

## Perceiving the writing sequence of Chinese characters: An ERP investigation

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### ABSTRACT

The neural dynamics in perceiving well-learned sequences and its modulation by task demand were investigated in this study in which participants were asked to observe stroke-by-stroke display of Chinese characters composed of two radicals while their brain activity was monitored with the event-related potential (ERP) technique. Experiment 1 used an accuracy judgment task that would draw participants' attention to the violation of the writing sequence whereas Experiment 2 required participants to judge the completion of the display and thus the more automatic aspects of sequence processing could be revealed. In Experiment 1, the within-radical boundary reversal produced bilateral posterior N2 enhancement and the cross-boundary reversal elicited a left N2 effect and right posterior N2 reduction on the critical stroke. Both types of reversal elicited P3 effects on the critical stroke and sustained negativity effects on the following stroke, with the size being larger for the cross-boundary reversal. In Experiment 2, in addition to the P3 effects, the within-boundary reversal elicited a left posterior N2 effect and the cross-boundary reversal elicited right posterior N2 reduction on the critical stroke. Moreover, on the following stroke, the cross-boundary reversal elicited a right N2 effect and both types of reversal elicited sustained positivity effects. These findings demonstrate that native Chinese readers use their sequential knowledge to predict upcoming strokes in perceiving the writing of characters and to construct appropriate representations for the action sequence regardless of whether such predictions and constructions are required by the task.

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### Introduction

Many aspects of human behavior involve sequencing skills. We cannot only produce a continuous flow of action, but also extract structural regularities from a series of perceptual events about the action. Such capacities allow us to actively anticipate the upcoming events and to improve the efficiency of action and the perception of action sequence. However, new perceptual input may occasionally deviate from our expectancy and our brain must quickly detect such deviation and construct the right representation. In this study, we investigate the neural dynamics in perceiving the writing sequence of Chinese characters and its modulation by task demand. Implications of our findings for general mechanisms of sequence processing are discussed.

Early studies on sequential processing focus on how sequential knowledge of action or events is learned and represented. An influential paradigm used to investigate the sequential sensorimotor activity is the serial reaction time task or SRTT (Nissen and Bullemer, 1987), in which the participants are asked to react rapidly, by pressing

corresponding buttons, to different locations cued by visual stimuli. After a period of learning, regular sequences result in faster responses compared to random patterns. In variations of the SRTT using the event-related potential (ERP) technique, it has been found that stimuli that violate the sequence rules elicit enhanced N2 (a negativity occurring approximately at about 200 ms post-onset of the stimuli) and P3 (a positivity peaking at about 300 ms post-onset of the stimuli) in participants who became aware of the sequential structures during learning (Eimer et al., 1996; Ferdinand et al., 2008; Schlaghecken et al., 2000). These studies, however, cannot distinguish to what extent the neural activity is elicited by the deviance of stimuli perceived and to what extent this neural activity has been modulated by the demand of action.

Other studies are more concerned with the neural correlates of perceiving sequential events. For instance, Rüsseler and colleagues differentiated perceptual deviants and motor deviants in their SRTT studies (Rüsseler and Rösler, 2000; Rüsseler et al., 2003). The participants were asked to react to stimulus letters with corresponding fingers and every finger was associated with two letters. Perceptual deviants were created by replacing the regular letters used in learning with the alternative letters corresponding to the same finger responses, and motor deviants were created by replacing the critical letters with other letters corresponding to other finger responses. For

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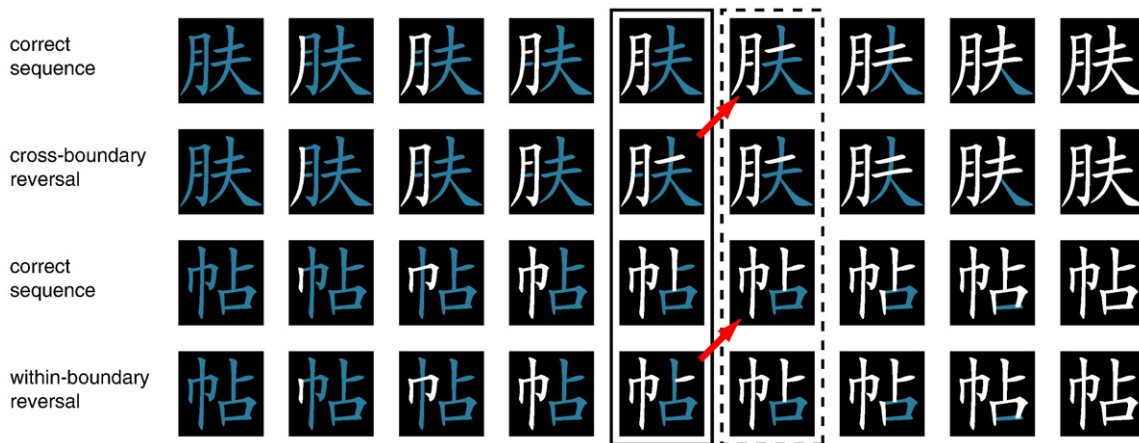
participants who became aware of the sequence structures, both perceptual and motor deviants evoked enhanced N2 but only motor deviants elicited enhanced P3, suggesting that N2 and P3 may have differential sensitivities to deviants at the perceptual and response levels.

Another line of research on sequential processing uses artificial grammar (Reber, 1967), in which the participants are exposed to rule-based sequences of stimuli and are expected to acquire the underlying structure or grammar. They are then asked to make grammaticality judgment to new sequences. Bahlmann et al. (2006) visually presented the participants with sequences of meaningless syllables which were generated on the basis of local transitions (finite-state grammar, FSG) or hierarchical structures (phrase structure grammar, PSG). FSG violations resulted in an early posterior negativity (possibly N2) and a late positivity (possibly P3) relative to grammatical sequences. PSG violations evoked no early negativity but a late positivity whose magnitude varied as a function of the position of violation in the sequence. Carrión and Bly (2007) used auditory letter sequences specified by FSG and found that ungrammatical letters in test sequences generated N2 and P3 effects. Koester and Prinz (2007) also observed an enhanced P3 when visually presented geometrical shapes violated the sequence rules learned earlier.

Most of the above-mentioned studies have used rather abstract or symbolic stimuli, with the sequence rules learned in short times. A few other studies focus on the perception of realistic action or event sequences. When the participants were asked to watch video clips depicting everyday events and to make event plausibility judgment, contextually incongruent information in movie endings (e.g., an electric iron used in place of a knife in a cutting bread scenario) elicited an anterior negativity effect in the 250- to 600-ms time window and a late posterior positivity effect in the 600–1500 ms time window (Sitnikova et al., 2003; Sitnikova et al., 2008). de Bruijn et al. (2007) asked the participants to observe short sequences of pictures depicting steps of everyday actions and to judge whether the execution of action was correct. Execution errors presented by the critical pictures (e.g., using a teapot to water flowers but directing the spout to the outside of the flowerpot) elicited enhanced P3 on the observers. The authors proposed that the P3 effects elicited by deviant sequences might reflect a general monitoring process of unexpected events. Indeed in listening to music, violations of harmonic structures in the music input elicited positivity effects that were suggested to be similar to P3 or P600 (Besson and Faita, 1995; Janata, 1995; Patel et al., 1998; Regnault et al., 2001).

The observation of comparable ERP responses (e.g., P3-like positivities) to sequence deviance in studies using various types of stimuli and experimental paradigms seems to suggest the existence of “generalized” neuro-cognitive mechanisms for sequence processing which involves the prediction of upcoming events in a stimulus stream. In accordance with this idea, some theoretical models of sequence learning and processing postulate abstract and effector-independent (and conceivably domain-general) representation of sequential regularities (e.g., Keele et al., 2003; Schubotz, 2007). The hypothesis of a generalized sequence processing system finds support in some recent functional imaging studies. For instance, the neural correlates of perceiving abstract sequences have been demonstrated to be comparable to those underlying sequential motor planning for action execution (Schubotz and von Cramon, 2002a,b, 2003). In an fMRI study on music perception, Leaver et al. (2009) found that musical expectancies share overlapping neural basis with motor sequence processing, suggesting common predictive mechanisms in both domains. Neural structures belonging to the human motor system (e.g., premotor and supplementary motor areas) have also been reported to be involved in processing everyday event scripts (Krueger et al., 2007; Kuchinke et al., 2009).

Previous studies on the neural correlates of the perception of natural or realistic events, whether daily activity or music, rely on activation of world knowledge or rules that are learnt implicitly. In this study, we investigate ERP responses to the deviance of writing sequence of Chinese characters. Unlike most daily activities or music structure, to an educated native Chinese, the stroke-by-stroke writing of Chinese characters are explicitly taught and well practiced through school education. Modern Chinese uses thousands of different characters, which represent different morphemes or words, but all of them were built on combinations of a finite set of basic strokes (e.g. horizontal, vertical, left-falling, dot, and turning strokes). The stroke order follows consensual principles (e.g. left before right, horizontal before vertical, center vertical before bilateral wings, etc. See Fig. 1 for a demonstration) and is object of a national standard (State Language Commission, 2000). In spite of occasional ambiguities, there are in general strict rules governing the writing sequence of strokes in a character. These rules are even applied in writing pseudo-characters. Unlike alphabetic letters, a stroke in a Chinese character is purely a visuo-spatial component, corresponding to no phonetic, semantic or syntactic features. However, strokes may group together to form semantic and phonetic radicals which may provide clues to the meaning and the pronunciation of the whole character, respectively



**Fig. 1.** Sample stimuli of the experiments. All the stimulus characters had a left–right structure. The strokes of each character were displayed incrementally in white on the background of the whole character in blue. In the reversal conditions, two adjacent strokes in a character were reversed and they belonged to either two different radicals (the cross-boundary reversal) or one single radical (the within-boundary reversal). The critical and following strokes are highlighted by the solid and dashed boxes respectively. The arrows indicate additional comparisons between the deviant strokes in the critical frame (the solid box) and the same, correct strokes in the following frame (the dashed box).

(see Zhou and Marslen-Wilson, 1999a,b for more elaborative description). These characteristics make it feasible for us to examine the neural dynamics in perceiving the writing sequence of Chinese characters in particular and to investigate the neural mechanisms of sequence processing in general.

