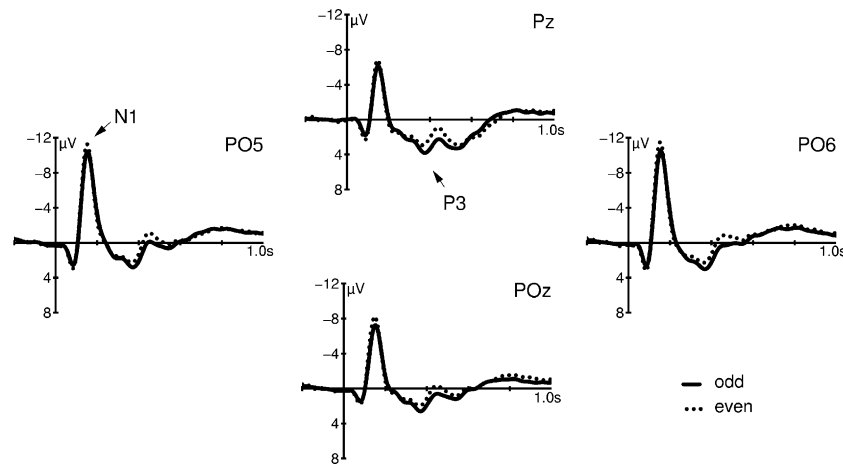


Fig. 3. Grand average ERPs, averaged over both target and distracter numbers, for different parity judgments.

that subjects might easily guess the maximal number in the item set.

### 3.2. Electrophysiological results

The ERP traces for the *subitizing* and *counting* ranges with the different distracter numbers are depicted in Fig. 2. Fig. 3 illustrates that the parity judgment did not have any influence on the ERP. Table 2 lists the results from the overall three-way ANOVAs for the amplitudes of N1, N2, and P3 components.

#### 3.2.1. N1 component

The N1 was identified as the maximum negative response in the time range between 100 and 250 ms at occipital and parietal electrode sites. The mean latency for the N1 component was 157 ms with a standard deviation of 2 ms. There was no statistically significant latency difference between conditions. The N1 amplitude (averaged over Pz, PO5, PO6, and POz) increased significantly with both target number ( $F(5, 65) = 32.361, p < 0.001$ ) and distracter number ( $F(2, 26) = 28.191, p < 0.001$ ). Also, the effect of target number was more pronounced for smaller numbers of distracters, while the increase with distracter number was stronger with lower target numbers. This is confirmed by a significant interaction between the two factors ( $F(10, 130) = 3.879, p < 0.001$ ). If one plots the N1 amplitude against the number of items (combined numbers of targets and distracters), it becomes clear that only the total number of items matters, irrespective of how many targets and distracters this number comprises (Fig. 4). Pairwise comparisons across different target numbers for different distracter conditions yielded no evidence of a dichotomy.

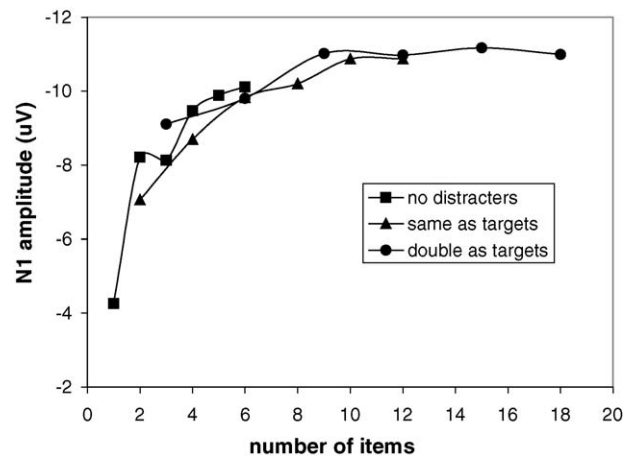


Fig. 4. Grand average amplitude of the N1 component for different target and distracter numbers as a function of item number. Target numbers 1–6 are sequentially depicted within each series with different distracter numbers.

