Effects of symbol type and numerical distance on the human event-related potential

Ting Jiang[a], Sibing Qiao[a], Jin Li[a], Zhongyu Cao[a], Xuefei Gao[b], Yan Song[a], Gui Xue[c], Qi Dong[a,*], Chuansheng Chen[d]

[a] Beijing Normal University, China
[b] University of Illinois at Urbana-Champaign, Urbana, United States
[c] University of Southern California, Los Angeles, United States
[d] University of California, Irvine, United States

A B S T R A C T

This study investigated the influence of the symbol type and numerical distance of numbers on the amplitudes and peak latencies of event-related potentials (ERPs). Our aim was to (1) determine the point in time of magnitude information access in visual number processing; and (2) identify at what stage the advantage of Arabic digits over Chinese verbal numbers occur. ERPs were recorded from 64 scalp sites while subjects ($n = 26$) performed a classification task. Results showed that larger ERP amplitudes were elicited by numbers with distance-close condition in comparison to distance-far condition in the VPP component over centro-frontal sites. Furthermore, the VPP latency varied as a function of the symbol type, but the N170 did not. Such results demonstrate that magnitude information access takes place as early as 150 ms after onset of visual number stimuli and the advantage of Arabic digits over verbal numbers should be localized to the VPP component. We establish the VPP component as a critical ERP component to report in studies of numerical cognition and our results call into question the N170/VPP association hypothesis and the serial-stage model of visual number comparison processing.

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1. Introduction

The present experiment attempts to define the influence of two crucial parameters of printed numbers, symbol type and numerical distance, on the event-related potential (ERP) response. Numbers can be represented in one of two symbolic formats: as Arabic digits (e.g., "8"), or as verbal words (e.g., "Eight"). These two systems differentiate in several dimensions: frequency of use, visual complexity, and processing characteristics. Although both Arabic digits and verbal numbers are among the most frequent words of any language (Dehaene, 1997), the frequency of Arabic digits is even higher than that of verbal numbers (Dehaene & Mehler, 1992). The Arabic numeral system has a simple surface format, which can be characterized as a logographic notational system. English verbal numeral system, on the other hand, has a complex surface format. They are notated alphabetically, much like words in an alphabetic writing system. Visual recognition of verbal numbers is more complex than that of Arabic digits. The former may involve several cognitive operations, such as encoding of letters, integrating the letters' forms into a sequence of graphemes and orthographic patterns, activating the lexical/phonological structures, and then accessing their meanings (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). The latter may involve perceptual features encoding and semantic information accessing (Brysbaert, 2005). The difference between these two numeral systems raises the interesting question of how the mind represents different symbol formats. For example, it has been reported behaviorally that Arabic digits should have an advantage over number words in semantic tasks (Damian, 2004; Ito & Hatta, 2003). However, it is still unknown at what stage does this advantage occur? Does it necessarily occur only at the notation identification level? The excellent time resolution of ERP methodology may enable us to accomplish the first focus of our work: to detail the temporal course of visual number recognition, and figure out at what stage the advantage of Arabic digits over verbal number words occurs.

A well-documented behavioral phenomenon concerning number processing is the numerical distance effect (Butterworth, 1999; Dehaene, 1997; Moyer & Landauer, 1967). That is, the comparison of two numbers is more difficult when they are close to each other in their magnitude than when they are far apart. This numerical

* Corresponding author at: State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing, 100875, China.
E-mail address: dongqi@bnu.edu.cn (Q. Dong).

distance effect is usually explained by a comparison process operating on magnitude information retrieved from mental number representations (Dehaene, 1992). The distance effect has been found for both the classification and selection tasks (Dehaene, 1989; Hinrichs, Yurko, & Hu, 1981; Moyer & Landauer, 1967). In the classification task, only one target number is presented, and the participant presses a key to indicate whether the target is larger or smaller than a reference number. In the selection task, two digits are presented simultaneously. The participants were instructed to press the LEFT or RIGHT button depending on whether the digit on the left or right was the larger one numerically. The second focus of this ERP study was to examine the early influence of numerical distance in the classification task (Dehaene, 1996), in order to provide an upper limit for the time course of number-magnitude representation accessing.

A significant and reliable amplitude difference between ERPs as a function of an experimental manipulation (e.g., numerical distance) demonstrates that the manipulation engenders differential brain activity. It is important to note that the absence of such a difference does not permit the opposite conclusion. Namely, even if differences in brain activities have occurred, they were in tissue unfavorably configured for the generation of field potentials, or their signal at the scalp may be too small to be detectable (Rugg & Coles, 1995). Therefore, the ERP difference only places an upper bound on the time by which processing is different. It is entirely possible that processing begins to differ at an earlier point in time, but that such a difference is not evident in the ERPs (Rugg & Coles, 1995). Therefore, the earliest amplitude effect of numerical distance on ERPs provides an upper limit for the latency of magnitude information access.

A few previous ERP studies reported findings on the variation of the parameters with symbol type and numerical distance. Their respective characteristics concerning stimuli, task and methodology are summarized in Table 4. The findings concerning amplitude effects of numerical distance are sparse and inconsistent. They tested with adults and found that numerical values close to 5 (i.e., 4 and 6) compared to numerical values far from 5 (i.e., 1 and 9) elicited a greater positivity that started around 175 ms after stimulus onset for Arabic digits and 190 ms after stimulus onset for number words (mainly the P2p component). Temple and Posner (1998) added a non-symbolic condition (dots) and compared it with a symbolic condition (Arabic digits) by testing both adults and 5-year-old children in the numerical judgment task (i.e., 1, 4, 6 and 9 compared to a standard of 5). In contrast, they found numerical close condition to produce more negativity in the early latency range 124–174 ms (mainly the N170 component) and the opposite pattern between 184 and 234 ms (mainly the P2p component). More recently, Libertus, Woldorff, and Brannon (2007) replicated the symbolic distance effects in both the N170 and P2p time windows (see their Fig. 3, p. 6).

