

# Training by visual identification and writing leads to different visual word expertise N170 effects in preliterate Chinese children



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## ABSTRACT

The N170 component of EEG evoked by visual words is an index of perceptual expertise for the visual word across different writing systems. In the present study, we investigated whether these N170 markers for Chinese, a very complex script, could emerge quickly after short-term learning (~100 min) in young Chinese children, and whether early writing experience can enhance the acquisition of these neural markers for expertise. Two groups of preschool children received visual identification and free writing training respectively. Short-term character training resulted in selective enhancement of the N170 to characters, consistent with normal expert processing. Visual identification training resulted in increased N170 amplitude to characters in the right hemisphere, and N170 amplitude differences between characters and faces were decreased; whereas the amplitude difference between characters and tools increased. Writing training led to the disappearance of an initial amplitude difference between characters and faces in the right hemisphere. These results show that N170 markers for visual expertise emerge rapidly in young children after word learning, independent of the type of script young children learn; and visual identification and writing produce different effects.

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## 1. Introduction

Perceptual expertise for visual words enables individuals to rapidly and effortlessly decode visual words (McCandliss et al., 2003). At the neural level, a cortical area located in the left occipito-temporal cortex (termed as Visual Word Form Area, VWFA) has been identified for specifically processing written words (e.g. Cohen et al., 2000; McCandliss et al., 2003; Cohen and Dehaene, 2004; Liu et al., 2013). This area has been proposed to be associated with a negative ERP component, termed as N170, elicited by visual words between 150 ms and 250 ms after the onset of stimuli (Allison et al., 1994; Maurer et al., 2005a; Rossion et al., 2003; Brem et al., 2006). Compared to meaningless symbols, the word-related N170 shows larger amplitude in the left occipital-temporal region in skilled readers (Maurer et al., 2005a, 2006, 2008; Bentin et al., 1999). Further, this effect can be observed in different writing systems (Baker et al., 2007; Maurer et al., 2008; Wong et al., 2005; Lin et al., 2011; Zhao et al., 2012).

N170 markers for word expertise develop rapidly after children receive formal training in schools (Maurer et al., 2006; Brem et al., 2009; Cao et al., 2011; Zhao et al., 2014) and are attenuated in children who suffer from, or are at risk of dyslexia (Maurer et al., 2006; Brem et al., 2013). Word-related N170 expertise emerges even before children receive formal training. A higher N170 for words, relative to symbols, in the right hemisphere was found in kindergarten children (6 years old) with high letter knowledge (Maurer et al., 2005b). This N170 selectivity for words, together with left-lateralization, was also found in Chinese kindergarten children with high reading ability (S. Li et al., 2013).

Notably, a recent training study asked 6 years old preschoolers to learn grapheme to phoneme correspondence. Although these children had already acquired some letter knowledge (10 upper case letters and 5.8 lower case letters) prior to training, they did not possess neural tuning for words associated with visual expertise. However, compared with the N170 amplitude for symbols, neural tuning for words emerged soon after a short-term training (about 3.6 h), especially in the left hemisphere (Brem et al., 2010). However, fast emergence of N170-markers for visual expertise may not necessarily occur for children who learn to read Chinese. A N170 study from skilled Chinese readers found that both characters and unpronounceable pseudo-characters evoked a larger N170,

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which suggested that orthography rather than phonology serves as the main driver for the enhanced and left-lateralized N170 to visual words (Lin et al., 2011). Compared to alphabetic written scripts, the Chinese written system is very complex and is considered one of the most difficult scripts to learn in the world (Shu, 2003; Tong and Yip, 2015). Unlike an alphabetic word which is linearly composed of a limited number of letters, a Chinese character is composed of strokes and radicals which are typically arranged both vertically and horizontally. This pattern is visually much more complicated than that of alphabetic words. Grapheme to phoneme correspondences in alphabetic writing systems are much more direct compared to the Chinese writing system, where a single syllable is shared by many words (a syllable shares 10 characters on average) (Shu, 2003). Thus, it is an inefficient way to learn the character-syllable correspondence at the beginning stage of learning to read Chinese. Consequently, it is a great challenge for Chinese beginning readers to acquire the minimum 3000 to 4000 characters required for skilled readers in short time (H. Li et al., 2012). Therefore, although similar effects of expertise on the N170 are found across different scripts (Alphabetic language: e.g. Bentin et al., 1999; Maurer et al., 2005a; Logographic language: Lin et al., 2011; Cao et al., 2011; Maurer et al., 2008; Wong et al., 2005), it is not clear whether N170 word expertise for Chinese characters, a writing system with very complicated orthography, can emerge very quickly in young children.