#### 3.2.2. N2 component

The frontal–centrally distributed negative response occurring in the time window of 200–400 ms was recognized as the N2 component. Because of the variability of the wave across situations (in some conditions, as *subitizing* without distracters, there is no N2 at all) we measured the mean amplitude (averaged over C3, C4, and Cz) instead of the peak amplitude (as we did for the other two components). The overall three-way ANOVA demonstrated significant main effects for target number ( $F(5, 65) = 3.048, p < 0.05$ ), distracter number ( $F(2, 26) = 16.811, p < 0.001$ ), and an interaction between target number and distracter number ( $F(10, 130) = 5.000, p < 0.001$ ). The interaction was caused by a strong suppression of the N2 by

Table 2

The results of two-way ANOVA (target number = 1–6) performed on the mean amplitudes of N2 and the peak amplitudes of N1 and P3

	N1 (100–250 ms)	N2 (200–400 ms)	P3 (350–600 ms)
Target number	$F(5, 65) = 32.361, p < 0.001$	$F(5, 65) = 3.048, p < 0.05$	$F(5, 65) = 29.689, p < 0.001$
Distracter number	$F(2, 26) = 28.191, p < 0.001$	$F(2, 26) = 16.811, p < 0.001$	$F(2, 26) = 10.054, p < 0.001$
Target $\times$ distracter number	$F(10, 130) = 3.879, p < 0.001$	$F(10, 130) = 5.000, p < 0.001$	$F(10, 130) = 2.365, p < 0.05$

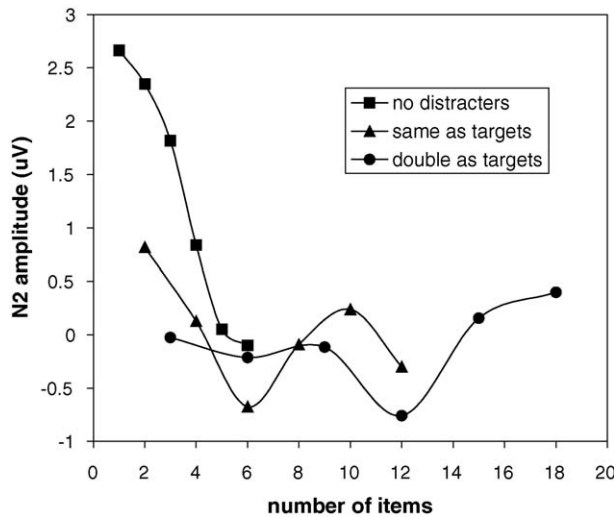


Fig. 5. Grand average amplitude of the N2 component for different target and distracter numbers as a function of item number. Target numbers 1–6 are sequentially depicted within each series with different distracter numbers.

the presence of distracters in the smaller target number range (from 1 to 3) but not in the larger one (from 4 to 6), as suggested by Fig. 5. Pairwise comparisons done with the difference in N2 amplitudes between the two lower distracter levels (no distracters versus as many distracters as targets) across different target numbers showed the significant pairwise differences as follows: 1–4, 2–4, 3–4, 1–5, 2–5, 3–5, 1–6, 2–6, and 3–6 ( $p < 0.05$ ), i.e. all differences that cross the boundary between 3 and 4 targets.

### 3.2.3. P3 component

The maximum positive response measured in the time window of 350–600 ms was referred to as the P3 component. The mean latency for the P3 component was 480 ms with a standard deviation of 5 ms. There was no statistically significant latency difference between conditions. The P3 component was largest over central electrode sites. A three-way repeated-measures ANOVA performed on the peak amplitude (as averaged over C3/4, Cz, F3/4, Fz, Pz, PO5/6, and POz) of the P3 component showed significant main effects of target number ( $F(5, 65) = 29.689, p < 0.001$ ) and distracter number ( $F(2, 26) = 10.054, p < 0.001$ ). The P3 component increased with decreasing target and distracter numbers. Additionally, there was a statistically significant interaction of target number  $\times$  distracter number ( $F(10, 130) = 2.365, p < 0.05$ ). Pairwise comparisons done with the P3 amplitudes across different target numbers for all the different distracter conditions yielded significant differences ( $p < 0.05$ ) between any pair comprising one target number between 1 and 3 and one target number between 4 and 6, but not for pairs within any of these ranges.

