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Research report

# Event-related potentials during digit recognition tasks

Jun Ji<sup>a,b</sup>, Bernice Porjesz<sup>a,\*</sup>, David Chorlian<sup>a</sup>, Henri Begleiter<sup>a</sup>

<sup>a</sup> State University of New York, Health Science Center at Brooklyn, NY 11203, USA <sup>b</sup> Institute of Mental Health, Beijing Medical University, Beijing 100083, China

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#### Abstract

<u>Objective</u>: An event-related potential (ERP) correlate of visual short-term memory (VMP) has been identified in our laboratory. This study aims to determine how stimulus load modulates recognition processing of digits. <u>Methods</u>: ERPs were recorded from 117 healthy right-handed subjects during a delayed matching-to-sample paradigm, using number stimuli that were either low load (three digits long) or high load (five digits long). The bootstrap method [R. Srebro, A bootstrap method to compare the shapes of two scalp fields, Electroenceph. Clin. Neurophysiol. 100 (1996) 25–32.] was employed to evaluate the topographic features of the VMP revealed in the current source density (CSD) maps. <u>Results</u>: Response times were significantly shorter for matching stimuli than for non-matching stimuli only for low loads; longer response times were related to higher loads compared to low loads only for matching stimuli. The high loads were related to larger ERP responses. The ERP was significantly smaller for matching than for non-matching three-digit numbers, but not for five-digit numbers. The ERP was also reduced to the test stimuli compared to sample stimuli regardless of stimulus load. Both temporal and frontal regions were involved in the recognition of the digit stimuli, and the left hemisphere was more active in the non-matching processing of digits. <u>Conclusions</u>: The VMP spatial pattern in addition to its amplitude is sensitive to stimulus load in the encoding process. © 1998 Elsevier Science B.V. All rights reserved.

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#### 1. Introduction

We have observed an event-related potential (ERP) component, labeled a 'visual memory potential' (VMP), which appears to index visual short-term memory in humans in a delayed matching-to-sample (DMS) paradigm [6]. This positive component (an upward deflection at the most posterior electrodes with respect to the Cz electrode), occurring between 170 and 240 ms, was significantly smaller to matching visual stimuli compared to non-matching stimuli, and appeared to be independent of the interstimulus interval, as well as stimulus probability. The VMP amplitude reduction to the matching stimuli may index the influence of the memory of the sample visual stimulus (S1) on the neurophysiological response to the test stimulus (S2). The VMP was best illustrated in the posterior region while less discernible at the frontal elec-

trodes. The current source density (CSD) map indicated that the active fields involved in the VMP are quite compatible with the localization of visual short-term memory in temporal cortex of monkeys [22,36]. The similarity between the matching test stimulus and the memory trace for that stimulus (or the dissimilarity between the nonmatching stimulus and the sample) has been suggested to be responsible for this significant reduction of the ERP [6].

The matching/non-matching process in the DMS task may take place consciously or without clear consciousness, and the VMP may reflect both repetition priming and recognition. In order to assess if the VMP possesses features which distinguish priming from recognition, studies using face stimuli under different conditions were conducted in our laboratory. In one study [20], the priming was operationalized by repeating faces and scrambles without awareness, while subjects made judgments of whether the next stimulus was a face or a scramble; in a subsequent explicit recognition task, conducted with the same group of subjects with the same sequence of stimuli, the subject was specifically told that the faces and scrambles would be

<sup>&</sup>lt;sup>\*</sup> Corresponding author. Department of Psychiatry, Box 1203, SUNY, HSCB, 450 Clarkson Ave. Brooklyn, NY 11203, USA. Fax: +1-718-270-4081; E-mail: bp@bp.neurodyn.hscbklyn.edu

repeated and was asked to press one button to repeated stimuli, and another button to non-repeated stimuli. Priming was indexed by a diminution of the VMP amplitude in the responses to repeated pictures compared to novel pictures in both conditions; when the task required explicit recognition of the repeated faces, the VMP changes were more pronounced, with significantly reduced response times to the recognized stimuli. In the third investigation, employing familiar and unfamiliar faces as stimuli [7], priming was indexed as the change in response to repeated stimuli while recognition was indexed as the difference in response to familiar vs. unfamiliar stimuli. The results confirmed the hypothesis that the VMP elicited by familiar and well-encoded stimuli such as famous faces was different from unrecognized stimuli such as unfamiliar faces; priming to familiar and unfamiliar faces yielded a significantly different VMP component. The priming was typically reflected by a reduction of the VMP at the occipitotemporal region, whereas recognition resulted in a diminution of the VMP at both the occipito-temporal region and at the frontal region. In addition, significant differences in response times were obtained between primed and unprimed familiar faces, but not between primed and unprimed unfamiliar faces [7].