In this study, we examined the ERP responses elicited by Chinese characters displayed in either correct or reversed stroke order (Fig. 1). The sequence reversal was introduced by swapping two successive strokes in a character and the one that violated the sequence rule served as the critical stroke. We distinguished two types of sequence violation, taking into account the structure of the Chinese character. The characters used in the experiments were all of the left–right structure, with a semantic radical on the left and a phonetic radical on the right. The two strokes involved in reversal were either from two different radicals (i.e., cross-boundary reversal) or from one single radical (within-boundary reversal). Since the former type of reversal extended across the radical boundary, the appearance of the violating stroke, always in the right visual field, should cause attentional shift across space, making the violation easier to be detected. The within-boundary reversal could occur either within the left or the right visual field. Moreover, the whole character was presented before and during the sequential presentation of strokes, to minimize of potential influence of semantic and phonological activation of the whole character or its semantic and phonetic radicals on the neural responses to stroke reversal.

We varied the task demand across two experiments using the same set of stimuli, such that the detection of sequence deviance was either task-relevant (Experiment 1) or less relevant (Experiment 2). In behavioral and neuro-imaging versions of the SRTT, it has been demonstrated that sequence learning may recruit dissociable mechanisms depending on the attentional requirement of the task (e.g., under a single-task or dual-task condition; see Keele et al., 2003 for a review). Similarly, we can hypothesize that the perception of over-learned sequential structures, such as the stroke-by-stroke writing of Chinese characters, may also be modulated by task demand. A limitation of the previous ERP studies on sequence processing, however, is that the participants are often asked to make explicit judgment as to whether a rule embedded in the sequence input is violated or to make immediate motor response to the target. It is not clear whether a deviance from the sequence rule would be automatically detected in a task that does not require the activation of this rule and whether the patterns of neural responses to sequence deviance in different tasks are similar. For instance, most previous studies have reported P3-like effects for sequence deviation. The amplitude, time course and scalp distribution of the P3 component are known to be influenced by task demand (For reviews, see Donchin and Coles, 1988; Polich, 2007). In studies using the oddball paradigm, the task-relevant deviance elicits P3 with a posterior distribution and a relatively longer latency (i.e., P3b) whereas the task-irrelevant deviance evokes P3 with a fronto-central distribution and a shorter latency (P3a; Knight et al., 1989; Squires et al., 1975). By manipulating the task relevancy of stroke reversal in this study, we expect to observe topographic changes of the P3 effect across experiments.

In Experiment 1, the participants were asked to observe the stroke sequence for a delayed judgment on the accuracy of the stroke order. As the stroke reversal was reflected in spatial location change like in SRTT, we hypothesize that it may elicit N2 and P3 effects in ERP responses. Moreover, since P3 is known to be sensitive to stimulus saliency (Johnson, 1986; Pritchard, 1981), it is possible that the cross-boundary reversal would elicit stronger P3, with shorter peak latency, than the within-boundary reversal. In Experiment 2, the participants were asked to judge whether the stroke sequence of each character was written completely or stopped before the end. Here the stroke reversal became less task-relevant and any ERP effects observed on the violating stroke (and the following strokes) may reflect more automatic neuro-cognitive processes of deviance detection. It is

possible that the ERP effects obtained in Experiment 1 might be attenuated in amplitude by the change of task demand. In particular, the task relevancy might shift the scalp distribution of the P3 effects given previous findings from the oddball paradigm (Donchin and Coles, 1988; Knight et al., 1989; Polich, 2007; Squires et al., 1975). More specifically, we hypothesize that the P3 effects in Experiment 2 would have a more anterior localization and a shorter peak latency than those in Experiment 1.

## Experiment 1

### Method

#### Participants

Twenty-two right-handed students from the Southeast University at Nanjing participated in the experiment (11 female, mean age 23 years,  $SD = 1.90$ ). All were native speakers of mandarin Chinese and had normal or corrected-to-normal vision. None of them reported to have neurological or psychiatric disorders. Two participants (one female) were excluded from the ERP analysis for low accuracy in the judgment task. This study was approved by the Academic Committee of the Research Center for Learning Science at the Southeast University.

#### Design and stimuli

The experimental design and sample stimuli are presented in Fig. 1. Two hundred characters were selected as critical stimuli, with one hundred for the cross-boundary reversal and one hundred for the within-boundary reversal. All of them were of the left–right structure with a semantic radical on the left and a phonetic radical on the right. The two sets of characters were matched in terms of character frequency, number of strokes, position of the critical stroke and variety of semantic radicals. The mean and median character frequencies were 109 and 19 per million ( $SD = 272$ ) for the cross-boundary reversal and 140 and 26 per million ( $SD = 318$ ) for the within-boundary reversal (Institute of Language Teaching and Research, 1986). The number of strokes per character varied between 5 and 11, with a mean of 8.89 ( $SD = 1.58$ ), for the cross-boundary reversal and 8.97 ( $SD = 1.60$ ) for the within-boundary reversal.

The position of the critical stroke for the cross-boundary reversal occurred as the first stroke of the right phonetic radical while the corresponding correct stroke occurred as the last stroke of the left semantic radical (see the first box in Fig. 1). That is, the reversed and the correct strokes differed in spatial location across the visual fields. The within-boundary reversal occurred in the same hemifield, equally often in the left or the right hemifield, as the corresponding correct stroke although they differed slightly in spatial location. Each stimulus character comprised one of the 40 different semantic radicals with 2 to 6 strokes and one of the 166 different phonetic radicals with 2 to 9 strokes. Given that semantic radicals are used to indicate the semantic category (i.e., water- or metal-related) and are used more repetitively in different characters, the number of semantic radicals in Chinese is much smaller than the number of phonetic radicals.

The sequence deviation occurred at a variety of stroke positions, preventing the participants from focusing on a particular position in character writing. The stroke positions where the sequence deviation occurred were matched between the within-boundary and cross-boundary reversals. In addition to the critical stimuli, 40 characters with 9 or 10 strokes served as fillers and half of them had reversed sequence at the 7th or 8th stroke. This was to balance the proportions of stimuli that had reversals at different stroke positions.

To determine the stroke sequences of the stimulus characters, we referred to the national standard (State Language Commission, 2000) and discarded characters containing ambiguous stroke sequence as revealed by a pilot study. Sixteen participants, who were not tested for the ERP experiment, were asked to write up, stroke-by-stroke, 360

characters. Any sequences deviant from the national standard were deemed as ambiguous and the characters were then excluded.

#### Procedure

The participants were seated in an electrically shielded and sound-attenuated chamber. They were instructed to watch the stimulus characters displayed in a stroke-by-stroke manner and judge whether it had been correctly written at the end of each trial. The stimuli were presented at the center of a CRT display at 90 cm from the participant. Each trial started with a fixation cross displayed for 600 ms, followed by a blank screen for 600 ms. Then the entire character was displayed in blue on a black background for 1200 ms, allowing the participants to recognize the character before the display of strokes and minimizing the potential influence of semantic and phonological activation of the whole character or its semantic or phonetic radical. The character subtended a visual angle of 2° approximately for both height and width. In the following frames (with duration of 800 ms each and no inter-stimulus interval), the strokes in white were progressively added onto the blue character. Each stroke was displayed entirely at the onset, with no slow motion of stroke writing. The last frame was the character completely in white (see Fig. 1). After that, the participants were prompted by three question marks, with duration of 600 ms and followed by a blank screen of 2000 ms. They were asked to judge, by pressing “yes” or “no” button on the response pad, whether the character was written in the right order.

Four versions of test lists were created using a Latin Square design, with each version having 50 characters each for the within- and cross-boundary reversals and 50 characters each for their corresponding baseline conditions. Together with filler items, the 240 characters in each test list were pseudo-randomized so that no more than three consecutive characters were from the same condition and no more than five consecutive characters were in normal or reversed stroke order. The experiment began with a practice block of 20 characters. The main session was divided into three blocks of 80 characters and participants took a short break after each block. The mean duration of a trial was 10.42 s and the entire experiment lasted about 1.5 h including electrode preparation.

#### EEG recording

The EEGs were recorded with 64 Ag/AgCl electrodes mounted in an elastic cap (NeuroScan Inc., USA) and referenced to the linked bilateral mastoids. The vertical electrooculogram (VEOG) was monitored from electrodes located above and below the left eye and the horizontal electrooculogram (HEOG) from electrodes located at the outer canthus of each eye. Electrode impedances were maintained below 5 k $\Omega$ . The EEG and EOG were amplified by Synamps2 (NeuroScan Inc., USA) using a band-pass filter from DC to 70 Hz and were continuously digitized at 500 Hz.

#### Data analysis

The accuracy rate was computed as the percentage of correct responses. A correct response was defined as “yes” to normal sequences and “no” to reversed sequences in the judgment task. The EEGs were processed offline with NeuroScan Edit 4.3 software (NeuroScan Inc., USA). DC drift was corrected using a method based on Hennighausen et al. (1993). Trials with incorrect responses and those contaminated by ocular or other artifacts (exceeding a threshold of 70  $\mu$ V) were excluded from data analysis, resulting in 78.7% artifact-free trials on average for the critical conditions. Thus, there were on average 41 trials ( $SD=6.62$ ) for the cross-boundary reversal and 39.05 trials ( $SD=6.68$ ) for the corresponding correct sequences; there were 38.45 trials ( $SD=7.07$ ) for the within-boundary reversal and 38.85 trials ( $SD=6.71$ ) for the corresponding correct sequences.

ERPs were computed for each participant and each electrode over an epoch from 200 ms before to 800 ms after the onset of the critical

stroke and over the same period for the following stroke. For the critical stroke, the 200 ms pre-stimulus interval was used for baseline correction. For the following stroke, baseline correction was performed with the 100-ms post-onset EEG activity, so that the expected effects of the critical stroke would not affect the early components on the following stroke and any residual effects on the following strokes would be due to the impact of the processing of the critical stroke upon the processing of the following stroke (Baggio et al., 2008; Hagoort, 2003; Jiang et al., 2009).

Statistical analysis was performed separately for midline electrodes and lateral regions of interest (ROI). Preliminary analyses were conducted to compare the ERP responses in the two baseline conditions. Because they did not differ significantly they were merged to form a single baseline, simplifying the statistical analyses for the whole experiment and allowing direct comparisons between the cross-boundary and the within-boundary reversals. Also, there could be two ways to examine the ERP effects elicited by the experimental manipulation. The first is to compare the deviant stroke with the corresponding stroke at the same frame in the baseline, that is, between strokes in the solid box in Fig. 1. The second is to compare the deviant stroke with the correct stroke in the next frame (i.e., in the dashed box), as indicated by the red arrow in Fig. 1. The first type of comparisons would have all the critical strokes presented at the same time while the second type of comparisons would have identical strokes across conditions. Given that the two strokes (i.e., the one in the solid box and the one in the dashed box) in the baseline conditions elicited very similar ERP responses, these two types of comparisons for the experimental manipulation gave almost identical results. Therefore, in this study we report the results from the first type of analysis. But we do report the outcome of the second type of analysis when it is different from the results of the first.