Furthermore, it was found that conditions with no distracters differed significantly from the other two distracter number levels ( $p < 0.05$ ; see Fig. 6). Plotting the P3 amplitude against the total number of items shows that it matters how many targets and distracters a certain number of items comprises (see Fig. 6).

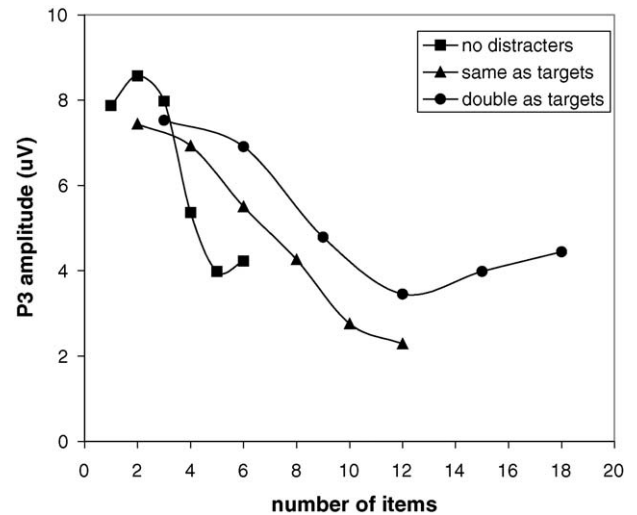


Fig. 6. Grand average amplitude of the P3 component for different target and distracter numbers as a function of item number. Target numbers 1–6 are sequentially depicted within each series with different distracter numbers.

Moreover, the three-way ANOVA with the enumeration process factor showed a significant main effect for target number ( $F(1, 13) = 67.315, p < 0.001$ ; as Fig. 6), but no interaction between target number and distracter number was found. Thus, there is a clear distinction between enumeration and discrimination processes, which seem to be independent.

For source localization, a time period of 480–500 ms was selected, because the P3 component peaked within this time period for most participants. The localization yielded almost identical areas near the precuneus for *subitizing* and *counting* conditions (see Fig. 7).

## 4. Discussion

The two main goals of the present study were: (1) to investigate the putative dichotomy between two enumeration processes—*subitizing* and *counting* and (2) to investigate the relationship between the discrimination and the enumeration processes.

### 4.1. Brain processes for subitizing and counting

The reaction time measures did not provide any evidence for a dichotomy between a fast *subitizing* and a slower *counting* process, which seems to confirm some of the previous behavioral work (e.g. Balakrishnan & Ashby, 1991, 1992). However, the different distracter effects in the error rates between *subitizing* and *counting* ranges confirm our prediction that behavioral performance deteriorates due to the presence of distracters to a much greater extent in *counting* range than in *subitizing* range. This fits well with the assumption that *counting* and discrimination both recruit spatial selective attention and compete with each other, as concluded by Watson and Humphreys (1999) from their neuropsychological study. Moreover, it is not surprising that we obtained the distracter effect in the accuracy measure but not in the reaction time measure. It seems from the visual