However, since the DMS task involves not only the retrieval process but also a number of different processes including encoding of the sample stimulus, the maintenance of the memory of the sample stimulus during the delay interval, and a subsequent retrieval and comparison of the sample and test stimuli, it is not obvious which cognitive processes underlie the VMP. Yet these findings [6,7,20] indicated that stimuli which initially are well-encoded will subsequently be better recognized, suggesting the influence of the encoding property on the subsequent recognition process. In contrast, when the to-be encoded stimuli are unfamiliar to the subjects, the recognition performance is poorer compared to familiar stimuli. This is possibly due to the fact that unfamiliar stimuli do not have pre-existing representations in long-term memory and hence, the recognition of unfamiliar stimuli becomes different and more difficult [1]. In comparison to the nonsense line drawings and faces which elicited the VMP in our previous studies, the encoding properties of digital numbers may be more complicated. The recognition of digits may be based on their perceptual features, or on their verbal/phonological code, or on their algorithmic code, which could also be stored in long-term memory. In humans, digital numbers are some of the most familiar stimuli as recognition of digital numbers is vital for daily life. Furthermore, the topographical features of the VMP have indicated a stronger source in the right hemisphere

compared to the left [6,7]. We noted that the visual stimuli in our former studies with nonlinguistic material were mainly processed by the right hemisphere [12]. The digit numbers are abstract verbal material that manifest the most robust right ear advantage (REA/left hemisphere dominance) in dichotic listening studies [24], whereas when presented visually, hemispheric asymmetries are primarily dependent on the digit characteristics, not task requirements [10]. Boles' study showed that a right visual field (RVF/left hemisphere) superiority for processing the word names of numbers and multiply presented digits is the rule nearly without exception; however, when digits are presented as numerical indicators (dot cluster, bar graphs and dials), a LVF/right-hemisphere advantage is well-established. We were interested in examining whether this lateral effect in processing digits could influence the spatial pattern of the VMP. This experiment attempted to determine whether the VMP could be elicited by digits because the verbal feature of digits could probably influence the lateral pattern of the elicited ERP component.

The VMP component observed in DMS paradigms shows the effect of a sample on a test stimulus. In this experiment, we have chosen numbers as visual stimuli to expand our investigation of the effects of stimulus load of sample stimuli on subsequent recognition of test stimuli. We selected three-digit numbers, which give the best performance in retention [34], and increased the digit load to five-digit numbers, which were hypothesized to be more difficult to encode than three-digit numbers. We hypothesized that the different stimulus loads during the encoding process would result in different VMP patterns during the recognition process. The present study investigated ERPs elicited by numbers in a delayed matching-to-sample task analogous to that employed to elicit the VMP in our previous studies. The purpose of the current study is to investigate the digit recognition process and to determine how the stimulus load modulates the recognition indexed by the VMP.

## 2. Materials and methods

#### 2.1. Subjects

Seventy-one males  $(25.4 \pm 3.8 \text{ years old})$  and 46 females  $(23.0 \pm 3.0 \text{ years old})$  were recruited either through newspaper ads or via notices posted in the Health Science Center. All subjects who participated in this study were right-handed and had normal or corrected normal vision. None of the 117 volunteers reported any history of neurological or psychiatric disease.

Fig. 1. Grand mean waveforms. (a) Three-digit stimuli, (b) Five-digit stimuli. Sample elicited ERPs were superimposed by matching S2-elicited ERPs, as well as non-matching S2-elicited ERPs. Three electrodes (left, midline, right) are presented for the frontal, central, parietal, and occipital region, respectively, four electrodes (two left, two right) for the temporal region.