Neuroimaging studies for the numerical domain have consistently found activation in the intra-parietal sulcus (IPS) in arithmetic and number comparison tasks (Dehaene, Piazza, Pinel, & Cohen, 2003). These findings suggest that the IPS plays a role in the semantic manipulation of visual numbers. Several researchers even claimed that number magnitude may be represented in this parietal region (Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Thioux, Pesenti, Costes, De Volder, & Seron, 2005). However, several other researchers suggested that activation of the IPS during magnitude comparison may be related to some general processes (e.g., response selection) rather than specific number magnitude accessing (Göbel, Johansen-Berg, Behrens, & Rushworth, 2004). Though a large body of neuroimaging studies has focused on this "specificity" research question for the number domain (Cohen Kadosh et al., 2005; Cohen Kadosh, Henik, & Rubinsten, 2008; Eger et al., 2003; Piazza, Pinel, Le Bihan, & Dehaene, 2007; Pinel, Dehaene, Rivière, &

Stimuli used in the experiment:

Fig. 1. All of the stimuli used in the experiment.

LeBihan, 2001; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Shuman & Kanwisher, 2004; Tang, Critchley, Glaser, Dolan, & Butterworth, 2006; Thioux et al., 2005), the results were still mixed. Piazza et al. (2007) pointed out that the question of domain specificity might be an ill-posed question, and it was very difficult to answer with fMRI (functional Magnetic Resonance Imaging) alone. Alternatively, the ERP technique may compensate for the limited time resolution of fMRI. The combination of ERP and fMRI may be useful for characterizing the neural responses associated with the early specific process (e.g., number magnitude information accessing) as well as these late general processes of visual number processing (e.g., response selection, working memory, and motor execution).

Using ERP and fMRI techniques, Pinel et al. (2001) relied on the additive-factors method (Sternberg, 1969) and varied orthogonally two parameters: numerical distance and symbol type. They required participants to perform a classification task ("larger or smaller than 65?") with Arabic digits and English verbal numbers. They demonstrated that the notation effect at bilateral occipito-temporal sites (N170) could be localized to the fusiform gyrus. Furthermore, they also detected the distance effect in the parietal ERPs (mainly in the P2p time window), which could be localized to the bilateral horizontal intra-parietal sulci (Pinel et al., 2001). They suggested that these results appeared to provide neural evidence for Dehaene's (1996) serial-stage hypothesis of mental comparison: visual identification (involving fusiform), magnitude processing (involving intra-parietal sulci), and motor response (involving language and motor areas).

Unfortunately, these previous studies (Dehaene, 1996; Pinel et al., 1999, 2001) suffered from two main shortcomings: First, the low-level visual characteristics between Arabic digits and English verbal numerals (e.g., 8 vs. Eight) might have had a crucial effect on the way the numerals were recognized and their magnitudes were processed. For example, the numerical distance effect might be confounded by the word length effect for English verbal numerals. It was suggested that "the distance and word length effects cancelled each other: target NINE is one letter longer than SIX, but it is numerically more distant from the standard of comparison. Once a correction for word length was applied to RTs, the distance effect was again found to be strictly identical for arabic and for verbal numerals" (see Fig. 2, Dehaene, 1996, p. 52). One solution to this uncontrolled methodological artifact was to use different categories of stimuli with highly visual similarity (Rossion & Jacques, 2008). The present study used two categories of numerals (Arabic digits and Chinese numerals, see Fig. 1), and their pixels were matched.

Second, the attention of the researchers in this field was focused on these components over posterior sites (e.g., P100, N170, P2p, and P300). Why has the previous ERP research not documented such evidence at anterior sites? One possible explanation was that the proposed models of number processing did not lead us to anticipate any valuable difference at anterior sites. Nevertheless, a number of studies have already suggested that the involvement of the prefrontal regions in number comparison (Ansari, Garcia, Lucas, Hamon, & Dhital, 2005; Kaufmann et al., 2006; Pinel et al., 2001). More importantly, earlier ERP studies of face processing showed a large and consistent positive wave between 140 and 200 ms over frontal midline sites. Researchers (Jeffreys, 1989, 1996) have referred to this component either as the P170 or as vertex-positive potential (VPP). It has been generally accepted that the

N170 and VPP components elicited by faces manifest the same brain processes. However, as Joyce and Rossion (2005) suggested, the relationship of these two components should also be addressed to non-face stimuli (e.g., words and numbers). It was still unclear whether these two components elicited by numerals manifested the same brain processes.

To our knowledge, only one previous study has directly investigated the effects of symbol type and numerical distance using single Arabic digits and English verbal numerals, in order to provide further evidence for the proposed serial-stage model under the additive-factors method framework (Dehaene, 1996). The goal of the present study, employing well-controlled stimuli, is to test the validity of Dehaene's (1996) serial-stage model. We had two main hypotheses: first, we reasoned that if the distance effect in the P2p time window reflected the early number-specific processing, the numerical distance should not affect the ERPs during the N170 time window (e.g., N170 and VPP). Second, we expected that if the N170 and VPP elicited by numbers are manifestations of the same neural generators (Joyce & Rossion, 2005; Rossion, Joyce, Cottrell, & Tarr, 2003), then they should present identical functional response. In order to test these two hypotheses, we attempted to determine the time range in which number-magnitude representation is accessed, with an emphasis on these early components (e.g., N170 and VPP).

Dehaene (1996) found that the N170 latency was inversely related to reaction time for symbol type conditions (see the middle panel of his Fig. 4, p. 54). As Dehaene (1996, p. 60) suggested, "it is possible that at least part of the visual analysis starts earlier for verbal than for arabic stimuli. This onset difference would be later compensated by the longer duration of word identification as compared to digit identification". Surprisingly, few studies have attempted to directly examine this crucial theoretical question: at what stage the advantage of Arabic digits over verbal number words occur. In order to answer this question, we attempted to decide whether there exist any peak latency difference between the Arabic digits and Chinese verbal numerals.

2. Methods

2.1. Participants

Twenty-six undergraduate volunteers (13 males) were recruited from Beijing Normal University for this study. All participants were right-handed and had normal eyesight in both eyes. They had a mean age of 22 years (ranging from 19 to 25 years). Participants gave written informed consent before the experiment.