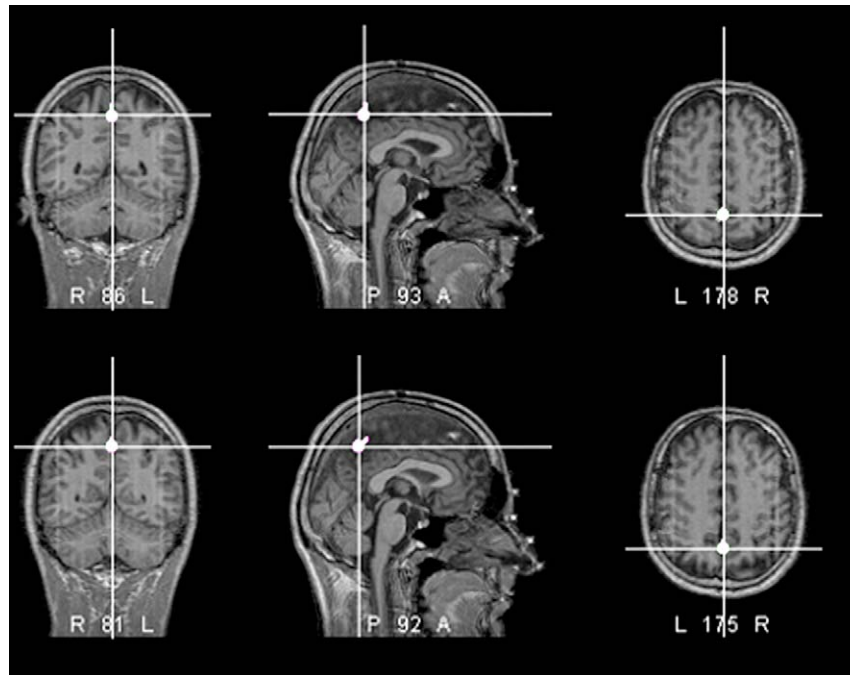


Fig. 7. Results of single dipole fit for the grand average scalp potentials for the subitizing range (one to three targets; upper row; position: 43.2 mm posterior, 0.2 mm right, 47.3 mm superior to the anterior commissure) and for the counting range (more than three targets; lower row; 47.7 mm posterior, 0.2 mm right, 45 mm superior to the anterior commissure).

search literature (Santee & Egeth, 1982; Wolfe, 1998) that, for the briefly presented stimulus (in the range of a few hundred milliseconds, as employed in the current study), accuracy is more consistent than reaction time. It is postulated that accuracy is sensitive to early perceptual interference between target and noise items, whereas reaction time is more sensitive to later processes involved in response interference (Santee & Egeth, 1982). This is confirmed by a recent study (Prinzmetal, McCool, & Park, 2005), where voluntary and involuntary attention were manipulated and accuracy as well as reaction time were measured. The authors concluded that in attention research, these two measures might yield different results. In the current study, when the target number was 6, reaction times were shorter and error rates were lower. This indicates that the subjects, when identifying the extreme numerosity, did not totally rely on *counting* or estimating, but rather some other strategies. The same phenomenon has also been found in another study (Jackson & Coney, 2004), in that the extreme array size with ‘five’ items elicited shorter reaction times compared with smaller sets (such as four or three items). The authors explained this as evidence for an adopted estimation strategy rather than counting.

The ERP curves did indeed show a grouping effect in the difference of N2 amplitudes between low numbers of targets (one to three) and high numbers of targets (four and more) while distracter number changed between the two lower distracter levels (no distracters versus as many distracters as targets). A similar dichotomy effect was observed in the P3 time range as well, not for the change between two lower distracter levels, but for all the distracter conditions instead. On the other hand, at earlier latencies (N1), no evidence for a dichotomy was found. The fact that both types of items (targets and distracters) seem to have

the same influence onto the N1 amplitude (Fig. 4) even suggests that there is none or little enumeration-related brain activity in this time range.

The spatial distribution and the supporting source analysis suggested that the enumeration effect in the P3 time range might be associated with activity in inferior parietal regions (close to precuneus) for both *subitizing* and *counting* processes. This partially converges with recent fMRI findings on the neural bases of *subitizing* and *counting* processes (Piazza, Giacomini, Le Bihan, & Dehaene, 2003), which suggested a sudden increase of activity in posterior parietal and frontal areas for numbers equal to or greater than 4. In contrast to the fMRI findings in literature, our ERP results provide more detailed information regarding the time course of enumeration processes. Specifically, it is suggested that enumeration processes occur mainly from 200 to 600 ms (within N2 and P3 time window) after stimulus onset.