## 2.2. Stimuli

The stimuli consisted numbers that were either three or five digits long (N = 240). A modified delayed matchingto-sample task was used in which framed pairs of three (half of the trials) or five (half of the trials) numbers were presented with a 1.6 s interstimulus interval and a stimulus duration of 300 ms. The interval between each trial was fixed to 3.2 s. Each number was presented on a computer screen subtending a vertical and horizontal visual angle of 6-8°. On half of the trials, S2 was identical to S1; on the other half of the trials S2 was different from S1, in which two out of three digits (simple condition) or three out of five digits (complex condition) were different. A three-digit S1 was always followed by a three-digit matching or non-matching S2, while a five-digit S1 was followed by a five-digit matching or non-matching S2. The presentation of trials with three-digit and five-digit stimuli were randomized as were trials with matches and non-matches.

#### 2.3. Procedure

The subject was seated in a reclining chair located in a sound-attenuated RF shielded room (IAC) and fixated a point in the center of a computer display located 1 m away from his or her eyes. On each trial, after the presentation of S2, the subject was asked to press a mouse key in one hand if S2 matched S1, and to press a mouse key in the other hand if S2 differed from S1. The designation of the hand indicating match or non-match was alternated across subjects. Response accuracy and speed were equally emphasized.

#### 2.4. ERP recording and measurements

All individuals were fitted with a 61-lead electrode cap (Electro-Cap International), using all sites in the Standard Electrode Position Nomenclature (America Electroencephalographic Society 1990). The impedances were kept below 5 k $\Omega$ . Cz was used as the reference electrode since some components, such as the VMP, could be best visualized with this electrode montage, as well as our interest in studying topographic distributions using the Laplacian operator [see Ref. [6]]. Subjects were grounded with a forehead electrode. The vertical and horizontal EOG were recorded. Trials with artifacts (> 73.3  $\mu$ v) were rejected on-line. The signals were amplified with a gain of 10,000 by a set of amplifiers (Sensorium 2000) with a bandpass of 0.02-50 Hz, and recorded on a Concurrent 5550 computer with subsequent 32 Hz low pass digital filtering. The sampling rate was 256 Hz. The total length of the ERP epoch was 1600 ms including a pre-stimulus baseline of 125 ms

The ERPs were averaged for six cases (Fig. 1): threedigit S1, three-digit matching S2, three-digit non-matching S2 (Fig. 1a), five-digit S1, five-digit matching S2, and five-digit non-matching S2 (Fig. 1b). There are three major components (C) which can be discerned from the grand average of ERPs at the more posterior electrodes, which are labeled as C1, C2, and C3, respectively as designated at electrode P8 in Fig. 1. The analyses in this paper will be focused on the C3 component only. The upgoing wave represents relative positivity at the recording electrode compared to the reference at Cz; yet there was no determination of absolute polarity. The C3 was the prominent upgoing wave around 247 ms. We identified the C3 as the VMP due to its temporal and morphological similarity to the VMP recorded in previous studies ([6,7,20]). The terms C3 and VMP will be used interchangeably in this paper. For each subject, a semi-automatic peak detection program finds the desired extremum in a time window determined by the extremum of a given electrode, in this case the P8, which was used to identify the components at the other electrode sites. P8 was selected due to its morphological consistency. The validity of the peaks chosen by the program was assessed by visual inspection. The peak latency varied across electrodes within the time window around the peak latency at P8. The amplitudes of the C3 were measured from baseline to peak for each case at each electrode. Latencies were measured from the time of the stimulus onset to the peak of the C3 component. C3 peak analyses were conducted in four brain regions corresponding to the underlying brain cortex in general: central (FC5/6, FC3/4, FC1/2, FCZ, C5/6, C3/4, C1/2), parietal (CP3/4, CP1/2, CPZ, P3/4, P1/2, PZ), occipital (PO7/8, PO1/2, POZ, O1/2, OZ), and temporal (FT7/8, T7/8, TP7/8, CP5/6, P7/8, P5/6). At the frontal electrodes (see Fig. 1: F3, FZ, and F4), the ERP waveforms are quite different from those at the posterior electrodes; therefore, we calculated the average amplitude within the latency range of 340-410 ms for 17 electrodes at the frontal region (FP1/2, AF7/8, AF1/2, F7/8, F5/6, F3/4, F1/2, FPZ, AFZ, FZ).