2.2. Stimuli and task

There were two categories of numerals (Arabic digits and Chinese verbal numbers). Each number symbol (3.5 cm × 4 cm) subtended approximately 1.9° × 2.2° of visual angle. Visual complexity in terms of pixels was strictly matched across these two categories (see Fig. 1).

Participants were seated 105 cm away from the computer screen in a dimly lit, sound-attenuated room. The stimuli were presented visually in white against black background at the center of the screen. All number stimuli (320 trials in total) were presented randomly. Each trial began with a fixation sign shown for 500 ms. The fixation was followed by a pause (mean: 500 ms, range from 400 to 600 ms). Then a stimulus was shown for 200 ms, followed by a blank screen, which remained present until the participant gave a response. The inter-stimulus interval was 1000 ms. Before the formal test, participants were presented 20 practice trials. During the practice period, the participants were instructed to judge the numerical value (magnitude) of numbers. Both speed and accuracy were emphasized in the instructions. Half of the participants were instructed to press the LEFT when they saw the larger numbers (i.e., 6, 7, 8, and 9) and to press the RIGHT when they saw the smaller numbers (i.e., 1, 2, 3, and 4), whereas the other half of the participants were instructed to do the opposite. They were also instructed to avoid blinking within a trial.

2.3. EEG recording and data analysis

Scalp voltages were recorded by a NeuroSCAN system, using a 64-channel Quick-cap with silver chloride electrodes (Neurosoft, Inc., Sterling, USA). The impedance of all electrodes was kept below 5 kΩ. EEG was amplified with a band pass of 0.1–40 Hz, digitized on-line at a sampling rate of 1000 Hz. EEG was physically referenced to the left mastoid and then was off-line re-referenced to the average of the left and right
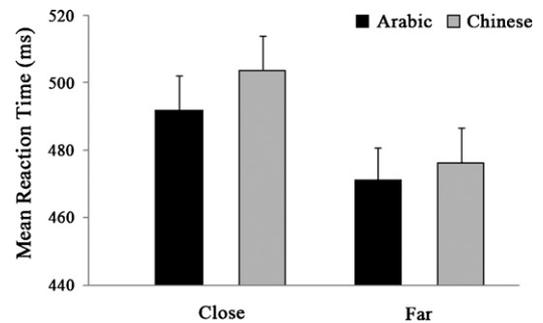
Fig. 2. Behavioral results show decreasing reaction times for increasing numerical distance in both conditions (Arabic digits and Chinese numerals).

mastoid. Trials contaminated by eye blinks, eye movement, or muscle potentials exceeding ±75 μV at any electrode were excluded from the ERP averages, resulting in exclusion of about 14% of the trials from the average. The remaining trials were averaged for each type of stimuli separately for each subject. The valid trials used for averaging were 69, 69, 70 and 69 for Arabic close, Arabic far, Chinese close, and Chinese far, respectively. The baseline for ERP measurements was the mean voltage of a 200 ms pre-stimulus interval. The averaged ERPs were filtered with a low-pass filter of 30 Hz (zero-phase, 12 dB/octave). Scalp topographies were visualized with EEGLAB (http://sccn.ucsd.edu/eeglab/).

2.4. Statistical analysis

Based on visual inspection of each subject's data, the N170 was identified as the first visible negative peak 100–220 ms post-stimulus over occipito-temporal sites, and the VPP was identified as the first visible positive peak 110–230 ms post-stimulus over centro-frontal sites. Because the N170 response was most obvious in Po7 and Po8 and the VPP was most obvious in Fcz and Cz (see Fig. 3), further data quantification and statistical analysis focused on these four electrodes. Peak amplitude and latency values of the N170 and VPP were extracted on the 100–220 ms and 110–230 ms time windows. Repeated measures analyses of variance (ANOVA) were conducted to examine the effects of experimental factors. For amplitude and latency analyses, numerical distance (2), symbol type (2) and position (2) were within-subject factors. $p < .05$ values were considered significant.

3. Results

3.1. Behavioral data

Mean RTs are shown in Fig. 2. Both symbol type and numerical distance had significant main effects on mean RTs ($F(1, 25) = 12.77$, $p < .01$; $F(1, 25) = 108.27$, $p < .01$). Their interaction was not significant.

Error rates distinguished between numerical close and far, but not between Arabic digits and Chinese numerals. The significant result was a main effect for Numerical Distance ($F(1, 25) = 16.23$, $p < .01$).

3.2. ERP data

For the early N170 and VPP components, with high signal-to-noise ratio, we did peak amplitude analysis (see Table 1). For these late N250, P2p and P300 components, we did mean amplitude analysis (see Table 2).

Table 1
The peak amplitude means (μV) and standard errors (in parentheses) of the N170 and VPP for all conditions based on grand mean ERP responses.