It is noteworthy to mention that the current study does not support any hemispheric superiority for the *subitizing* and/or *counting* processes. Previous investigations that have addressed the hemispheric asymmetries for enumeration processes provide quite controversial results. On the one hand, some studies support a right hemisphere advantage for *subitizing* and a left hemisphere advantage for *counting* (Jackson & Coney, 2004; Kimura, 1966; Pasini & Tessari, 2001). On the other hand, the left hemisphere has also been proposed as the dominating hemisphere for *subitizing* (Butterworth, 1999).<sup>1</sup> Finally, there is a number of brain imaging studies (Piazza et al., 2002; Sathian et

<sup>1</sup> There is even an attempt to apply those findings to clinical uses (Bruder et al., 1989).



al., 1999) that did not reveal any clear evidence for the hemisphere domination of either enumeration process. Given the fact that some of the aforementioned studies employed different tasks (such as comparison in Pasini & Tessari, 2001), as well as variable ranges<sup>2</sup> for *subitizing* and *counting*, the results are not easily comparable. Thus, more studies are needed to clarify this issue.

#### 4.2. Enumeration and discrimination processes

Both the behavioral and the ERP results demonstrate that enumeration and discrimination processes take place. On one hand, adding distracters increases the RT for any given number of targets (Fig. 1a). On the other hand, an increased number of distracters is associated with more errors in the *counting* range as compared to the *subitizing* range. These results are, on one hand, partially in agreement with the work of Pylyshyn et al. (1994), in that the increased distracter number does not produce higher error rates within the *subitizing* range; on the other hand, conflicting with their results in the reaction time measures, where they found no worse performance within the *subitizing* range while increasing distracter number.

The ERP results allow for disentanglement of the time courses of the two processes. For the N1 amplitude, the combined influences of target and distracter numbers can be readily explained by the mere total of items (see Fig. 4). This indicates that during this early time range (100–250 ms after stimulus onset), an item identification and/or discrimination process is dominant and little or no enumeration takes place. This finding is consistent with a recent ERP and magnetoencephalography (MEG) study that has shown that discriminative processing leads to differential ERP and MEG activity beginning within 150 ms of stimulus onset (Hopf et al., 2002). Moreover, the graded influence of the number of items onto the amplitude of the N1 suggests that this component might reflect the difficulty of the discrimination process.

If the N1 is reflective of the initial period of discrimination/identification of the targets from distracters, the N2 is representative of the participation of spatial selective attention in *counting* and as well as in discrimination. As suggested by Vuilleumier and Rafal (1999), the *subitizing* condition without distracters recruits no spatial selective attention, thus results in no development of an N2 at all. Once the target number exceeds the *subitizing* range or distracters appear that need to be distinguished from targets, spatial selective attention comes into play and an N2 appears. This spatial selection attention effect of the N2 component (sometimes referred to as N2b) has been discussed also in other discrimination and/or visual search studies (Eimer, 1996; Senkowski & Herrmann, 2002). *Counting* and discrimination compete for the limited spatial attention resources (Trick & Pylyshyn, 1993, 1994). Especially in patients with temporo-parietal damage (Watson & Humphreys,

1999), such a situation can easily exhaust the limited spatial attention resources, causing a decline in performance. The current results could also be well accounted for by a primitive multiple indexing mechanism such as Fingers of Instantiation (FINST), which was postulated by Trick and Pylyshyn (1993, 1994).

As for the last component of interest, the P3 (350–600 ms after stimulus onset) demonstrates different influence from targets as compared to distracters. With a higher percentage of targets, the P3 amplitude is generally larger and the dichotomy between *subitizing* and *counting* ranges is much more pronounced. Therefore, enumeration processes must be clearly present during the late time window. On the other hand, the influence exercised by the distracter number proves that discrimination processes also remain active. More distracters produced more decreased P3 amplitudes. This is in good agreement with previous studies demonstrating that more difficult discrimination processes decreased P3 amplitude (Comerchero & Polich, 1999; Grillon et al., 1990; Hoffman et al., 1985; Palmer et al., 1994; Polich, 1987, 1997; Vogel and Luck, 2000). Moreover, this distracter effect confirmed the one found in the error rates of the behavioral results. However, the behavioral dichotomy seems to only present in the distracter conditions, while the P3 one appears not only in the distracter conditions, but also in the no-distracter condition. This is not surprising given that the ERP results are able to provide much richer temporal information as compared to the behavioral ones.