#### 2.5. Data analyses

Statistical analyses of ERP data were only conducted on artifact-free trials with correct behavioral responses. The average amplitudes in the frontal region or the C3 peak amplitudes/latencies in each of the other four brain regions served as dependent vectors for statistical comparisons. To compare S1 to S2 for three-digit and five-digit stimuli, as well as to compare matching and non-matching responses to S2, a number of MANOVAs (SAS v6.09, PROC GLM) were carried out separately. *Gender* with *Age* regression were considered as the between-subject effect, while *Condition*, which has two repeated levels (i.e., matching vs. non-matching, or S1 vs. matching S2, or S1 vs. non-matching S2), and *electrode site*, whose repeated levels depend on the brain region involved (e.g., the

Table 1 Reaction time (ms) for three-digit and five-digit stimuli

		e	0
		Matching numbers, Mean $\pm$ S.D.	Non-matching numbers, Mean $\pm$ S.D.
Three-digits	Male Female Total	$\begin{array}{c} 641.04 \pm 154.39 \\ 670.84 \pm 165.83 \\ 652.75 \pm 158.95 \end{array}$	$739.58 \pm 161.96 769.47 \pm 191.39 751.33 \pm 173.94$
Five-digits	Male Female Total	$713.94 \pm 160.12 748.55 \pm 192.41 727.55 \pm 173.56$	$\begin{array}{c} 739.69 \pm 157.68 \\ 742.26 \pm 164.35 \\ 740.70 \pm 159.64 \end{array}$

parietal region has 10 electrode sites, etc.), were considered as the within-subject effects. To test the effect of stimulus load, similar MANOVAs were conducted, with *Load* (matching three-digits vs. matching five-digits or non-matching three-digits vs. non-matching five-digits, or three-digit S1 vs. five-digit S1), instead of *Condition* as the repeated within-subject effect. The SAS output includes results of univariate, modified univariate (Greenhouse–Geisser), and MANOVAs. The appropriate output was employed whenever applied (see Ref. [19], pp. 306–378).

The topographic analysis of the C3 was based on a model-free and reference-independent technique [see Ref. [37]], the Current Source Density (CSD) map. Positive values of the current source density indicate local current flow out of the skull, whereas negative values indicate current flow into the skull.

#### 3. Results

There was a significant group mean age difference (t(115) = -3.69, P = 0.0003) between female  $(23.0 \pm 3.0)$  years old) and male  $(25.4 \pm 3.8)$  years old) subjects, although the age span for all subjects was quite narrow (19-38) years old).

#### 3.1. Behavioral performance

Subjects responded accurately on 99% of the trials for three-digit stimuli and 97.5% for five-digit stimuli. Although the accuracy was unanimously high for both threeand five-digit trials, the paired *t*-test revealed that the accuracy of the three-digit trials was higher than that of five-digit matching trials (t = 3.91, P < 0.001), nonmatching trials (t = 2.01, P = 0.0473), and trials regardless of the matching/non-matching condition (t = 4.16, P < 0.001). The response times for each stimulus condition are shown in Table 1. Four Two-way ANOVAs indicated that response times were significantly shorter for three-digit matching stimuli than for three-digit non-matching stimuli (F = 20.46, P < 0.001). For five-digit stimuli, the response times did not differ between the matching and non-matching stimuli (F = 0.36, P = 0.55). For matching stimuli, the response times were significantly shorter for three-digit numbers than for five-digit numbers (F = 11.82, P = 0.001). For non-matching stimuli, the response times were not significantly different between three-digit and five-digit numbers (F = 0.24, P = 0.63). Neither gender nor stimulus by gender showed any statistically significant effect.



Fig. 2. *P*-values for C3 amplitude from regional (central, parietal, occipital, temporal) MANOVAs of matching vs. non-matching comparison. (a) Low load. (b) High load.