	Arabic digits		Chinese numerals	
	Close	Far	Close	Far
N170				
Po7	−2.82 (0.75)	−2.82 (0.76)	−2.90 (0.76)	−3.06 (0.72)
Po8	−3.11 (0.69)	−3.60 (0.68)	−3.20 (0.69)	−3.37 (0.68)
VPP				
Fz	7.29 (0.60)	6.51 (0.60)	7.22 (0.59)	6.48 (0.61)
Fcz	7.11 (0.62)	6.49 (0.67)	6.98 (0.66)	6.25 (0.66)
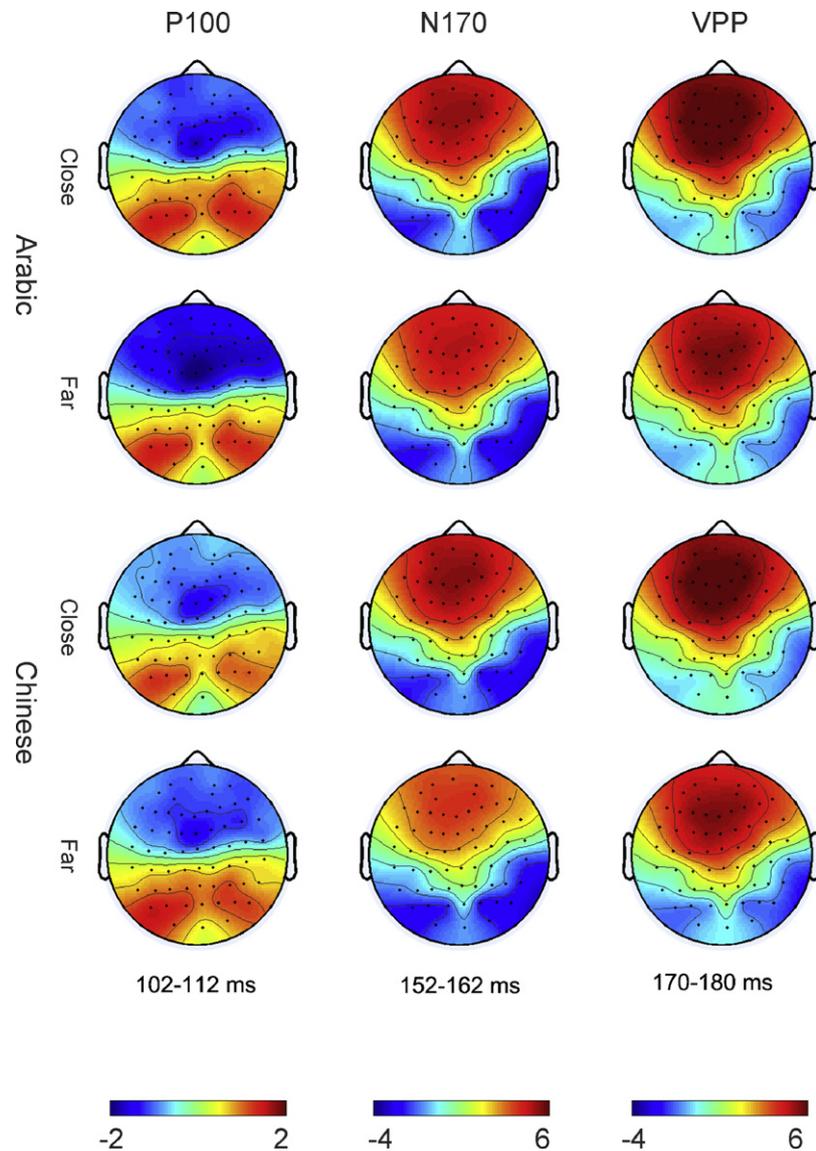
Fig. 3. Topographical maps of the amplitude averages over a time window of ±5 ms around the peak of each component (P100, N170, and VPP).

3.2.1. Peak amplitude analyses

For N170 component, no main effect reached significance (symbol type: $p = .79$; numerical distance: $p = .24$). There was no significant 2-way or 3-way interaction (all $p > .05$).

For VPP component, only a main effect of Numerical Distance was found ($F(1, 25) = 16.69$, $p < .01$), with larger amplitude for close

condition than for far condition. No 2-way interaction or 3-way interaction reached significance (all $p > .05$).

In order to clarify the relationship between the N170 and VPP, we directly compared the effect sizes of numerical distance on

Table 2
The mean amplitude means (μV) and standard errors (in parentheses) of the N250, P2p, and P300 for all conditions based on grand mean ERP responses.

	Arabic digits		Chinese numerals	
	Close	Far	Close	Far
N250				
Fz	1.64 (0.70)	0.94 (0.78)	1.33 (0.75)	0.84 (0.69)
Fcz	1.64 (0.69)	1.05 (0.75)	1.12 (0.71)	0.58 (0.68)
P2p				
Po7	3.90 (0.53)	3.14 (0.53)	3.64 (0.48)	2.81 (0.46)
Po8	4.31 (0.51)	3.47 (0.54)	3.68 (0.50)	2.74 (0.57)
P300				
Po7	4.33 (0.62)	5.10 (0.68)	3.82 (0.59)	4.95 (0.69)
Po8	3.96 (0.63)	4.34 (0.72)	3.41 (0.62)	4.12 (0.77)

Table 3
The peak latency means (ms) and standard errors (in parentheses) of the N170, VPP, N250 and P500 for all conditions based on grand mean ERP responses.

	Arabic digits		Chinese numerals	
	Close	Far	Close	Far
N170				
Po7	156 (3.83)	159 (2.74)	154 (4.25)	163 (2.99)
Po8	159 (3.07)	156 (3.93)	153 (2.73)	159 (2.78)
VPP				
Fz	172 (2.67)	170 (2.76)	173 (3.56)	175 (3.01)
Fcz	172 (2.92)	171 (2.91)	173 (3.09)	177 (3.13)
N250				
Fz	253 (7.24)	252 (6.44)	265 (7.33)	260 (7.30)
Fcz	253 (7.24)	255 (6.22)	262 (7.77)	258 (6.11)
P500				
Fz	441 (14.2)	430 (16.4)	445 (13.4)	458 (16.1)
Fcz	438 (14.8)	430 (12.9)	456 (12.1)	458 (16.0)

Table 4
Summary of studies examining the effects of numerical distance or notation type.

Reference	Stimuli	Design	Task	Method	No. of channels	No. of subjects
Grune et al. (1993)	Arabic digits (from 11 to 20)	Distance (−7 to 7)	Selection	EEG (Linked Earlobeβ (Fz, Cz, and Pz)		10
Grune et al. (1994)	Arabic digits (from 11 to 20)	Distance (−7 to 7)	One-back comparison	EEG (Linked Earlobeβ (Fz, Cz, and Pz)		10
Dehaene (1996)	Arabic and English numerals (single)	Symbol × Distance	Classification (5)	EEG (Right Mastoid)	64	12
Temple and Posner (1998)	Arabic digits and dots (single)	Notation × Distance	Classification (5)	EEG (Average Reference)	128	28
Pinel et al. (2001)	Arabic and English numerals (double)	Symbol × Distance	Classification (65)	EEG (Vertex)	128	13
Plodowski et al. (2003)	Arabic, English, Roman, and dots (single)	Notation	Parity judgment	EEG (Vertex)	128	14
Libertus et al. (2007)	Arabic digits and dots (single)	Notation × Distance	Classification (5)	EEG (Right Mastoid)	64	12

these two components. The effect size was calculated as the amplitude difference between close condition and far condition. The effect sizes from the Po7 and Po8 sites and those from the Fz and Fcz sites were pooled, respectively. The ANOVA was performed on the pooled effect size data. The ANOVA consisted of 2 factors: Component (N170 vs. VPP) and symbol type (Arabic digits vs. Chinese numerals). Only a main effect of component was found ($F(1, 25) = 8.82$, $p < .01$). The interaction did not reach significance.