#### 4.3. Influence of task

It is widely accepted that parity information is extracted directly from semantic memory, where it is stored along with other semantic properties (Dehaene, Bossini & Giraux, 1993; Lemaire & Fayol, 1995). It was assumed that the resources recruited for parity judgment were the same regardless of the numerical magnitude. In our study, direct comparison between stimuli with odd and even parities shows that there is no influence of parity within the N1 and P3 time ranges (Fig. 3).

### 5. Conclusions

We have demonstrated the influence of both object discrimination and object enumeration on behavioral as well as electrophysiological measures. First of all, the behavioral as well as the EEG results lead us to believe that there is a dichotomy between *subitizing* and *counting*. Secondly, the current results confirm the previous assumptions about the role that spatial attention might play in enumeration and discrimination processes, in that the lack of the involvement of spatial attention is regarded as a label for *subitizing* as compared to *counting*, and *counting* competes with discrimination for the limited spatial attention resources. Finally, it could be shown that the object identification and discrimination processes start early in the N1 time range (from 100 ms after stimulus onset) and continue through N2 and P3 range. In contrast, the enumeration process takes place in the N2 range beyond 200 ms after stimulus onset and lasts through the P3 time window. However, source estimation suggests that

<sup>2</sup> There is a long debate on the exact boundary between *subitizing* and *counting*. Most of the researchers in the field accept that it lies at three to four items, but Dehaene and Cohen (1994) demonstrated that it might be two to three. Kimura (1966) who employed an array of 3–10 items, and Jackson and Coney (2004) have found the right hemisphere advantage only with 3–4 items.

subitizing and counting, though being distinct brain processes, do recruit quite similar brain areas.

## Acknowledgements

This work was supported by the National Natural Science Foundation of China (30325026), by the Chinese Academy of Sciences (KSCX2-SW-221), by the Ministry of Science and Technology of China (2002CCA01000), by the Germany Research Foundation (DFG KN588/1), and by a scholarship for the promotion of scientific cooperation with foreign countries of the Max-Planck-Society, which was awarded to Yun Nan. The authors wish to thank Xing Wei for her experimental assistance, and Dr. Shirley-Ann Rueschemeyer for her kind proofreading of the final draft.