In repeated-measures ANOVA, the experimental factor “sequence type” (correct sequence vs. cross-boundary reversal vs. within-boundary reversal) was crossed with the factor “electrode” for the midline (Fz vs. Cz vs. Pz) or with “hemisphere” (left vs. right) and “region” (anterior vs. central vs. posterior) for the lateral sites. The voltage of each lateral ROI was the mean amplitude of six electrodes: left anterior (F3, F5, F7, FC3, FC5, FT7); right anterior (F4, F6, F8, FC4, FC6, FT8); left central (C3, C5, T7, CP3, CP5, TP7); right central (C4, C6, T8, CP4, CP6, TP8); left posterior (P3, P5, P7, PO3, PO7, O1); right posterior (P4, P6, P8, PO4, PO8, O2). Based on previous studies on sequence processing and visual inspection of ERP responses two time windows were defined for the analysis of mean amplitudes at the critical stroke: 170–270 ms post-onset for early negativity and early positivity, 300–500 ms and 500–800 ms post-onset for late positivity effects. The stroke following the critical one was analyzed using three time windows: 100–250 ms, 250–450 ms and 450–800 ms post-onset. The Greenhouse–Geisser correction was applied when evaluating effects with more than one degree of freedom in the numerator. In such cases, the uncorrected degrees of freedom, the corrected probability value and the correction factor  $\epsilon$  are reported. For all pairwise comparisons, the probability value was Bonferroni-adjusted. Interpolated topographic maps of the voltage fields were created using the “topoplot” function of the EEGLab package (Delorme and Makeig, 2004).

#### Results

##### Behavioral performance

The accuracy rate in judgment was 88.7% ( $SD=4.8\%$ ) for the collapsed correct sequences, 95.0% ( $SD=4.9\%$ ) for the cross-boundary reversal and 88.5% ( $SD=8.0\%$ ) for the within-boundary reversal. A repeated-measures ANOVA revealed a significant main effect of sequence type,  $F(2, 38) = 13.31$ ,  $p < 0.0001$ ,  $\epsilon = 0.939$ . In pairwise comparisons, the accuracy rate for the cross-boundary reversal was significantly higher than those for the correct sequence ( $p < 0.0005$ )



and the within-boundary reversal ( $p < 0.001$ ). Thus the participants showed the highest sensitivity to the cross-boundary reversal.

*Electrophysiological data*

*The critical stroke.* Fig. 2 presents the ERP waveforms in response to the critical stroke at 9 representative electrodes. Clearly, both types of reversal elicited more positive P3 compared with the correct sequences, with the effect being larger for the cross-boundary than for the within-boundary reversal. In addition, while the within-boundary reversal elicited an early posterior N2 effect at both hemispheres, the cross-boundary reversal elicited a left posterior N2 enhancement and a right posterior N2 reduction (see also Fig. 3).

For the mean amplitudes in the 170–270 ms time window, the midline analysis with sequence type (correct sequence vs. cross-boundary reversal vs. within-boundary reversal) and electrode (Fz vs. Cz vs. Pz) as two within-participant factors revealed a significant interaction between the two factors,  $F(4, 76) = 4.24, p = 0.01, \epsilon = 0.662$ , with the effect of sequence type being significant at Pz only,  $F(2, 38) = 3.46, p < 0.05, \epsilon = 0.963$ . The contrast between the cross-boundary and within-boundary showed a marginal difference ( $1.26 \mu V, p = 0.089$ ). No other effects were found. The lateral analysis with sequence type, hemisphere, and region as three-within participant factors revealed a significant main effect of sequence type,  $F(2, 38) = 9.50, p = 0.001, \epsilon = 0.953$ , a two-way interaction between sequence type and hemisphere,  $F(2, 38) = 22.72, p < 0.0001, \epsilon = 0.757$ , a two-way interaction between sequence type and region,  $F(4, 76) = 6.22, p < 0.005, \epsilon = 0.645$ , and a three-way interaction

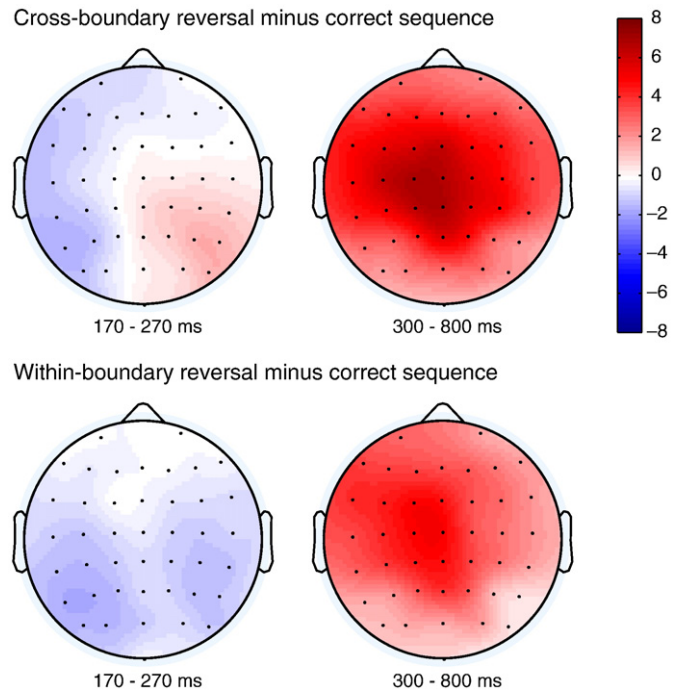


Fig. 3. Scalp topographies based on the difference waves between the reversed and correct sequences on the critical strokes in Experiment 1.

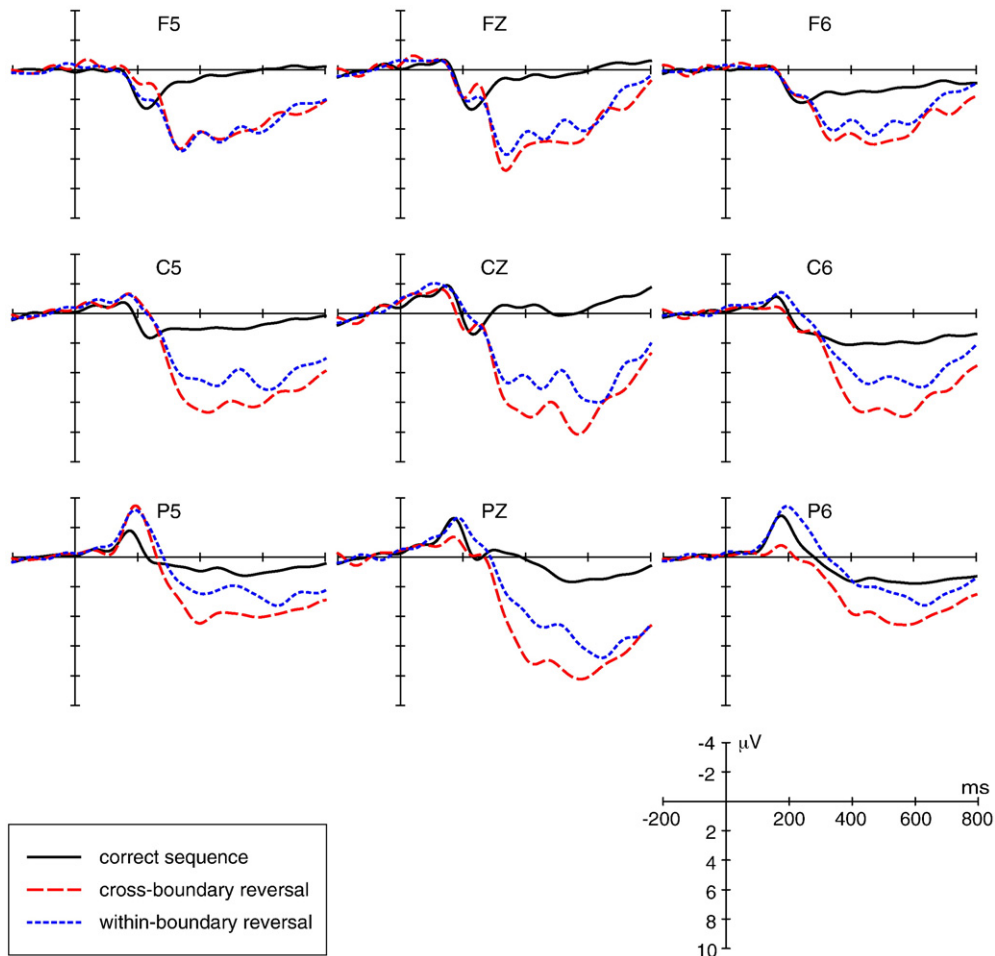


Fig. 2. Grand average ERPs at 9 exemplar electrodes in response to the critical stroke for the experimental conditions of Experiment 1.

between sequence type and hemisphere and region,  $F(4, 76) = 11.07$ ,  $p < 0.0001$ ,  $\epsilon = 0.678$ . Detailed comparisons showed that the cross-boundary reversal, compared with the correct sequences, elicited a widespread negativity (N2) effect in the left hemisphere (see Fig. 3): left anterior ( $-1.12 \mu\text{V}$ ,  $p < 0.05$ ), left central ( $-1.29 \mu\text{V}$ ,  $p < 0.01$ ), left posterior ( $-1.37 \mu\text{V}$ ,  $p < 0.0005$ ). In contrast, the cross-boundary reversal showed only an N2 reduction at the right posterior region ( $1.20 \mu\text{V}$ ,  $p < 0.01$ ). The contrast between the within-boundary reversal and the correct sequences showed that parietal and posterior negativity (N2) effects were present on both hemispheres and stronger on the left than on right hemisphere (Fig. 3): left central ( $-1.24 \mu\text{V}$ ,  $p < 0.01$ ), left posterior ( $-1.51 \mu\text{V}$ ,  $p < 0.0001$ ), right central ( $-1.09 \mu\text{V}$ ,  $p < 0.005$ ) and right posterior ( $-1.14 \mu\text{V}$ ,  $p < 0.005$ ) regions.