3.2.2. Mean amplitude analyses

For N250 component, a main effect of Numerical Distance was found ($F(1, 25) = 7.69$, $p < .05$), with larger amplitude for far condition than for close condition. An interaction between position and symbol type ($F(1, 25) = 5.75$, $p < .05$) was found. No other 2-way interaction or 3-way interaction reached significance (all $p > .05$).

For P2p component, a main effect of Numerical Distance was found ($F(1, 25) = 23.30$, $p < .01$), with larger amplitude for close condition than for far condition. P2P amplitude also showed a main effect of symbol type ($F(1, 25) = 10.11$, $p < .01$), due to larger amplitude for Arabic digits as compared to Chinese numerals. The interaction between symbol type and numerical distance was not significant. Only an interaction between position and symbol type was significant ($F(1, 25) = 5.11$, $p < .05$). To investigate the significant interactions, we did further simple effect analyses to examine the symbol effect separately on different position (Po7 and Po8). On Po7 electrode, P2P amplitude showed no difference between Arabic digits and Chinese numerals. On Po8 electrode, P2P amplitude for Arabic digits was significantly larger than for Chinese numerals ($p < .01$).

P300 mean amplitude showed a main effect of Numerical Distance ($F(1, 25) = 10.59$, $p < .01$), with smaller amplitude for close condition than for far condition. The interaction between Position and Numerical Distance was significant ($F(1, 25) = 4.61$, $p < .05$). To investigate the significant interactions, we did further simple effect analyses to examine the distance effect separately on different position (Po7 and Po8). On Po7 electrode, P300 amplitude was significantly larger for far condition than for close condition ($p < .01$). On Po8 electrode, P300 amplitude also showed significant difference, due to larger amplitude for far condition than for close condition ($p < .05$).

3.2.3. Peak latency analyses

In order to decide whether there exist any peak latency difference between Arabic digits and Chinese verbal numerals, we did the peak latency analysis on the N170, VPP, N250, and P500 components (see Table 3). Peak latency values of the N170 and VPP components were extracted on the 100–220 ms and 110–230 ms time windows. For the N250 and P500 components, the time windows were defined on the 180–360 ms and on the 300–600 ms, respectively.

For occipito-temporal N170 component, there was no main effect of symbol type ($p = .97$). Over the centro-frontal sites, VPP latency showed a main effect of symbol type ($F(1, 25) = 7.04$, $p < .05$), due to shorter latencies for Arabic digits as compared to Chinese numerals. Similar data patterns were found on the N250 component ($F(1, 25) = 11.15$, $p < .01$) and the P500 component ($F(1, 25) = 5.81$, $p < .05$).

In order to clarify the relationship between the N170 and VPP, we directly compared the effect sizes of symbol type on these two components. The effect size was calculated as the latency difference between Arabic digits and Chinese numerals. The effect sizes from the Po7 and Po8 sites and those from the Fz and Fcz sites were pooled, respectively. The ANOVA was conducted to test the significance of the main effects (component and numerical distance) and the interaction effect. A main effect of component was found ($F(1, 25) = 5.14$, $p < .05$). The interaction did not reach significance.

4. Discussion

We investigated the impact of symbol type (Arabic vs. Chinese) and numerical distance (close vs. far) on the ERPs in the classification task. The main results were as follows: (a) the effects of symbol type and numerical distance were significant on reaction times, but not their interaction; (b) the VPP peak latencies were modulated by symbol type, with shorter latencies for Arabic digits; (c) similar data patterns were also found on the N250 and P500 components; (d) the earliest influence of numerical distance on the amplitude of the ERPs occurred during 150–190 ms. Amplitude decreased with increasing numerical distance; (e) the amplitude effects of numerical distance were also observed on frontal N250, and occipito-temporal P2p component.

In this section, we will first discuss the effects of symbol type and numerical distance, respectively. We will then discuss the relationship between the N170 and VPP components. Finally, we will discuss the implications of the present results for the theories of visual number comparison processing.

4.1. What is symbol effect and why?

The basic function of numbers is to represent quantities. Although quantities are associated spontaneously with Arabic digits, they can also be represented as several other symbolic formats (e.g., English, Roman, and Chinese), or in non-symbolic stimuli (e.g., sets of dots). The degree to which surface formats affect visual number processing is an important theoretical question for numerical cognition (Ansari, 2007). In these previous studies (Dehaene, 1996; Pinel et al., 2001; Plodowski, Swainson, Jackson, Rorden, & Jackson, 2003), Arabic digits and English number words were used. There was the question to what extent the empirical evidence of symbolic notation effect in these studies was due to the high-level visual identification processing or to some confounded low-level perceptual factors.

In order to accomplish this research question, it is necessary to summarize the results concerning: (1) the commonalities and the differences across different formats of numerals; (2) the interaction between the symbol type and numerical distance.

The results concerning symbolic effect are sparse and inconsistent (see Table 4). Dehaene (1996) found a significant symbol effect in N170 responses. Based on visual inspection of Dehaene's N170 waveform (1996, p. 54), Arabic digits produced smaller activity than verbal numerals at the left site (T5P). This symbolic notation effect was reversed at the right site (T6P). Plodowski et al. (2003) did not present this asymmetry data pattern (Dehaene, 1996) as their waveforms across 12 electrodes were averaged. They found that the amplitude of P1 (or P100) component was significantly greater for Arabic digits compared to all other numerical forms (e.g., Roman, English numerals, and dots). However, the amplitude effect in N170 responses was reversed, with greater activity for English numerals. The P100 symbolic effect was also observed by Pinel et al. (2001).

Contrarily, the interaction between symbol type and numerical distance seems consistent. Using sample-by-sample analyses in the P2p time window, Dehaene (1996) found that the first significant effect of numerical distance emerged at 174 ms for Arabic digits and at 190 ms for English verbal numerals. Evidence convergent with this finding was observed by Pinel et al. (2001) that no numerical distance effect appeared with English verbal numerals until 220 ms, or about 60 ms later than with Arabic stimuli.