Fig. 3. P-values for C3 amplitude from regional (central, parietal, occipital, temporal) MANOVAs of S1 vs. matching S2 comparison. (a) Low load. (b) High load.

#### 3.2. VMP: amplitude

#### 3.2.1. Three-digit numbers

The amplitudes of C3s obtained from matching S2s were smaller than those of non-matching S2s (Fig. 1a); this effect was significant at the central, parietal, and temporal

regions (Fig. 2). Compared to S1s, S2s were smaller regardless of matching or non-matching trials (Fig. 1a). Fig. 3 illustrates that the effect of sample vs. matching stimuli was statistically significant at all four brain regions, while Fig. 4 demonstrates that the effect of sample vs. non-matching stimuli reached significance only at central and occipital regions.



Fig. 4. *P*-values for C3 amplitude from regional (central, parietal, occipital, temporal) MANOVAs of S1 vs. non-matching S2 comparison. (a) Low load. (b) High load.

#### 3.2.2. Five-digit numbers

Although the amplitudes of C3s obtained from matching S2s appeared smaller than those of non-matching S2s at temporal electrode sites (Fig. 1b), there were no statistically significant differences at any of the four brain regions (Fig. 2). The amplitudes of S2s under all conditions were significantly smaller than S1s (Fig. 1b, Figs. 3 and 4).

#### 3.2.3. Load effect

Direct comparisons of the C3 component between three-digit and five-digit numbers demonstrated significant sample load effects at occipital (F = 7.56, P < 0.01) and temporal regions (F = 4.55, P < 0.04); an examination of the ERP amplitudes at these electrode sites indicated that

> 50.0 50.0 33.3 33.3 16.7 16.7 0.0 0.0 -16.716.7 -33.3-33.3 SAMPLE -50.0 -50.0 50.0 50.0 33.3 33.3 16.7 16.7 0.0 0.0 -16.716.7 MATCH -33.3 -33.3 -50.0 -50.050.0 50.0 33.3 33.3 NONMATCH 16.7 16.7 Q.D 0.0 -16.7-16.7-33.333.3 -50.0 -50.0

## LOW LOAD

the five-digit sample numbers elicited larger C3 responses compared to the three-digit sample numbers. Five-digit numbers elicited significantly larger C3 responses than three-digit numbers at occipital electrode sites for both matching (F = 5.59, P < 0.02) and non-matching stimuli (F = 7.99, P < 0.01).

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#### 3.2.4. Frontal data

**HIGH LOAD** 

The ERP mean amplitudes (340–410 ms) at the frontal electrodes were significantly different (F = 4.13, P < 0.05) between three-digit matching and non-matching stimuli; the matching three-digit numbers elicited less up-going amplitudes than the non-matching numbers (Fig. 1a). However, this effect was not significant for five-digit stimuli (F = 0.85, P = 0.36).

Fig. 5. Two-dimensional current source density maps for the C3 (peak latency around 247 ms). The upper left: three-digit sample; the upper right: five-digit sample; the middle left: three-digit matching numbers; the middle right: five-digit matching numbers; the bottom left: three-digit non-matching numbers; the bottom right: five-digit non-matching numbers. The unit of current density is  $(\mu v/r^2)/cm^2$ , r = radius of head.

Table 2				
Pearson cross-co	rrelation coefficien	ts (Student's t-	test, all	P < 0.0001)

	Three-digit sample	Three-digit match	Three-digit non-match	Five-digit sample	Five-digit match	Five-digit non-match
R	0.63	0.64	0.56	0.72	0.69	0.56
R'	0.97	0.97	0.95	0.93	0.93	0.89

R: correlation of left-right CSD data.

R': correlation of 200 basis-grand mean CSD data.

#### 3.3. VMP: latency

The latency of the C3 component did not manifest any significant differences between: (1) matching vs. non-

matching conditions, (2) sample vs. matching test stimuli, (3) sample vs. non-matching test stimuli, (4) male vs. female subjects. This result was obtained at all brain regions, both for three-digit stimuli and for five-digit stim-



Fig. 6. Two-dimensional current source density maps for the frontal component around 382 ms. The upper left: three-digit sample; the upper right: five-digit sample; the middle left: three-digit matching numbers; the middle right: five-digit matching numbers; the bottom right: five-digit non-matching numbers. The unit of current density is  $(\mu v/r^2)/cm^2$ , r = radius of head.