For the mean amplitudes in the 300–500 ms time window, the midline analysis revealed a significant main effect of sequence type,  $F(2, 38) = 50.66$ ,  $p < 0.0001$ ,  $\epsilon = 0.761$ . Both types of reversal (cross-boundary,  $5.81 \mu\text{V}$ ; within-boundary:  $4.19 \mu\text{V}$ ) were more positive than the correct sequences ( $0.14 \mu\text{V}$ ). The cross-boundary reversal differed significantly from the within-boundary reversal ( $p < 0.005$ ). The interaction between sequence type and electrode was significant,  $F(4, 76) = 5.14$ ,  $p < 0.001$ ,  $\epsilon = 0.582$ . It is clear from Fig. 3 that the P3 effects were the strongest on fronto-central sites. The lateral analysis revealed also a significant main effect of sequence type,  $F(2, 38) = 52.03$ ,  $p < 0.0001$ ,  $\epsilon = 0.808$ , with ERP responses becoming increasingly more positive over the correct sequences ( $1.10 \mu\text{V}$ ), the within-boundary reversal ( $3.10 \mu\text{V}$ ) and the cross-boundary reversal ( $4.41 \mu\text{V}$ ). Moreover, interactions between sequence type and hemisphere and between sequence type and region were significant,  $F(2, 38) = 16.73$ ,  $p < 0.0001$ ,  $\epsilon = 0.977$ , and  $F(4, 76) = 24.64$ ,  $p < 0.0001$ ,  $\epsilon = 0.517$ , respectively. These interactions indicate that the positivity effects differed in magnitudes across hemispheres and regions. Separate ANOVAs showed that the effects tended to be larger at left anterior-central sites (see Fig. 3).

For the mean amplitudes in the 500–800 ms time window, we found, in the midline analysis, a significant main effect of sequence type,  $F(2, 38) = 45.03$ ,  $p < 0.0001$ ,  $\epsilon = 0.774$ . The cross-boundary reversal ( $5.44 \mu\text{V}$ ) and within-boundary reversal ( $4.23 \mu\text{V}$ ) elicited more positive ERPs than the correct sequences ( $0.20 \mu\text{V}$ ). The cross-boundary reversal differed also significantly from the within-boundary reversal ( $p < 0.05$ ). The interaction between sequence type and electrode was significant,  $F(4, 76) = 9.36$ ,  $p < 0.0001$ ,  $\epsilon = 0.768$ . As evidenced in Fig. 3, the positivity effects had a centro-parietal maximum. For the lateral regions, there was a significant main effect of sequence type,  $F(2, 38) = 45.28$ ,  $p < 0.0001$ ,  $\epsilon = 0.852$ . The ERP responses to the cross-boundary reversal ( $4.34 \mu\text{V}$ ) and the within-boundary reversal ( $3.15 \mu\text{V}$ ) were more positive than those of the correct sequences ( $1.04 \mu\text{V}$ ). In addition, we found significant two-way interactions between sequence type and hemisphere and between sequence type and region,  $F(2, 38) = 8.53$ ,  $p = 0.0001$ ,  $\epsilon = 0.896$ , and  $F(4, 76) = 15.37$ ,  $p < 0.0001$ ,  $\epsilon = 0.599$ . The three-way interaction between sequence type, hemisphere, and region was marginally significant,  $F(4, 76) = 3.15$ ,  $p < 0.05$ ,  $\epsilon = 0.621$ . As in the 300–500 ms time windows, the positivity effects of sequence reversal were relatively stronger at left anterior-central sites (see Fig. 3).

It appears in Fig. 2 that, in the frontal regions, the ERP responses to the two types of reversal showed negative deflections in the 220–260 ms time window. These effects were very likely a variant of the feedback-related negativity (FRN; Gehring and Willoughby, 2002; Holroyd and Coles, 2002; Holroyd, 2004; Miltner et al., 1997; Yu and Zhou, 2006a,b). Mean amplitudes in this time window were computed and entered into ANOVA, with sequence type (correct sequence vs. cross-boundary reversal vs. within-boundary reversal) and electrode (F3, F1, Fz, F2, F4, FC3, FC1, FCz, FC2, FC4) as two within-participant factors. Although the FRN effect did not reach significance when the strokes from the same frame (i.e., the solid box in Fig. 1)

were compared,  $F(2, 38) = 1.98$ ,  $p = 0.163$ ,  $\epsilon = 0.789$ , it was significant when the critical strokes in the two types of reversal were compared with the same strokes in the next frame in the baseline condition,  $F(2, 38) = 4.51$ ,  $p < 0.05$ ,  $\epsilon = 0.723$ . Both the cross-boundary reversal ( $1.05 \mu\text{V}$ ) and the within-boundary reversal ( $1.53 \mu\text{V}$ ) were less positive than the baseline ( $2.82 \mu\text{V}$ ),  $p < 0.05$  and  $p < 0.1$  respectively after Bonferroni correction.

*The following stroke.* Fig. 4 presents the ERP responses elicited by the stroke following the critical one, after the 100-ms post-onset baseline correction. This baseline correction was conducted on the assumption that the ERP effects elicited by the critical stroke would not affect the early components elicited by the following stroke. Any residual effects observed on the following stroke would be due to the interaction between sequential reversal detected on the critical stroke and the presentation of the following stroke, rather than deviance detection alone. In other words, these residual effects may reflect neuro-cognitive processes that aim to rectify the deviance, i.e., the second-pass processing (Baggio et al., 2008; Hagoort, 2003; Jiang et al., 2009).

Apparently, compared to the correct sequence, both types of reversal elicited widespread and sustained negativities starting from 100 ms and extending beyond 800 ms post-onset of the stroke. The two types of reversal also differed in an early time window (100–250 ms) encompassing N2 and in a later time window (450–800 ms). Separate analyses were conducted to confirm the above observations.

For the mean amplitudes in the 100–250 ms time window, the midline analysis revealed a significant main effect of sequence type,  $F(2, 38) = 41.90$ ,  $p < 0.0001$ ,  $\epsilon = 0.903$ , and an interaction between sequence type and electrode,  $F(4, 76) = 4.06$ ,  $p < 0.05$ ,  $\epsilon = 0.459$ . The N2 responses were increasingly negative over the correct sequences ( $0.83 \mu\text{V}$ ), the within-boundary reversal ( $-0.57 \mu\text{V}$ ) and the cross-boundary reversal ( $-2.05 \mu\text{V}$ ). The lateral analysis revealed also a significant main effect of sequence type,  $F(2, 38) = 39.06$ ,  $p < 0.0001$ ,  $\epsilon = 0.954$ , and interactions between sequence type and hemisphere,  $F(2, 38) = 19.54$ ,  $p < 0.0001$ ,  $\epsilon = 0.960$ , between sequence type and region,  $F(4, 76) = 15.43$ ,  $p < 0.0001$ ,  $\epsilon = 0.566$ , and between sequence type, hemisphere and region,  $F(4, 76) = 5.90$ ,  $p < 0.005$ ,  $\epsilon = 0.611$ . It is clear from Fig. 4 that the N2 responses were increasingly negative over the correct sequences ( $0.31 \mu\text{V}$ ), the within-boundary reversal ( $-0.53 \mu\text{V}$ ) and the cross-boundary reversal ( $-1.38 \mu\text{V}$ ); moreover, the differences between conditions were stronger on the right than on the left hemisphere and were the smallest in the left posterior regions.

For the mean amplitudes in the 250–450 ms time window, the midline analysis revealed a significant main effect of sequence type,  $F(2, 38) = 10.26$ ,  $p < 0.001$ ,  $\epsilon = 0.865$ , and an interaction between sequence type and electrode,  $F(4, 76) = 5.83$ ,  $p < 0.005$ ,  $\epsilon = 0.577$ . Both types of reversal (cross-boundary,  $-0.99 \mu\text{V}$ ; within-boundary,  $-1.13 \mu\text{V}$ ) differed significantly from the correct sequences ( $1.31 \mu\text{V}$ ). The lateral analysis revealed also a significant main effect of sequence type,  $F(2, 38) = 10.18$ ,  $p = 0.0005$ ,  $\epsilon = 0.893$ , and an interaction between sequence type and region,  $F(4, 76) = 5.67$ ,  $p < 0.005$ ,  $\epsilon = 0.648$ . The two types of reversal (cross-boundary,  $0.19 \mu\text{V}$ ; within-boundary,  $0.16 \mu\text{V}$ ) were less positive than the correct sequences ( $1.56 \mu\text{V}$ ) but were not significantly different from each other. Thus, unlike the ERP responses in the earlier time window, the two types of reversal did not differ from each other although both of them were more negative than the correct sequences.

For the mean amplitudes in the 450–800 ms time window, the midline analysis revealed a significant main effect of sequence type,  $F(2, 38) = 20.68$ ,  $p < 0.0001$ ,  $\epsilon = 0.885$ , and an interaction between sequence type and electrode,  $F(4, 76) = 5.37$ ,  $p = 0.005$ ,  $\epsilon = 0.607$ . Both types of reversal (cross-boundary:  $-1.96 \mu\text{V}$ ; within-boundary:  $-1.56 \mu\text{V}$ ) differed significantly from the correct sequences ( $1.30 \mu\text{V}$ ) although the difference between them did not reach significance. The lateral analysis revealed a significant main effect of sequence type,  $F$