To summarize, the P100 and N170 responses seems correlated with symbol type, which may suggest that these early processes may be influenced by the variation of the physical properties (e.g., size, luminance, or visual complexity) between different symbolic formats. This assumption was confirmed by the fact that occipital

clusters showed greater activation to verbal than to Arabic stimuli in fMRI studies (Pinel et al., 1999, 2001).

More importantly, the difference in these early processes may further modulate the initial timing point of the subsequent processes in the P2p time window. Therefore, the physical properties of the stimuli may have a crucial effect on its subsequent processes (e.g., high-level identification, specific number magnitude processing, response selection, working memory and motor execution).

The physical properties of the stimuli in the present study were carefully controlled by employing two categories of numbers with inherent similarity (Arabic digits vs. Chinese numerals). The same amount of pixels were used (on the average) for the stimuli in each category. However, it is not sufficient to ensure that their visual complexity (e.g., spatial frequency) has been completely matched. Similarly, the close-far comparison may also be confounded by the factor of visual complexity. Using training paradigm will be helpful, as the training manipulation changed the familiarity and meaningfulness of the artificial stimuli without changing their low-level visual properties (McCandliss, Posner, & Givón, 1997). Contrary to those previous studies (Dehaene, 1996; Pinel et al., 2001; Plodowski et al., 2003), we could not detect strong evidence for ERP amplitude difference with symbol type in the P100 and N170 time windows (all $p > .05$). The use of Chinese numerals does largely, if not completely, overcome the confounds of using numbers written in a phonetic alphabet. More importantly, we detected the symbolic effect in VPP latency, with shorter latency for Arabic digits. We also found similar latency difference on the N250 and P500 components.

Three points should be worth noting. First, the present results, together with those of previous studies (Dehaene, 1996; Pinel et al., 2001; Plodowski et al., 2003), indicate that the physical property variation of numbers is an important factor determining the intensity of brain activity elicited by visual number stimuli. Therefore, these low-level perceptual factors should be controlled in studies of number evoked brain activity. Second, the dissociable data pattern of our electrophysiological results on the N170 and VPP components is contradictive with the N170/VPP association hypothesis (Joyce & Rossion, 2005; Rossion et al., 2003). Finally, most importantly, based on the present symbolic effect, it still cannot be decided whether the effect of symbolic type in VPP latency should be due to differential neural processing with respect to notation-specific identification processing or other subsequent processes.

Although Dehaene's serial-stage model (1996) proposed the existence of a visual identification level and interpreted the notation difference as an index of this visual identification module, notably this was not the only possible interpretation (Bentin & Golland, 2002; Brysbaert, 2005; Campbell, 1994; Seidenberg & McClelland, 1989; Xue, Jiang, Chen, & Dong, 2008). For instance, the most robust finding in the field of numerical cognition is that Arabic digits can be processed faster than other types of numerals in semantic tasks (Cohen Kadosh et al., 2008; Damian, 2004; Dehaene & Akhavein, 1995; Henik & Tzelgov, 1982; Ito & Hatta, 2003). The effects of notation were taken to indicate faster access to numerical knowledge from Arabic digits, but slower access from other types of numerals. Accordingly, the present latency difference in VPP latency can be due to either the visual identification processing or the semantic numerical processing. This question will probably not be answered unless the effect of numerical distance on the temporal N170 component is reported combined with that on the frontal VPP component.

4.2. Late vs. early effects of numerical distance

Consistent with previous ERP studies (Dehaene, 1996; Grune, Mecklinger, & Ullsperger, 1993; Libertus et al., 2007; Schwarz & Heinze, 1998; Temple & Posner, 1998), we detected numerical dis-
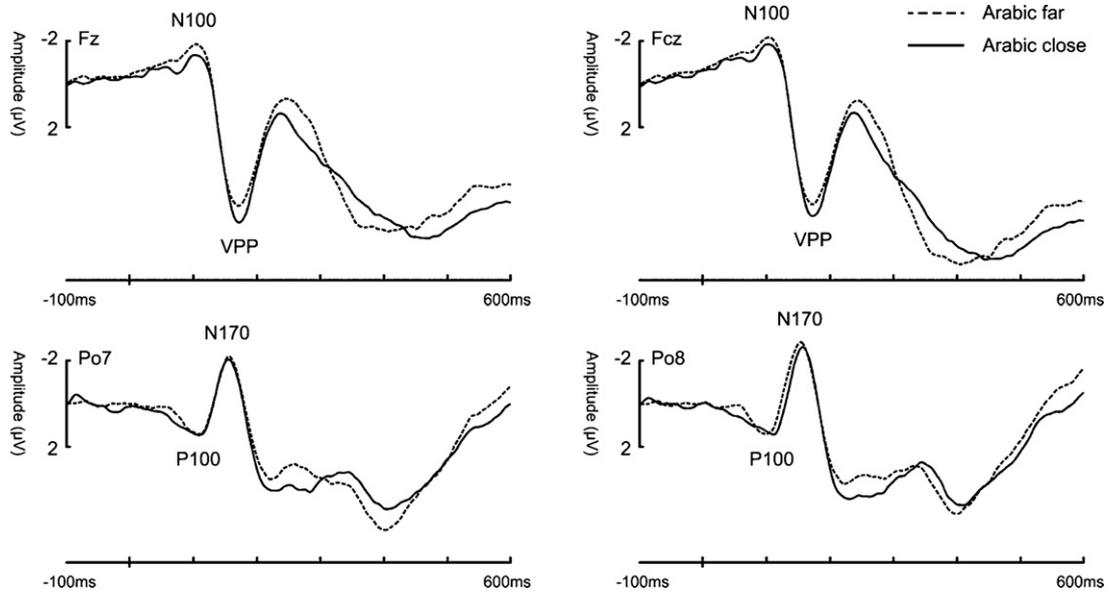
Fig. 4. Grand average ERPs at frontal sites (Fz and Fcz) and occipito-temporal sites (Po7 and Po8) for Arabic digits.

tance effect on top of the P300 component, which was characterized by larger mean amplitude in distance-far condition in comparison to distance-close condition.