## References

- Akin, O., & Chase, W. (1978). Quantification of three-dimensional structures. *Journal of Experimental Psychology: Human Perception and Performance*, 4, 397–410.
- Atkinson, J., Campbell, F. W., & Francis, M. R. (1976). The magic number  $4 \pm 0$ : A new look at visual numerosity judgment. *Perception*, 5, 327–334.
- Atkinson, J., Francis, M. R., & Campbell, F. (1976). The dependence of the visual numerosity limit on orientation, colour, and grouping in the stimulus. *Perception*, 5, 335–342.
- Balakrishnan, J. D., & Ashby, F. G. (1991). Is subitising a unique numerical ability? *Perception and Psychophysics*, 50, 555–564.
- Balakrishnan, J. D., & Ashby, F. G. (1992). Subitising: Magical numbers or mere superstition? *Psychological Research*, 54, 80–90.
- Bruder, G., Kayser, J., Tenke, C., Rabinowicz, E., Friedman, M., Amador, X., et al. (1998). The time course of visuospatial processing deficits in schizophrenia: An event-related brain potential study. *Journal of Abnormal Psychology*, 107, 399–411.
- Bruder, G. E., Quitkin, F. M., Stewart, J. W., Martin, C., Voglmaier, M. M., & Harrison, W. M. (1989). Cerebral laterality and depression—Differences in perceptual asymmetry among diagnostic subtypes. *Journal of Abnormal Psychology*, 98, 177–186.
- Butterworth, B. (1999). *The mathematical brain*. London: MacMillan.
- Comerchero, M. D., & Polich, J. (1999). P3a and P3b from typical auditory and visual stimuli. *Clinical Neurophysiology*, 110(1), 24–30.
- Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, 26, 87–116.
- Dehaene, S. (1997). *The number sense: How the mind creates mathematics* (pp. 67–70). New York: Oxford University Press.
- Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, 122, 371–396.
- Dehaene, S., & Cohen, L. (1994). Dissociable mechanisms of subitising and counting: Neuropsychological evidence from simultanagnosic patients. *Journal of Experimental Psychology: Human Perception and Performance*, 20, 958–975.
- Donchin, E., & Coles, M. G. H. (1988). Is the P300 component a manifestation of context updating. *Behavioral and Brain Sciences*, 11(3), 357–374.
- Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology*, 99(3), 225–234.
- Gallistel, C. R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition*, 44(12), 43–74.
- Grillon, C., Courchesne, E., Ameli, R., Elmasian, R., & Braff, D. (1990). Effects of rare nontarget stimuli on brain electrophysiological activity and performance. *International Journal of Psychophysiology*, 9(3), 257–267.
- Hoffman, J. E., Houck, M. R., Macmillan, F. W., Simons, R. F., & Oatman, L. C. (1985). Event-related potentials elicited by automatic targets—A dual-task analysis. *Journal of Experimental Psychology: Human Perception and Performance*, 11(1), 50–61.
- Hopf, J. M., Vogel, E., Woodman, G., Heinze, H. J., & Luck, S. J. (2002). Localizing visual discrimination processes in time and space. *Journal of Neurophysiology*, 88(4), 2088–2095.
- Iguchi, Y., & Hashimoto, I. (2000). Sequential information processing during a mental arithmetic is reflected in the time course of event-related brain potentials. *Clinical Neurophysiology*, 111, 204–213.
- Jackson, N., & Coney, J. (2004). Right hemisphere superiority for subitising. *Laterality*, 9, 53–66.
- Kaufman, E. L., Lord, M. W., Reese, T. W., & Volkman, J. (1949). The discrimination of visual number. *American Journal of Psychology*, 62, 498–525.
- Kida, T., Nishihira, Y., Hatta, A., & Wasaka, T. (2003). Somatosensory N250 and P300 during discrimination tasks. *International Journal of Psychophysiology*, 48(3), 275–283.
- Kimura, D. (1966). Dual functional asymmetry of the brain in visual perception. *Neuropsychologia*, 4, 275–285.
- Lemaire, P., & Fayol, M. (1995). When plausibility judgments supersede fact retrieval: The example of the odd–even effect on product verification. *Memory and Cognition*, 23, 34–48.
- Mandler, G., & Shebo, B. J. (1982). Subitising: An analysis of its component processes. *Journal of Experimental Psychology: General*, 11, 1–22.
- Palmer, B., Nasman, V. T., & Wilson, G. F. (1994). Task decision difficulty—Effects on ERPs in a same-different letter classification task. *Biological Psychology*, 38(2–3), 199–214.
- Pasini, M., & Tessari, A. (2001). Hemispheric specialization in quantification processes. *Psychological Research*, 65, 57–63.
- Piazza, M., Giacomini, E., Le Bihan, D., & Dehaene, S. (2003). Single-trial classification of parallel pre-attentive and serial attentive processes using functional magnetic resonance imaging. *Proceedings of the Royal Society of London Series B: Biological Sciences*, 270(1521), 1237–1245.
- Piazza, M., Mechelli, A., Butterworth, B., & Price, C. J. (2002). Are subitising and counting implemented as separate or functionally overlapping processes? *NeuroImage*, 15, 435–446.
- Polich, J. (1987). Task-difficulty, probability, and inter-stimulus interval as determinants of P300 from auditory-stimuli. *Electroencephalography and Clinical Neurophysiology*, 68(4), 311–320.
- Polich, J. (1997). On the relationship between EEC and P300: Individual differences, aging, and ultradian rhythms. *International Journal of Psychophysiology*, 26(1–3), 299–317.
- Potts, G. F. (2004). An ERP index of task relevance evaluation of visual stimuli. *Brain and Cognition*, 56(1), 5–13.
- Potts, G. F., & Tucker, D. M. (2001). Frontal evaluation and posterior representation in target detection. *Cognitive Brain Research*, 11(1), 147–156.
- Prinzmetal, W., McCool, C., & Park, S. (2005). Attention: Reaction time and accuracy reveal different mechanisms. *Journal of Experimental Psychology: General*, 134(1), 73–92.
- Pylyshyn, Z., Burkell, J., Fisher, B., Sears, C., Schmidt, W., & Trick, L. (1994). Multiple parallel access in visual attention. *Canadian Journal of Experimental Psychology*, 48(2), 260–283.
- Ruijter, J., de Ruiter, M. B., Snel, J., & Lorist, M. M. (2000). The influence of caffeine on spatial-selective attention: An event-related potential study. *Clinical Neurophysiology*, 111(12), 2223–2233.
- Santee, J. L., & Egeth, H. E. (1982). Do reaction-time and accuracy measure the same aspects of letter recognition? *Journal of Experimental Psychology: Human Perception and Performance*, 8(4), 489–501.
- Sathian, K., Simon, T. J., Peterson, S., Patel, G. A., Hoffman, J. M., & Grafton, S. T. (1999). Neural evidence linking visual object enumeration and attention. *Journal of Cognitive Neuroscience*, 11, 36–51.
- Sawamura, H., Shima, K., & Tanji, J. (2002). Numerical representation for action in the parietal cortex of the monkey. *Nature*, 415, 918–922.
- Senkowski, D., & Herrmann, C. S. (2002). Effects of task difficulty on evoked gamma activity and ERPs in a visual discrimination task. *Clinical Neurophysiology*, 113(11), 1742–1753.