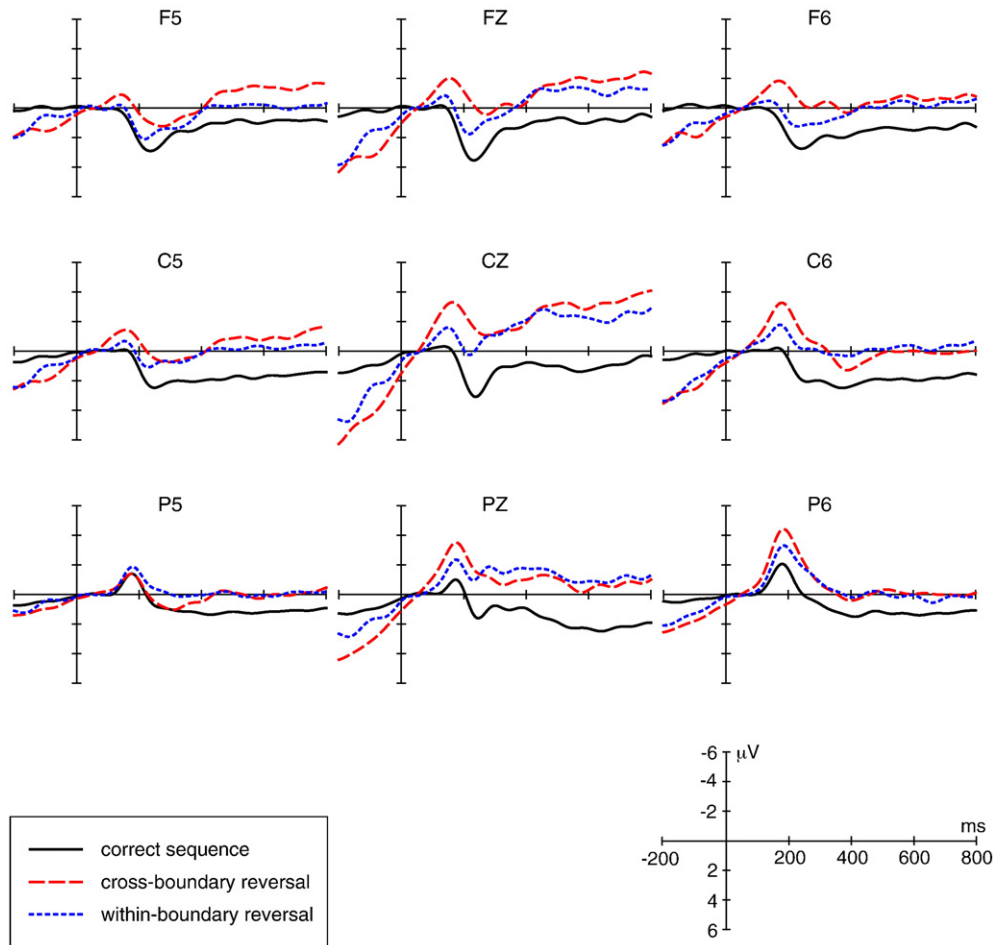


Fig. 4. Grand average ERPs at 9 exemplar electrodes in response to the stroke displays following the critical ones in Experiment 1.

(2, 38) = 17.50,  $p < 0.0001$ ,  $\epsilon = 0.958$ , and interactions between sequence type and hemisphere,  $F(2, 38) = 3.68$ ,  $p < 0.05$ ,  $\epsilon = 0.879$ , and between sequence type and region,  $F(4, 76) = 5.21$ ,  $p < 0.01$ ,  $\epsilon = 0.562$ . The ERP responses for both types of reversal (cross-boundary:  $-0.44 \mu\text{V}$ ; within-boundary:  $-0.01 \mu\text{V}$ ) were significantly more negative than for the correct sequences ( $1.39 \mu\text{V}$ ). The difference between the two types of reversal was also significant in the left anterior ( $-1.19 \mu\text{V}$ ,  $p < 0.01$ ) and left central ( $-0.92 \mu\text{V}$ ,  $p < 0.05$ ) regions.

### Discussion

In judging the correctness of Chinese character writing sequence, the observers showed, on the critical stroke, bilateral posterior N2 for the within-boundary reversal and left posterior N2 and right posterior N2 reduction for the cross-boundary reversal, in addition to the P3 effects for both types of reversal. Moreover, they showed sustained negativity effects, starting from 100 ms post-onset of the following stroke, compared with the baseline condition. In the following paragraphs, we discuss the neurocognitive processes underlying these findings on the critical and the following strokes respectively.

#### Early effects on the critical stroke

The N2 effects have been suggested to reflect a “conscious” detection of stimulus deviation during sequence processing (Eimer et al., 1996; Rüsseler et al., 2003; Rüsseler and Rösler, 2000). This idea would also hold for the present experiment as our participants must have acquired explicit knowledge of stroke sequences through school teaching. However, our results show subtle differences from previous

studies in terms of scalp distribution of the N2 effects. Although most previous works reported only the midline analysis (Eimer et al., 1996; Rüsseler and Rösler, 2000; Schlaghecken et al., 2000), recent studies did analyze the whole scalp (Bahlmann et al., 2006; Carrión and Bly, 2007; Ferdinand et al., 2008; Rüsseler et al., 2003) and revealed N2 effects at centro-parietal or posterior regions. While the N2 effect for the within-boundary reversal was very similar to those in Bahlmann et al. (2006) and Carrión and Bly (2007) with a bilateral, posterior distribution, the ERP responses in the same time window for the cross-boundary reversal showed a unique pattern, with a negative effect on the left hemisphere but a positive effect (or N2 reduction) on the right hemisphere, compared with the baseline. Such topography might reflect visuospatial properties of the Chinese characters used as experimental stimuli. As the critical stroke causing the cross-boundary reversal was always displayed to the right visual field while the expected stroke (i.e., the stroke that preceded the deviant stroke in the correct sequence) should be in the left visual field (see Fig. 1), attention had to be shifted from the expected position to the location of the deviant stroke. The reduction of N2 on the posterior part of the right hemisphere may reflect the disengagement of attention from the expected position while the increase of N2 on the posterior part of the left hemisphere may reflect the engagement of attention on the deviant stroke in the right hemifield. The N2 effect of the within-boundary reversal had a bilateral posterior distribution and was less significant at the midline. This effect may also reflect visual attention allocated to the reversed strokes.

The frontal FRN effect in the 220–260 ms time window strongly suggests that the participants actively anticipated the upcoming strokes of the writing sequence. When this expectancy was violated,

the negative deflection was generated. This finding is consistent with earlier studies suggesting that the FRN reflects the coding of prediction error (Hajcak et al., 2007; Holroyd and Coles, 2002). This prediction error can be defined not only in terms of the valence of the outcome but also in terms of whether the outcome fits the pre-established, non-valenced expectancy (Wu and Zhou, 2009). For example, in a monetary gambling task, Wu and Zhou (2009) found that the FRN is sensitive not only to reward valence (i.e., winning or losing money), but also to expectancy towards reward magnitude, with the violation of expectancy, which is built on the basis of a previous cue, eliciting more negative-going FRN. In a task in which the participants were presented with the result of simple arithmetic addition, e. g., “3 + 4 = ?”, compared with the correct result, an incorrect result (e.g., “8”) would elicit the negative deflection in the 250–300 ms time window (Wang et al., 2000). Together with the FRN effect in this experiment, these findings suggest that the FRN may reflect the detection of conflict between expectancy and the actual outcome, irrespective of on what attribute the expectancy is built.

### *P3 effects on the critical stroke*

The late P3 effects observed for the two types of reversal are consistent with previous studies on sequence processing (e.g., Bahlmann et al., 2006; Carrión and Bly, 2007; Eimer et al., 1996; Ferdinand et al., 2008; Rüsseler et al., 2003; Rüsseler and Rösler, 2000; Schlaghecken et al., 2000). The cross-boundary reversal engendered better behavioral performance and stronger P3 effect than the within-boundary reversal, suggesting that these positivities were sensitive to the manipulation of stimulus saliency (Johnson, 1986; Pritchard, 1981). Thus the P3 effects observed may have similar functions as those in the oddball tasks in which the P3 component is usually stronger for the deviant or unexpected items than for the standard stimuli (Donchin and Coles, 1988). This P3 effect in the oddball paradigm has been generally interpreted as reflecting the reorienting of attention to significant stimuli and the subsequent updating of working memory (Folstein and Van Petten, 2008; Polich, 2007). By analogy, the P3 effects here may reflect the attentional processes related to the detection of stimulus input which is deviant from the expectancy built upon the existing knowledge about the writing sequence of specific Chinese characters. The stronger P3 effect for the cross-boundary reversal than for the within-boundary reversal may simply reflect the degree of deviation from expectancy towards the writing sequence.

### *Sustained negativities on the following stroke*

An unexpected finding in this experiment was the sustained negativities associated with both types of reversal on the stroke immediately following the critical frame (Fig. 4). Again, the more salient cross-boundary reversal elicited stronger effects than the within-boundary reversal. Unlike the early negativities on the critical stroke, which were stronger on the left hemisphere, the early negativity effects on the following stroke were stronger on the right hemisphere. Although previous ERP studies on sequence processing did not report brain response to items following the deviants, careful inspection of the ERP plots from several studies (Bahlmann et al., 2006; Carrión and Bly, 2007; Rüsseler et al., 2003; Rüsseler and Rösler, 2000) suggests that the deviance-related positivities reported by the authors might be followed by negative slow waves.

Jiang et al. (2009) directly compared three views concerning the functional significance of sustained negativity in language processing. The first hypothesis is that the negativity may reflect the retention of violation information in working memory for the sake of the delayed judgment task. The second view associates the sustained negativity with the inhibition of inappropriate representation or response tendency. The third proposal assumes that the negativity may index a second-pass reinterpretation process following the detection of linguistic incongruity. In Jiang et al. (2009), the participants were

asked to read sentences for delayed judgment of semantic plausibility or mere comprehension. In the two experiments requiring plausibility judgment, the authors observed a sustained negativity effect for the violation of universal quantifier (i.e., *all, every*) on the word following the quantifier, whether the following word was a verb critical for the interpretation of the quantifier or an adverb irrelevant to the interpretation. This finding ruled out the inhibition account. Moreover, they did not observe the negativity effect on words following the verb or adverb, suggesting the memory retention hypothesis cannot stand either. In the present experiment, the sustained negativity effects occurred also on the stroke immediately following the critical one and this effect disappeared on the second stroke after the critical one (not reported here). We would like to agree with Jiang et al. (2009) and suggest that the sustained negativity observed here reflects a second-pass processing after coming across stimulus input violating sequence expectancy. After detecting the deviance of stimulus input, the participants may engage in a process of reconstructing the correct representation, trying to put the deviant stroke back into its normal order. This effortful operation would result in sustained negativities, with the effects larger for the cross-boundary than within-boundary reversal.

## **Experiment 2**

In Experiment 1, the ERP effects on the critical stroke and on the immediate following stroke were observed when the participants were asked explicitly to judge whether the writing sequence was deviant from the normal practice. It is not clear to what extent such patterns of ERP effects are modulated by task demand. In past studies on sequence processing, task relevance has not been systematically manipulated. Nonetheless, as suggested by studies using the oddball paradigm (Donchin and Coles, 1988; Folstein and Van Petten, 2008; Polich, 2007), the ERP components associated with sequence deviance, such as N2 and P3, may be influenced by the task relevancy. Experiment 2 was thus conducted with the same set of stimuli as Experiment 1 but with a judgment task that does not necessarily require the activation of knowledge about the writing sequence of Chinese characters.