Also consistent with previous studies (Dehaene, 1996; Libertus et al., 2007; Temple & Posner, 1998), the present study found a reversal in the polarity of the ERP distance effect in the P2p time window for both Arabic and Chinese stimuli (see Figs. 4 and 5). The occipito-temporal positivity was larger for distance-close condition rather than for distance-far condition.

In addition to the effects during the late P2p and P300 time windows, we also examined the modulation of numerical distance in the N170 time window (N170 and VPP) in both Arabic and Chinese numerals. Similar to the results reported by Dehaene (1996), the N170 component did not show a significant effect of numerical distance. However, we were able to demonstrate that VPP amplitude was elicited larger for the numerical close condition as compared to the numerical far condition. Temple and Posner (1998) showed a significant distance effect in the N170 time window (mainly N170),

with greater negativity for numerical close condition. Libertus et al. (2007) replicated the distance effect in the DIGITS condition on the amplitude of the N170 component over inferior parietal and occipito-temporal sites. These studies (Dehaene, 1996; Libertus et al., 2007; Temple & Posner, 1998) did not report the data over anterior sites (e.g., Fz and Fcz). It was understandable that the attention of researchers was focused on the N170 component since the specific visual processing of numbers was suggested to take place in occipito-temporal regions (Dehaene, 1996). The present study, however, suggests that the VPP should also be considered as a critical ERP component to report in the studies of numerical cognition.

Moreover, the early distance effects in these previous studies (Libertus et al., 2007; Temple & Posner, 1998) and our own, taken together, provide strong evidence for the modulation of early electrophysiological brain responses by numerical distance. On one hand, the upper limit for the latency of magnitude information access suggests that the symbol effect in VPP latency may not be only due to the visual identification processing. On the other hand,
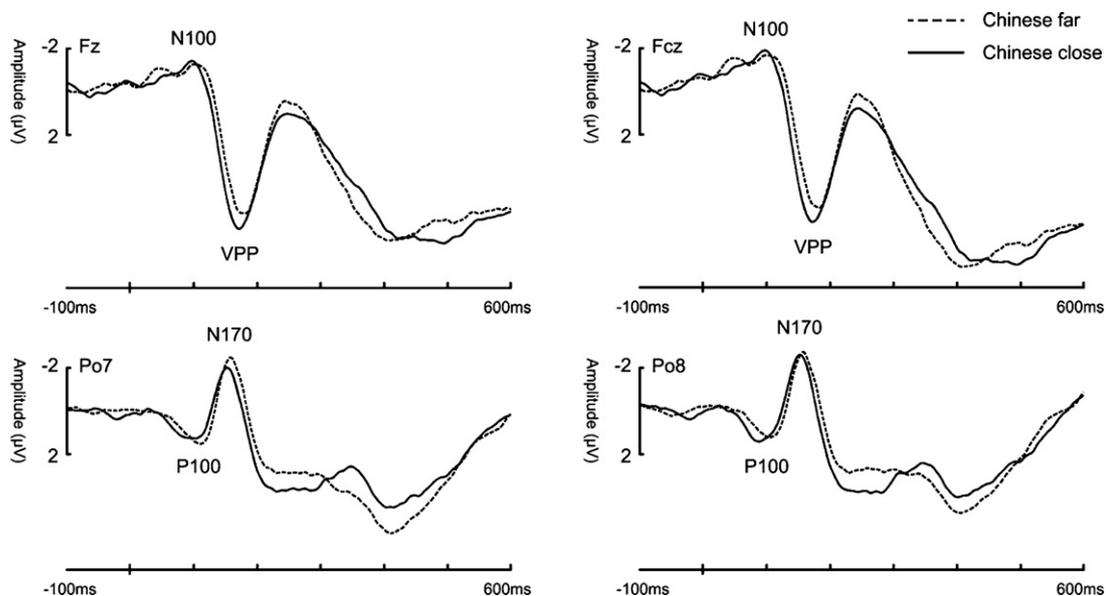
Fig. 5. Grand average ERPs at frontal sites (Fz and Fcz) and occipito-temporal sites (Po7 and Po8) for Chinese numerals.

the later numerical distance effect in the P2p and P300 time window are unlikely to reflect the number-specific processes, but may rather indicate some general processes, such as response selection, motor preparation, and executive function of working memory.

4.3. Relationship between the N170 and VPP

To resolve the issue whether the VPP and N170 are different manifestations of the same activity, the most critical factor to consider is their functional properties (Joyce & Rossion, 2005). Can the N170 and VPP be dissociated based on their different responses to different experimental manipulations? Since the N170 and VPP showed remarkable functional similarity to various manipulations of faces (Goffaux, Gauthier, & Rossion, 2003; Itier & Taylor, 2002; Jemel et al., 2003; Rossion et al., 1999a; Rossion et al., 1999b), Joyce and Rossion (2005) claimed that the N170 and VPP represented the same underlying generators (also see Rossion & Jacques, 2008 for a review).

Alternatively, several investigators have argued that the N170 and VPP might reflect two different brain processes (Bötzel, Schulze, & Stodieck, 1995; Bentin, Allison, Puce, Perez, & McCarthy, 1996; Eimer, 2000; George, Evans, Fiori, Davidoff, & Renault, 1996). The data from the developmental ERP studies demonstrated that the N170 had a different developmental pattern from that of the VPP. The N170 could be recorded in children from 4 years of age, however, the VPP was absent in children younger than 12 years of age (Taylor, McCarthy, Saliba, & Degiovanni, 1999). Similarly, Eimer (2000) also found the dissociable data patterns between the N170 and VPP components when presented centrally and peripherally. These findings might be interpreted as the evidence against the N170/VPP association hypothesis.