- Simon, T. J., Peterson, S., Patel, G., & Sathian, K. (1998). Do the magnocellular and parvocellular visual pathways contribute differentially to subitising and counting? *Perception and Psychophysics*, 60, 451–464.
- Smid, H. G. O. M., Jakob, A., & Heinze, H. J. (1999). An event-related brain potential study of visual selective attention to conjunctions of color and shape. *Psychophysiology*, 36(2), 264–279.
- Thompson, R. F., Mayers, K. S., Robertson, R. T., & Patterson, C. J. (1970). Number coding in association cortex of the cat. *Science*, 168, 271–273.
- Trick, L. M., & Pylyshyn, Z. W. (1993). What enumeration studies can show us about spatial attention: Evidence for limited capacity preattentive processes. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 331–351.
- Trick, L. M., & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently—A limited-capacity preattentive stage in vision. *Psychological Review*, 101(1), 80–102.
- van Oeffelen, M. P., & Vos, P. G. (1983). Configurational effects on the enumeration of dots: Counting by groups. *Memory and Cognition*, 10, 396–404.
- Vogel, E. K., & Luck, S. J. (2000). The visual N1 component as an index of a discrimination process. *Psychophysiology*, 37(2), 190–203.
- Vuilleumier, P., & Rafal, R. (1999). “Both” means more than “two”: Localizing and counting in patients with visuospatial neglect. *Nature Neuroscience*, 2(9), 783–784.
- Watson, D. G., & Humphreys, G. W. (1999). The magic number four and temporo-parietal damage: Neurological impairments in counting targets amongst distractors. *Cognitive Neuropsychology*, 16(7), 609–629.
- Wolfe, J. M. (1998). Visual search. In H. Pashler (Ed.), *Attention* (pp. 13–73). San Diego: Psychology Press.