LOW LOAD

## HIGH LOAD

uli. Further, there were no significant age effects or any two-way/three-way interactions.

#### 3.4. VMP: scalp distribution

A spherical surface spline interpolation using the entire electrode montage (61 electrodes) was performed, followed by computation of the second spatial derivatives on the spherical spline functions to obtain current density distributions (cf. [26,33]). Fig. 5 shows the CSD maps around the peak latency of the C3 component (247 ms). Two strong current fields were obtained around the occipital-temporal region to all the sample and test stimuli. For sample and matching S2, the activation on the right side was slightly stronger than the left side; for non-matching S2, the activation was greater on the left side (especially the five-digit non-matching numbers). In order to decide quantitatively whether the laterality patterns were statistically significant, a bootstrap method ([32]) was applied with modification to our CSD data by the third author of this study. The analysis as described below was performed on each stimulus condition. Initially, current density maps for each subject were calculated for five consecutive sample points centered around the peak latency derived from the grand mean. The values were then averaged. Then 117 maps chosen randomly with replacement from the 117 subject maps were averaged. This was done 200 times to provide a basis for statistical analysis. Two statistical calculations were performed: a comparison of the basis maps with the grand mean and a left-right comparison. For the grand mean comparison, the Pearson correlation of the grand mean map with each of the 200 maps in the basis was calculated and then subjected to the Fisher Z transform, in order to apply Student's *t*-test to the values. In every case, the P-value was 0.0. The results are reported as R' in Table 2. The correlations are all higher than 0.89, indicating that the 200 maps in the basis for each case are not much deviant from the grand mean CSD map; therefore, the 200 maps provide a statistically sound basis for the next step: left-right comparison which will serve as the statistical index of laterality pattern of the grand mean CSD map (Fig. 5). For the left-right comparison, the midline points of the 1251 points produced by the current density calculation were removed, leaving 604 points on each side for the left-right symmetry calculation. The Pearson correlation of the left and right points for each of the 200 maps was calculated and then subjected to the Fisher Z transform, in order to apply Student's *t*-test to the values. In every case, the P-value was 0.0. The results are reported as R in Table 2. In accord with the visual assessment, the congruity (R-values) between left and right topographic pattern is lower in non-matching process than in sample and matching processes, indicating the left-greater-than-right asymmetry in non-matching processes is significantly more pronounced.

Due to the unique morphology of ERPS at frontal electrode sites, separate current density maps for the frontal

component around 382 ms (which is a time point between 340–410 ms when the CSD pattern is most clear for both three- and five-digit numbers) were plotted in Fig. 6.

three- and five-digit numbers) were plotted in Fig. 6. Corresponding to the grand mean ERP waveforms at the frontal electrodes, strong current fields were apparent around the frontal region to the three-digit test stimuli at this later latency, and weak sources appeared at the frontal region to the five-digit test stimuli.

## 4. Discussion

The results demonstrate an ERP correlate of visual short-term memory for digits which is manifested as a significantly smaller C3 (VMP) to repeated digit stimuli. The suppressed ERP amplitudes to matching stimuli observed in this experiment are consistent with previous studies, including those from our own laboratory [6,7,20,35], and single cell studies [5,16,22,29], which reported that neuronal responses to matching stimuli were suppressed. One general interpretation across these studies was that matching stimuli benefited from the specific prior exposure to sample stimuli more than non-matching stimuli. This efficiency is manifested by both a reduction of the C3 responses to previously observed numbers in our experiment, and a decrease in the number of neural elements necessary to process familiar stimuli in animal studies. The effect of suppressed ERP amplitude to matching stimuli observed in this experiment is also consistent with pairedstimuli match/non-match studies [2,4,27,28,30], in the sense that the greater the degree of congruity between prime and target stimuli, the smaller the N4 effect. However N4 was elicited by judging whether the S1 and S2 are semantically relevant, or by judging whether the S1 and S2 are phonologically relevant, while the VMP was elicited by judging whether S1 and S2 are visually identical or not. When subjects were asked to judge whether the size of visual words are identical or not, Deacon et al. [14] argued that N2 rather than N4 was elicited. Whether each of these 'match-sensitive' [see Ref. [3]] ERP components (grouped by the match effect which refers to suppressed VMP/N2/N400/N450 to matching stimuli) convey information for a single functional system at a specific temporal pattern is an interesting question for the future. These potential shifts are actually the voltage differences between the scalp site and the reference site. Hence, this inconsistency across task and paradigms may alternatively relate to the reference scalp electrode. No scalp site is inactive, but the Cz reference selected for this experiment was more active than the nose or mastoid employed in other paradigms. However, the voltage differences between Cz and other scalp electrodes are in agreement with neuronal activity changes of specific brain regions (IT) in a primate visual memory study [22], and are sensitive to mnemonic comparisons of visual stimuli.