However, Joyce and Rossion (2005) suggested alternative explanations for the above evidence of dissociation. For the developmental evidence (Taylor et al., 1999), they suggested that "the absence of the VPP in young children is due to modifications of the cortex folding, and accordingly dipole orientation, with age and brain development" (Joyce & Rossion, 2005, p. 2626). For the peripheral presentation evidence (Eimer, 2000), they suggested that "the orientation of the equivalent occipito-temporal dipole is sensitive to the eccentricity of the visual field stimulation, as indicated by the modulation of the N170 itself to the eccentricity of the stimulus, and the observation that the N170 is larger for contra-lateral stimulations" (Joyce & Rossion, 2005, p. 2626).

Therefore, according to the 'strict' criterion set by Joyce and Rossion (2005), strong evidence against the N170 and VPP association hypothesis exists only when both components demonstrate different parameters and vary as a function of symbol type which are presented centrally to the adults (or more than 12 years of age). The present study met these requirements. Both Arabic and Chinese numerals in the present study were presented centrally and the subjects were adults. Our results showed that the VPP latency varied as a function of symbol type, whereas the N170 did not. Furthermore, we found that the VPP amplitude was modulated by the numerical distance, whereas the N170 did not. We also directly compared the effect sizes on the N170 and VPP, and the effect sizes were significantly different. The present findings should be considered as strong evidence against the N170 and VPP association hypothesis (Joyce & Rossion, 2005; Rossion et al., 2003). It has been generally assumed that ERP activity recorded on the scalp is due to a combination of neural generators located in various brain regions (Picton et al., 2000). Since the N170 and VPP are always observed in an overlapped time window, some processes may be shared (Schendan, Ganis, & Kutas, 1998). Thus, our results provide further evidence that the N170 may reflect processes that are similar to but somewhat distinct from those of the VPP.

4.4. Implications for theories of visual number comparison processing

Our results address three crucial questions with respect to visual number processing. First, at what stage does the advantage of Arabic digits over Chinese number words occur? Second, which is the latency range in which number-magnitude representations are accessed? Finally, is the semantic number processing temporally separate from visual identification processing?

The pattern of our electrophysiological results on symbol type was in agreement with our behavioral results: The shorter reaction times for Arabic digits were reflected by shorter peak latencies of the VPP, N250 and P500 components. Contrary to earlier report (Dehaene, 1996), we could not detect strong evidence for N170 latency shift that was inversely related to reaction time. In fact, Dehaene and his colleagues could not replicate this finding in their subsequent study (Pinel et al., 2001). However, we found that the VPP varied as a function of symbol type, with shorter latencies for Arabic digits. Furthermore, the latency shift was also observed in these later components, which might suggest that the early advantage of Arabic digits over Chinese numerals may affect its subsequent processes. Therefore, the symbolic effect on reaction time should be more likely localized to the underlying processes reflected by the VPP component.

According to Dehaene's serial-stage model, number-specific processing occurs during the P2p time window (Dehaene, 1996; Pinel et al., 2001). Alternatively, several studies have detected the numerical distance effect during the N170 time window, which suggest that the number-specific representations are activated prior to P2p component (Libertus et al., 2007; Temple & Posner, 1998). That is to say, the P2p component seems more likely to reflect some general processes rather than the semantic number-specific accessing. Since we found the numerical distance effect already around 170 ms post-stimulus onset, we argued that the number-magnitude representations were activated at or before this timing point. This argument also called into question the number specificity of the IPS, as Pinel et al. (2001) suggested that the source of the P2p component was localized to the IPS.

Many researchers believed that visual word-form representations were stored in the lexicon (Coltheart et al., 2001). Thus, the creation of a lexical system next to a word-meaning system seems more compelling for visual number processing models. Arabic digits and verbal numerals can be decomposed into perceptual features, which activate the corresponding semantic information. The traditional view (Coltheart et al., 2001; Dehaene, 1996) suggested that visual numbers should be processed first at the visual lexicon activating a visual form pattern. The output of this stage addresses its semantic representations. According to the serial-stage model, the semantic number processing is temporally separate from visual form processing. Alternatively, other models suggest that distributed representations (visual form level, phonetic level, and semantic meaning level) are processed in parallel, that is, a processing stage may begin before the previous stage is finished (Bentin & Golland, 2002; Brysbaert, 2005; Campbell, 1994; Seidenberg & McClelland, 1989; Xue et al., 2008). For example, according to Campbell's (1994) multiple encoding view, numbers are simultaneously encoded in multiple ways (Arabic, verbal, and analogue). Number recognition depends on the pattern of co-activation of the different representations in a neural network rather than on the activation of one particular dedicated representation (Brysbaert, 2005). Since we found the numerical distance effect in the N170 time window (on the VPP component), we argued that the specific number magnitude processing might occur earlier than the timing point (mainly the P2p component) that Dehaene's serial-stage model expected. The present results suggested that the specific number magnitude processing was not temporally separate from

the visual identification processing. Thus, the present results seem more likely to support the parallel model rather than the series-stage model of visual number processing.

The above "co-activation" model can explain not only the results observed in this study but also those of previous studies. For example, Damian (2004) demonstrated an interaction between notation and task, with slower naming but faster magnitude judgment latencies for Arabic digits than for English number words. These findings suggested that processing of the two notation formats was asymmetric, with Arabic digits gaining faster access to numerical magnitude representations, but slower access to lexical codes, and the reverse for English number words.

Dehaene (1996) observed the advantage of English verbal numbers over Arabic digits in N170 latency. Interestingly, this inverse relation between N170 latency and RT was replicated in another previous study (see Fig. 2, Plodowski et al., 2003, p. 2047). Under the serial-stage model, this unexpected data pattern could not be explained easily. However, according to the parallel model, it might be explained by the rapid accessing to lexical codes (task-irrelevant) for English verbal numbers.

In summary, the advantage of Arabic digits over verbal numbers should be localized to the underlying processes of the VPP component. The number-magnitude representations are activated at or before 170 ms after onset of printed number stimuli. Our results support the view that the distributed representations of the numbers are simultaneously processed in multiple ways.

5. Conclusion

This study has significant implications for future research in the field of numerical cognition. Our results establish the VPP component as a critical ERP component to report in studies of visual numerals. The Arabic number advantage should be localized to the VPP component. The magnitude information might be accessed at or before the N170/VPP time window (around 170 ms). The N170 and VPP components probably reflect different neural generators, and our results call into question the serial-stage model of visual number processing.

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