The new task required the participants to judge whether a writing sequence was completed or stopped before the last stroke. In this task, attentional resources should have been directed to the completion of writing, rather than to detecting whether a deviant of writing sequence has occurred. Thus any ERP effects observed on the critical stroke and/or on the following stroke should reflect more automatic processes related to sequence processing. Although we expected to observe patterns of brain activity similar to those in Experiment 1, the ERP effects could be generally weaker than those in the previous experiment, given that the participants were less likely to actively anticipate the upcoming stroke.

## *Method*

### *Participants*

Eighteen healthy, right-handed students from Peking University (Beijing), who were not tested for Experiment 1, participated in this experiment (10 female, mean age 21.33 years,  $SD = 1.53$ ). All were native speakers of mandarin Chinese and had normal or corrected-to-normal vision. None of them reported to have neurological or psychiatric disorders. Two participants (one female) were excluded from the ERP data analysis due to excessive artifacts.

### *Stimuli and procedure*

The same stimuli and similar procedures as Experiment 1 were used, except that for half of the stimulus characters, the display of the writing sequence was interrupted at a randomly chosen frame after the critical, deviant stroke. Three question marks were then presented



to prompt the participants to judge whether the stroke sequence was completed or interrupted by that time. The position of the reversal for critical strokes was the same as in Experiment 1.

#### EEG recording and data analysis

The same parameters of EEG recording as those in Experiment 1 were used except that another model of the amplifier (Synamps) for the NeuroScan system was used. The judgment accuracy rate was computed as the percentage of correct responses which were defined as “yes” to completed sequences and “no” to interrupted sequences. The rejection of incorrect and contaminated trials resulted in 84.4% artifact-free trials for the critical conditions (on average, for the cross-boundary reversal, 42.19 trials ( $SD = 6.27$ ) of correct sequences, 42.88 trials ( $SD = 6.32$ ) of reversed sequences; for the within-boundary reversal, 42 trials ( $SD = 6.90$ ) of correct sequences, 43 trials ( $SD = 5.66$ ) of reversed sequences). The data analyses followed Experiment 1 but with modified time windows: 180–230 ms, 300–500 ms and 500–700 ms post-onset of the critical strokes; 100–250 ms, 250–500 ms and 500–700 ms post-onset of the following strokes.

#### Results

##### Behavioral performance

The accuracy rate of the judgment was very high for all conditions (correct sequence, 97.9%,  $SD = 2.4\%$ ; cross-boundary reversal, 98.5%,  $SD = 2.6\%$ ; within-boundary reversal, 98.8%,  $SD = 2.0\%$ ). No significant differences were found between the conditions. At the end of experimental session, the participants were asked whether they had

noticed anything special during the experiment. All of them reported to have noticed the reversal of strokes in some of the trials.

##### Electrophysiological data

**The critical stroke.** Fig. 5 presents the grand average ERPs on the critical strokes in Experiment 2. Apparently, the effect of stroke reversal was mainly reflected as the enhanced P3 and possibly late positivity. A left posterior N2 effect for the within-boundary reversal and a right posterior N2 reduction for the cross-boundary reversal were also evident.

For the mean amplitudes during 180–230 ms post-onset, the midline analysis with sequence type (correct sequence vs. cross-boundary reversal vs. within-boundary reversal) and electrode (Fz vs. Cz vs. Pz) as two within-participant factors revealed only a significant interaction between sequence type and electrode,  $F(4, 60) = 4.65$ ,  $p = 0.01$ ,  $\epsilon = 0.638$ . In separate analyses for different electrodes, the effect of sequence type reached significance at Pz only,  $F(2, 30) = 5.43$ ,  $p < 0.05$ ,  $\epsilon = 0.789$ , where the cross-boundary reversal ( $-0.21 \mu\text{V}$ ) was less negative than the correct sequence ( $-1.32 \mu\text{V}$ ) and the within-boundary reversal ( $-1.61 \mu\text{V}$ ). The lateral analysis revealed a significant main effect of sequence type,  $F(2, 60) = 4.68$ ,  $p < 0.05$ ,  $\epsilon = 0.814$ , and interactions between sequence type and hemisphere,  $F(2, 30) = 7.42$ ,  $p < 0.005$ ,  $\epsilon = 0.989$ , between sequence type and region,  $F(4, 60) = 4.07$ ,  $p < 0.05$ ,  $\epsilon = 0.589$ , and between type, hemisphere and region,  $F(4, 60) = 7.33$ ,  $p < 0.005$ ,  $\epsilon = 0.448$ . As shown in Fig. 6, compared to the correct sequences, the ERP responses to the cross-boundary reversal were less negative in the right

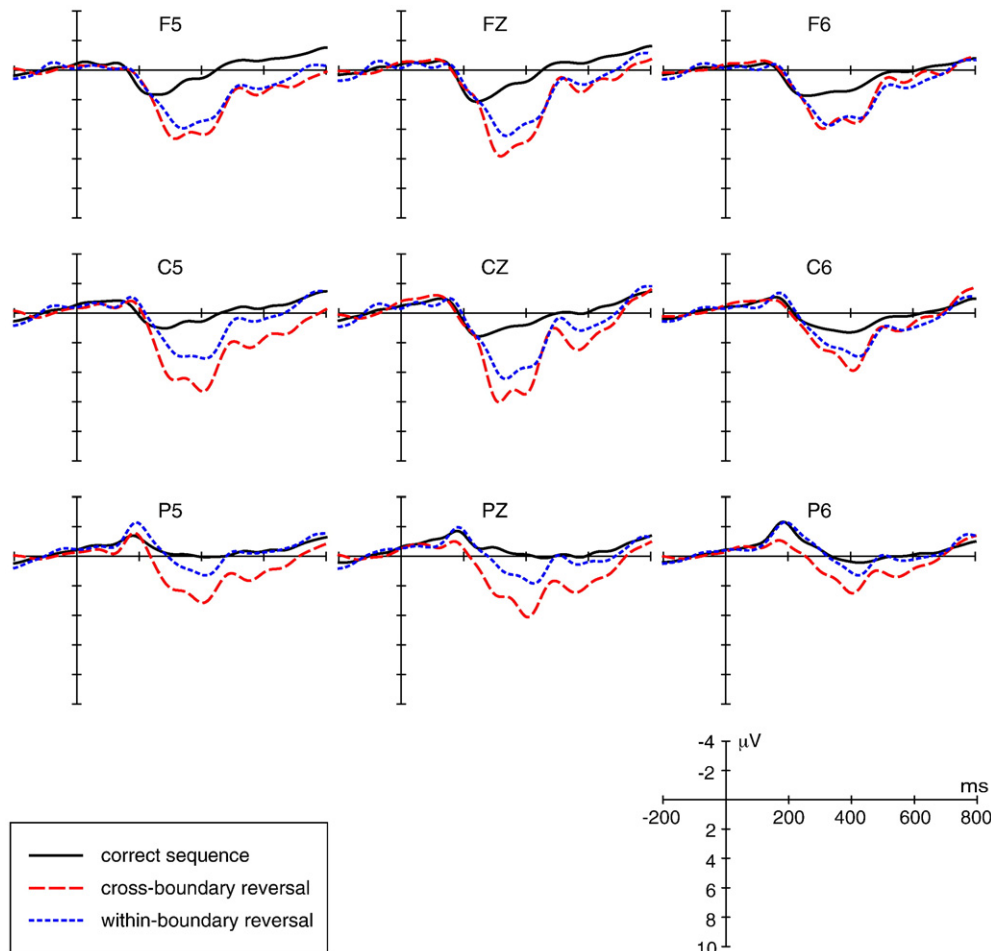
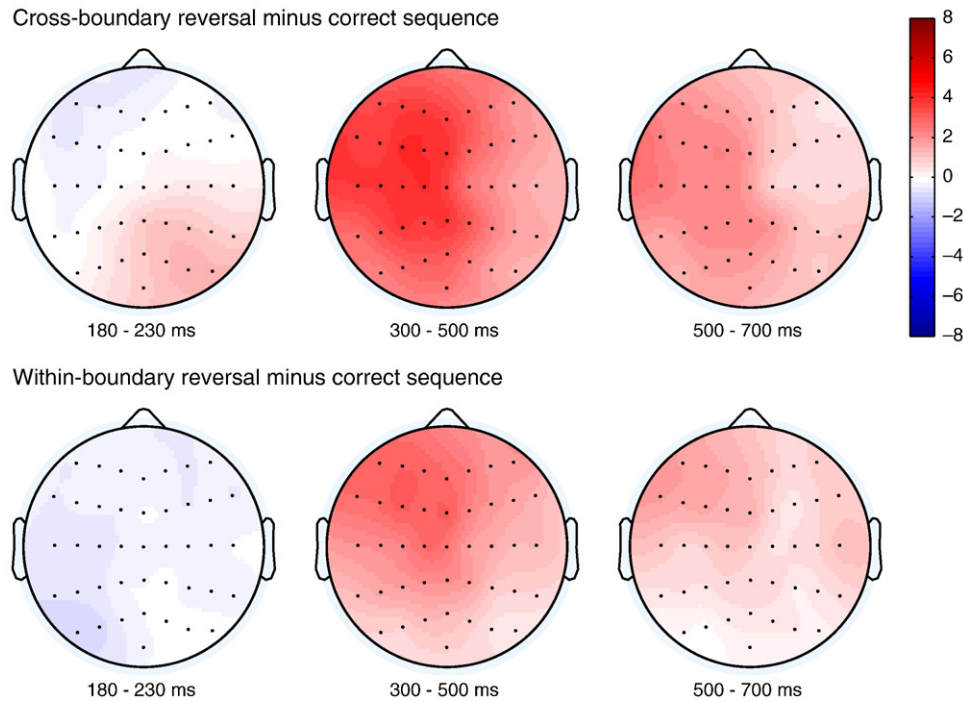


Fig. 5. Grand average ERPs at 9 exemplar electrodes in response to the critical stroke for the experimental conditions of Experiment 2.



**Fig. 6.** Scalp topographies based on the difference waves between the reversed and correct sequences on the critical strokes in Experiment 2.

posterior region (mean difference = 1.23  $\mu\text{V}$ ,  $p = 0.001$ ) and the ERP responses to the within-boundary reversal were more negative in the left posterior region (mean difference =  $-1.53 \mu\text{V}$ ,  $p < 0.01$ ).