In our study, extra efforts (or deficiency) in processing non-matching digit stimuli could be based on either the orthographic representation of digits maintained in working memory, or the verbal/arithmetic code of digits stored in long-term memory. The nature of the processes involved in this mnemonic trace left by a previous encounter with the sample stimulus is still a matter of intense debate between the proponents of an abstractionist and those of an episodic account for word stimuli [8,13,17]. The hemispheric laterality pattern of the current density map of the C3 provides indirect evidence of the possibility of the involvement of the verbal code of digits in the non-matching process. The greater activation of the right occipitotemporal area in matching trials is consistent with our previous findings; lack of laterality or even a greater left activation of this area in non-match trials is not a consistent finding. The VMP elicited by object recognition [35] also elicited a greater left activation than right during non-matching trials. The paradigm employed in this experiment is analogous to those employed in our previous studies, although the visual stimuli utilized in these experiments are different in their cognitive nature. Encoding of the digit number has long been considered one of the capacities dominated in the left hemisphere for the majority of right-handed subjects [1,10]. Findings from PET studies suggest that left or right posterior cerebral cortex is important depending on whether cognitive process is based on more abstract or more form-specific mechanisms [for a review see Refs. [9,31]]. Thus, when the test stimulus is different from the sample stimulus and when the tasks are more difficult (high load), subjects seemed to rely more on the verbal rather than the orthographic code comparison to make the non-matching decision, resulting in left-lateralized responses.

In addition to the effect of match/non-match process on the C3 amplitude, our results revealed a robust S1/S2 effect. The C3 in the test phase, regardless of stimulus condition (match/non-match or three-digits/five-digits), manifested a significant suppression in comparison to the C3 in the sample phase. The S1-S2 ERP differences could also be enhancing for non-matching visual lines as demonstrated in one of our previous studies [6]. For subjects to discriminate whether S2 is matching or non-matching, the underlying cognitive process for digit stimuli may differ from that for nonsense visual drawings in that the discrimination can be based on both a verbal code and arithmetic code in addition to an orthographic code. For non-matching digits, a similar verbal code or arithmetic code may already have been activated. Thus, the activated representations more or less facilitate the processing of non-match digits, resulting in an inhibiting ERP response to S2, while for non-matching lines, no similar representation code may exist in memory. The comparison of the encoding of the sample and the non-match lines is based solely on their orthographic codes, which are different for sample lines and non-matching lines; thus, there will be no facilitating effect, resulting in a non-inhibiting ERP response to S2 [6]. This C3 effect (S1/S2) is in agreement with neuronal

activity changes conducted in primates [29] where they also recorded different neuronal activity in response to S1 compared to S2. They observed 71% of the neurons in the hippocampal formation and parahippocampal gyrus responded more strongly to S2 than S1, whereas 66% of the neurons in temporal and rhinal cortex responded more strongly to S1 than to S2. They suggested that their results may be taken as an indication of a role in mnemonic processes for such differentially responsive neurons. The similar suppression effect observed for match and nonmatch S2 in comparison to S1 may be relevant to priming. Brysbaert [11] found that processing a number facilitates the processing of a subsequent number with a close value. Processing the sample number seems to facilitate processing not only for matching numbers identical to sample, but also for non-matching numbers, part of which share the same digits with the sample. Compared to the recognition effect (match/non-match) of the C3 discussed before, these S1/S2 differences are more prominent in this experiment. This agrees with results from studies that focused on IT neurons during matching-to-sample tasks, which indicated that the neurons convey less information about whether a stimulus was match or non-match than about whether a stimulus was first or second [15]. In their single-neuron study, Eskandar et al. [15] found that the responses of IT neurons to even the non-match stimuli did carry significant amounts of information about the pattern of the previous sample stimuli.

In a method similar to Eskandar et al. [15], our results allow us to associate the C3 with specific steps in the conceptual model for visual short-term memory. Eskandar et al. illustrated a simple visual memory system which must encode a current stimulus (test stimulus), recall the encoding of a previous stimulus (sample), compare the encoding of the two stimuli, and then make a decision on the basis of the outcome of the comparison. The cognitive feature of the C3 strikingly resembles the functional role of IT neurons which have been hypothesized to compare the internal representations of current visual stimuli with the internal representations of remembered stimuli [15]. The amplitude of the C3 is sensitive to a subset of processes that contribute to the visual mnemonic comparison between the trace held in short-term memory and the current input stimuli; it may reflect not solely the recognition or priming process, but also the processes underlying S1/S2 differences which could be unique to the S1 storage processes and/or the S2 judging match/non-match operations. Yet the CSD maps of the C3 were not so helpful in addressing this issue. The maps delineate the temporo-occipital sources shared by sample and test stimuli, indicating that this area is most likely responsible for the common process underlying S1 and S2, which would be the encoding process.

The S2 match/non-match process indexed by the C3 was affected significantly by the stimulus load, whose effect was apparently not limited to the laterality pattern of

the C3 topography mentioned before. Our results indicated that subjects made almost as many correct discriminations in the five-digit condition (98%) as in the three-digit condition (99%), and they manifested a longer response time for the five-digit matching stimuli than for the threedigit matching stimuli. However, load did not have a significant effect on RTs for non-matching stimuli. In contrast, the ERP data appeared more sensitive to the load effect. The C3 amplitudes were larger to the five-digit stimuli than to the three-digit stimuli in the sample, matching and non-matching processes. Five digits is obviously more difficult to encode than three digits, as demonstrated by the longer response time and larger ERP responses. The stimulus load did influence the recognition or priming effect indexed by the amplitude of the C3 component. An attenuation of the C3 recognition effect was associated with the higher memory load in this study (the C3 amplitude match/non-match effect was not observed for high loads). While the VMP recognition effect was observed for both the complex and simple visual stimuli in one of our previous studies [6], this recognition effect was statistically stronger for the simple visual stimuli. It appears that different stimulus load at the encoding process resulted in a different VMP recognition pattern, which indicates different processing difficulty in working memory. The significance of this VMP feature may be particularly interesting in the study of dementia where demented subjects are much more sensitive to the increase in stimulus load than normals [18]. Unlike the S2 match/non-match effect, the S1/S2 effect was not significantly affected by stimulus load. The S1/S2 difference was revealed in both high and low loads, though the difference was less widely distributed in low loads for S1/non-matching S2.

In addition, there was an activation of the frontal area (Fig. 6), which is involved in a relatively late phase of the ERP component. This observation is consistent with previous findings [7,35] that also reported the activation of frontal areas in the recognition of faces and pictures of objects. However, the involvement of the frontal cortex in our previous experiments took place relatively earlier than in this study. As discussed earlier, the cognitive nature of the digit stimuli employed in this study may be more complicated than that of faces or object pictures employed in previous studies [7,35]. This delay with regard to the involvement of the frontal cortex perhaps reflected the complexity in the encoding and recognition of digit stimuli. This frontal component is also sensitive to the match/non-match operation. We know that monkeys with bilateral removal of the frontal cortex demonstrate a memory impairment in delayed-response tasks [21]; patients with frontal-lobe lesions are impaired at monitoring and remembering the temporal order of contextually similar events [23]. The frontal cortex does play an important role in memory [9,25]. This result provides supporting evidence for the involvement of frontal cortex in the recognition of visual digit stimuli. However, whether the frontal component reflected the same cognitive process as the C3 is not yet clear.

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