For the mean amplitudes in the 300–500 ms time window, the midline analysis revealed a significant main effect of sequence type,  $F(2, 30) = 16.68$ ,  $p < 0.0001$ ,  $\epsilon = 0.752$ , and an interaction between sequence type and electrode,  $F(4, 60) = 3.56$ ,  $p < 0.05$ ,  $\epsilon = 0.533$ . The ERP responses were increasingly positive over the correct sequence (0.38  $\mu\text{V}$ ), the within-boundary reversal (2.59  $\mu\text{V}$ ) and the cross-boundary reversal (3.80  $\mu\text{V}$ ). The lateral analysis revealed a significant main effect of sequence type,  $F(2, 30) = 11.86$ ,  $p = 0.0005$ ,  $\epsilon = 0.812$ , and interactions between sequence type and hemisphere,  $F(2, 30) = 6.43$ ,  $p = 0.01$ ,  $\epsilon = 0.700$ , between sequence type and region,  $F(4, 60) = 7.68$ ,  $p < 0.005$ ,  $\epsilon = 0.482$ , and between sequence type, hemisphere and region,  $F(4, 60) = 3.51$ ,  $p < 0.05$ ,  $\epsilon = 0.472$ . The ERP responses were increasingly positive over the correct sequences (0.62  $\mu\text{V}$ ), the within-boundary reversal (1.92  $\mu\text{V}$ ) and the cross-boundary reversal (2.85  $\mu\text{V}$ ). It is evident in Fig. 6 that the positivity effects were relatively stronger on the left hemisphere than on the right hemisphere and were stronger at frontal and central regions than at posterior regions.

In the 500–700 ms time window, the positivity effects of stroke reversal faded rapidly. The midline analysis revealed only a marginally significant main effect of sequence type,  $F(2, 30) = 3.67$ ,  $p = 0.061$ ,  $\epsilon = 0.652$ . Only the cross-boundary reversal differed reliably from the correct sequence with an effect of 1.77  $\mu\text{V}$  ( $p = 0.001$ ). The lateral analysis revealed only marginally significant interactions between sequence type and region,  $F(4, 60) = 3.00$ ,  $p = 0.074$ ,  $\epsilon = 0.433$ , and between sequence type, hemisphere and region,  $F(4, 60) = 3.85$ ,  $p = 0.053$ ,  $\epsilon = 0.334$ . In separate analysis, the effect of sequence type was significant only in the left anterior,  $F(2, 30) = 7.59$ ,  $p < 0.01$ ,  $\epsilon = 0.739$ , and left central regions,  $F(2, 30) = 8.34$ ,  $p < 0.01$ ,  $\epsilon = 0.669$ . The difference between the cross-boundary reversal and the correct sequence reached significance in the left anterior (2.10  $\mu\text{V}$ ,  $p = 0.0001$ ) and left central (2.10  $\mu\text{V}$ ,  $p < 0.0001$ ) regions whereas the contrast between within-boundary reversal and the correct sequence was marginally significant in the left anterior region (1.68  $\mu\text{V}$ ,  $p = 0.054$ ).

*The following stroke.* Fig. 7 presents the ERP responses to stroke displays immediately following the deviant strokes. In comparison with the baseline, the cross-boundary reversal induced early negative enhancement, especially on the right hemisphere. Both types of reversal engendered sustained positivities, with the cross-boundary reversal being more positive than the within-boundary reversal.

For the mean amplitudes in the 100–250 ms time window, the midline analysis revealed a significant main effect of sequence type,  $F(2, 30) = 5.69$ ,  $p = 0.01$ ,  $\epsilon = 0.782$ , and a marginally significant interaction between sequence type and electrode,  $F(4, 60) = 3.06$ ,  $p = 0.060$ ,  $\epsilon = 0.515$ . This interaction was mainly due to the significant contrast between the two types of reversal at Fz and Cz ( $p < 0.05$ ). The lateral analysis revealed a significant interaction between sequence type and hemisphere ( $F(2, 30) = 6.34$ ,  $p < 0.05$ ,  $\epsilon = 0.620$ ) and a marginally significant main effect of sequence type,  $F(2, 30) = 3.23$ ,  $p = 0.073$ ,  $\epsilon = 0.718$ , as well as a marginally significant interaction between sequence type and region,  $F(4, 60) = 2.97$ ,  $p = 0.092$ ,  $\epsilon = 0.328$ . These interactions were due to the N2 enhancement elicited by the cross-boundary reversal ( $-0.86 \mu\text{V}$ ) on the right hemisphere compared with the correct sequences (0.13  $\mu\text{V}$ ) and the within-boundary reversal (0.19  $\mu\text{V}$ ).

In the following 250–500 ms time window, we found a marginally significant main effect of sequence type on the midline electrodes,  $F(2, 30) = 3.62$ ,  $p = 0.054$ ,  $\epsilon = 0.765$ , and at the lateral sites,  $F(2, 30) = 3.33$ ,  $p = 0.070$ ,  $\epsilon = 0.704$ , and a weak interaction between sequence type and region,  $F(4, 60) = 2.52$ ,  $p = 0.093$ ,  $\epsilon = 0.539$ . The two types of reversal elicited more positive ERP responses compared with the baseline, and these effects tended to be larger in the centro-posterior regions. In the 500–700 ms time window, there was only a significant interaction between sequence type and hemisphere,  $F(2, 30) = 5.27$ ,  $p < 0.05$ ,  $\epsilon = 0.541$ . Further analyses, however, did not reveal interesting results (see Fig. 7).

#### Discussion

The knowledge of writing sequence is not necessary for judging the completion of sequence display. Nevertheless the participants were sensitive to sequence deviance. The reversed sequences elicited

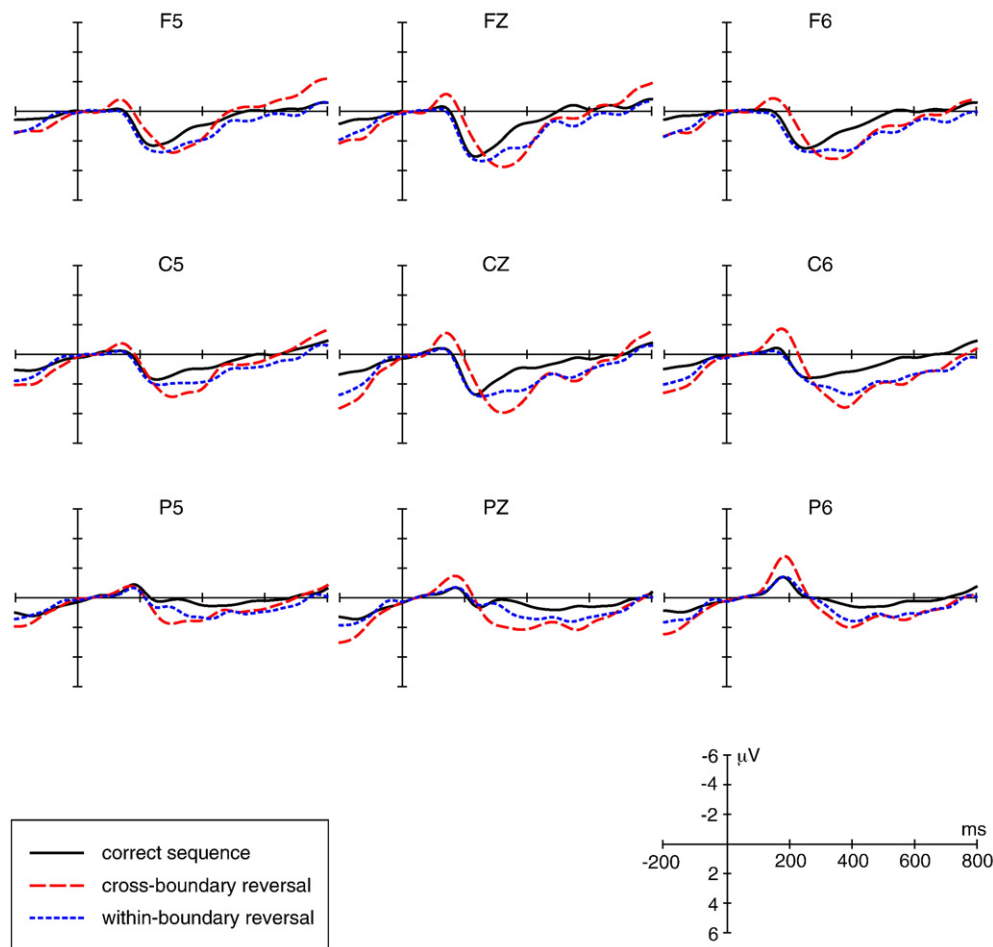


Fig. 7. Grand average ERPs at 9 exemplar electrodes in response to the stroke displays following the critical ones in Experiment 2.

similar ERP effects to those in Experiment 1 although the impact of the change in task demand was also evident. On the critical stroke, the within-boundary reversal elicited an early left posterior negativity effect whereas the cross-boundary reversal resulted in the right posterior N2 reduction. These effects were followed by P3 effects, with the ERP responses to the cross-boundary reversal being more positive. On the following stroke, both types of reversal elicited sustained, but relatively weak positivity effects, in addition to an early right negativity effect for the cross-boundary reversal.

#### Effects on the critical stroke

In the early time window, we found a small negativity with left posterior scalp distribution for the within-boundary reversal (see Fig. 6). As the critical strokes for this type of reversal were displayed equally often to the left and the right, this negativity cannot be an index of attentional shift across visual fields. Instead, we suggest that this early left posterior negativity effect is likely to be related to the automatic detection of orthographic irregularity in writing. This effect, often referred to as N170 (Bentin et al., 1996), has been observed in studies on visual processing of alphabetic words and letters (e.g., Bentin et al., 1999) and non-alphabetic logographs (Maurer et al., 2008; Wong et al., 2005). The source of this effect is likely to be the left fusiform which is responsible for the early orthographic processing (e.g., Bolger et al., 2005; Rossion et al., 2003; Wong et al., 2009), although further studies are needed to confirm this suggestion. On the other hand, as we argued in Experiment 1, the early right posterior N2 reduction for the cross-boundary reversal is likely to be related to the disengagement of attention from the expected position in the left visual field. The P3 effect demonstrates also that the irregularity in

writing sequence can automatically attract attention even though the task has no explicit demand on its detection.

#### Sustained positivities on the following stroke

Although we found the N2 enhancement for the cross-boundary reversal on the right hemisphere, as in Experiment 1, we did not observe sustained negativity effects for the two types of reversal (Fig. 7). Instead, we obtained sustained positivity effects even though these effects tended to be weak.

Clearly, the processing system is sensitive to different task demands and changes accordingly the coping strategy after detecting the violation of writing sequence. We have suggested that the sustained negativity in Experiment 1 reflects a second-pass processing, i.e., reconstructing the correct representation and putting the deviant stroke back into its normal order, after coming across stimulus input violating sequence expectancy. After all, the task in Experiment 1 required the participants to discriminate the correct and incorrect sequences. For the sustained positivity effect here, we suggest that the participants may pay more attention, compared with the baseline condition, to the stroke after the deviant stroke given that the skipped stroke is expected to be re-filled in white. Thus this effect is reminiscent of P3.

#### General discussion

In this study, we examined the ERP responses to the stroke order reversal in the writing sequences of Chinese characters. The participants were asked to make delayed judgment on the correctness (Experiment 1) or the completion (Experiment 2) of the stroke

sequence. On the critical stroke, the within-boundary reversal elicited bilateral (Experiment 1) or left (Experiment 2) posterior N2 enhancement while the cross-boundary reversal produced right posterior N2 reduction in both experiments and a left posterior N2 effect in Experiment 1. Both types of reversal elicited P3 effects in both experiments, although the magnitude and peak latency of the P3 differed between the experiments (see below). On the following stroke, both the within- and the cross-boundary reversal (Experiment 1) or only the cross-boundary reversal (Experiment 2) elicited right-lateralized early N2 effects. But while both types of reversal elicited the sustained negativity effects in Experiment 1, they elicited the sustained positivity effects in Experiment 2. These findings suggest that the Chinese readers exploit their sequential knowledge to predict upcoming strokes in perceiving the writing of characters and to construct appropriate representations for the action sequence whether or not such predictions and constructions are required by the experimental task.

#### Effects on the critical stroke

The main ERP effects associated with perceiving writing sequence reversal in Chinese characters (i.e., N2 and P3 enhancement on the critical stroke) seem to have affinity with previous studies on sequence processing (Bahlmann et al., 2006; Carrión and Bly, 2007; Eimer et al., 1996; Ferdinand et al., 2008; Rüsseler et al., 2003; Rüsseler and Rösler, 2000; Schlaghecken et al., 2000). Importantly, we manipulated the task demand and provided a more detailed characterization of the ERP correlates of perceiving the writing sequence. Although the task demand has not been systematically examined in previous ERP studies on sequence processing, the differential ERP effects elicited by the motor and perceptual deviants in Rüsseler et al. (2003) and Rüsseler and Rösler (2000) could be related to the difference in task-relevancy. In comparison, our data provide more direct evidence for the modulation of ERP responses to sequence deviance by the task demand.

Across the two experiments and in the early time window starting from 170 ms post-onset, we obtained left-lateralized effects for the stroke reversal. These effects were larger in Experiment 1 than in Experiment 2 (see Figs. 3 and 6), possibly due to the difference in task demand between the two experiments. However, the early negativity effect in Experiment 1 may be mixture of the N170 effect reflecting the automatic processing of orthographic information and a posterior N2 effect reflecting allocation of attentional resources to visual irregularity and/or detection of conflict between perceptual input and expectancy. The N2 effects have been associated with the detection of deviant sequences (Eimer et al., 1996; Rüsseler et al., 2003; Rüsseler and Rösler, 2000). This view would imply that in sequence processing, stimulus input is continuously checked against expectation generated on the basis of sequential knowledge. In case of mismatch, multiple perceptual and attentional processes may be engaged depending on the task requirements. For instance, our data show that visual attention can be actively directed to task-relevant (within-boundary and cross-boundary) deviants, as indicated by the presence of the posterior N2 effect in Experiment 1 and the absence of this effect in Experiment 2. Moreover, the FRN effect, which reflects

the detection of conflict between expectation and outcome, was observed in Experiment 1 in which the buildup of expectation towards the next stroke was required by the task, but not in Experiment 2 in which such buildup is not compulsory. On the other hand, the right posterior N2 reduction for the cross-boundary reversal appeared not to be affected by the change of task (see Figs. 3 and 6) given that this effect may reflect attentional shift across the visual fields, which took place in both experimental settings.

Similarly, the P3 enhancement for stroke reversal was also influenced by the task demand. It is clear from Figs. 2, 3, 5 and 6 that the P3 effects differed in terms of magnitude, peak latency and scalp distribution between the two experiments (see also Table 1). We conducted between-experiment comparisons for the peak amplitudes and latencies in the 300–700 ms time window, which was selected taking into account the common time courses of the positivity effects in the two experiments and the individual differences in the manifestation of the positivity effects. ANOVAs with sequence type (cross-boundary vs. within-boundary) and electrode (Fz vs. Cz vs. Pz) as within-participant factors and with experiment as a between-participant factor confirmed that, in both experiments, the cross-boundary reversal elicited P3 with higher peak amplitudes,  $F(1, 34) = 30.81$ ,  $p < 0.0001$ , and shorter peak latencies,  $F(1, 34) = 4.70$ ,  $p < 0.05$ , than the within-boundary reversal. Importantly, the P3 in Experiment 1 had higher peak amplitudes,  $F(1, 34) = 6.74$ ,  $p = 0.01$ , but longer peak latencies,  $F(1, 34) = 6.96$ ,  $p = 0.01$ , than in Experiment 2. For scalp distribution, we found a significant interaction between experiment and electrode,  $F(2, 68) = 5.35$ ,  $p = 0.01$ ,  $\eta^2 = 0.799$ . The P3 effects tended to be more anteriorly located in Experiment 2 than in Experiment 1 according to Figs. 3 and 6 and Table 1. Between-experiment comparisons conducted separately for the mean amplitudes in the 300–500 ms and 500–700/800 ms time windows confirmed the overall analyses.

The greater magnitudes of the P3 effects in Experiment 1 than in Experiment 2 probably indicates that more attentional resources were allocated to deviants when they were pertinent to the completion of the task than when they were less pertinent. The difference between the two experiments in P3 peak latency indicates also the effect of task demand, as more attentional resources and more time are needed in Experiment 1 to resolve the irregularity in stroke sequences while the P3 effect in Experiment 2 may reflect simply the attentional reorienting to the irregularity.

As for the subtle difference in scalp distribution, it is probably related to the differentiation of P3a and P3b in the literature (Polich, 2007). The P3b effect, with maximum at the centro-parietal regions, has been documented in past studies on sequence processing (Carrión and Bly, 2007; Eimer et al., 1996; Ferdinand et al., 2008; Rüsseler et al., 2003; Rüsseler and Rösler, 2000; Schlaghecken et al., 2000), in which the detection of sequence deviants was task-relevant. The P3a effect, with maximum at the frontal-central sites, is often associated with the detection of task-irrelevant deviants in the oddball task (Knight et al., 1989; Squires et al., 1975). It is not surprising that the P3 effects in Experiment 2 was more anteriorly located than in Experiment 1 given that the experimental task was to judge the completion of stroke sequence rather than the detection of sequence reversal.

**Table 1**

The P3 peak amplitudes (in microvolt) and peak latencies (in millisecond) in the two experiments, with their standard deviations in parentheses.

Exp.	Sequence type	Peak amplitude			Peak latency		
		Fz	Cz	Pz	Fz	Cz	Pz
1	Cross-boundary	10.21 (4.60)	11.28 (4.45)	10.69 (3.98)	437 (128)	484 (121)	518 (126)
	Within-boundary	8.89 (4.16)	8.95 (5.04)	9.14 (5.38)	448 (107)	525 (124)	591 (115)
2	Cross-boundary	8.04 (5.40)	8.75 (5.80)	6.30 (3.45)	383 (70)	415 (82)	467 (117)
	Within-boundary	5.82 (3.69)	5.92 (4.27)	3.20 (3.51)	404 (83)	400 (85)	525 (148)



### Effects on the following stroke

To our knowledge, no previous studies have examined ERP responses following the deviants in sequence processing. In this study, we found sustained negativity effects for stroke reversal in Experiment 1 but sustained positivity effects in Experiment 2, although both experiments found N2 effects, at least for the cross-boundary reversal. As we discussed previously, the sustained negativity may index second-pass repairing efforts following the detection of sequence deviants, while the sustained positivity may indicate that more attentional resources are attracted to the strokes following deviants. The difference here is probably determined by the experimental task as only in the first experiment the perceiver may incline to rebuild the correct structure after coming across stimulus input violating sequence expectancy. Thus, highly skilled perceivers are quite flexible in handling sequence deviance.

### Implication for general mechanisms of sequence perception

In ERP studies using different experimental paradigms and sequence stimuli, the N2 and P3 effects have been reported consistently (Bahlmann et al., 2006; Carrión and Bly, 2007; Eimer et al., 1996; Ferdinand et al., 2008; Rüsseler et al., 2003; Rüsseler and Rösler, 2000; Schlaghecken et al., 2000) and argued to be indexes of deviance detection. Our data extend the finding and the argument to the perception of well-learned writing sequence. In fact, existing models of sequence representation and processing derive their supporting evidence mainly from experiments that use only short-time training schemes (e.g., Curran and Keele, 1993) and thus their validity with regard to real-life sequential skills needs further empirical support (Keele et al., 2003). The compatibility of our findings with past ERP studies suggests that the perception of newly-learned or over-learned sequences may follow, at least partially, common processing principles. Realistic stimuli such as Chinese characters would be very suitable for testing elaborated arguments of models of sequence processing, for instance, the distinction between unidimensional and multidimensional systems proposed by Keele et al. (2003).

It is possible that there are common mechanisms in processing sequence information. However, the functioning of these mechanisms may be affected by properties of stimulus input. For example, across the two experiments, we found that the P3 effects on the critical stroke tended to be stronger on the left than on the right hemisphere for both types of reversal (see Figs. 3 and 6). However, the P3 effect tends to be maximal at the midline or lateralized to the right for visual pattern or auditory stimuli in the oddball paradigm (Alexander et al., 1996, 1995). In our study, although the critical strokes were always shown to the right visual field for the cross-boundary reversal, they appeared equally often in the left or right hemifield for the within-boundary reversal, and yet both types of deviance resulted in a left advantage for the P3, irrespective of the experimental task. Such topography may reflect the nature of the stimuli we used given that the orthographic information is processed mainly by the left hemisphere.

### Conclusion

In this study, we examined the ERP responses to the stroke order reversal in the writing sequence of Chinese characters, using a delayed judgment task on the correctness (Experiment 1) or the completion (Experiment 2) of the stroke sequence. We obtained ERP effects for the reversal on both the critical stroke and the following stroke. These effects demonstrate that the Chinese readers use their orthographic knowledge to actively predict upcoming strokes in the process of character writing, reflecting the functioning of general mechanisms of sequence processing.

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