Due to the unique visual and linguistic characteristic of Chinese characters, visual-orthographic skills are more essential for learning Chinese in beginning readers (Siok and Fletcher, 2001; Tan et al., 2005). Consequently, rote copying of characters is a typical way of learning Chinese characters in school education (Tan et al., 2005, 2013; Wu et al., 1999) and recently calligraphy is required as a subject in the curriculum of Chinese primary schools (China Ministry of Education, 2013). Many studies have shown that writing skills are associated with reading ability in both normal school age children and dyslexic children (D.W. Chan et al., 2006; McBride-Chang et al., 2011; Tan et al., 2005, 2013). Moreover, writing practice uniquely contributes to Chinese children's reading development even with phonological skills controlled for (Tan et al., 2005). Although kindergarten children in mainland China are not required to learn to write according to the Early Childhood Education Guideline (China Ministry of Education, 2001), Hong Kong kindergarten children start to learn to write Chinese characters as early as 4 years old (Curriculum Development Council, 1996; L. Chan et al., 2008; McBride-Chang et al., 2011). But no study has been reported to scientifically investigate the effect of this early writing training. Thus, it is important to know whether early writing experience in Chinese preliterate children can induce N170 markers for visual expertise

In the current study, we employed a training design in preliterate children, using Event Related Potential (ERP) methodology to answer the above two questions. These children had very limited reading ability and had not formally learnt to read or write Chinese characters. Two training conditions were adopted that are typically applied in educational practice in learning Chinese characters in children: the visual identification learning condition and the free writing condition. Children were randomly assigned to one of the groups and received different training. In the visual learning (VL) group, children learned to visually identify characters while their meanings and pronunciations were provided. In the free writing (FW) group, children were instructed to trace and copy each character manually, meanwhile, the meanings and pronunciations of characters were also provided as in the VL group.

Because Chinese characters have a very complicated orthographic structure which makes it harder for children to master reading skills, it is possible that the early emergence of N170 word expertise in young Chinese children needs a longer time to develop

(not as fast as children learn to read alphabetic scripts). Alternatively, the N170 word expertise in young Chinese children may emerge soon after short-term training since much evidence has shown that Chinese character and alphabetic word processing bear common characteristics at least at the perceptual level (Wong et al., 2012; Lin et al., 2011; Cao et al., 2011). If writing experience can prompt the early development of N170 word expertise, we would observe a stronger N170 word effect in children who received free writing training compared with children in VL group.

## 2. Methods

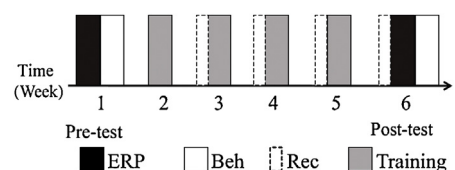
### 2.1. Participants

In order to ensure that children had little literacy experience before attending the study, only those who could read fewer than 30 words within 61 items of a Chinese word reading recognition test developed for preschoolers (Chow et al., 2008; S. Li et al., 2013) were included in the experiments. Initially, 34 children participated in this study. However, one child withdrew in the Post-test session and the data of 4 children were excluded due to extremely low EEG data quality (i.e. less than 20 trials for each condition). The remaining 29 right-handed children with no known neurological diseases or psychological disorders in a kindergarten (17 females, mean age = 58 months,  $SD = 3.32$ , range = 48–68 months in the pretest session) completed the training as well as the behavioral and the ERP recording and analyses. All children were Mandarin speakers in China and had no formal schooling experience. All parents were provided with full information about the study and were also told that their children were free to quit the study at any time and without claiming any reasons. Written consents from parents were obtained as well. All the experiment procedures and protocols were approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences.

### 2.2. Procedures

#### 2.2.1. General procedures

Children received a battery of tests to assess their non-verbal intelligence, reading ability, fine motor ability, and visual motor integration ability. They were assigned to one of the two training conditions (VL & FW). As illustrated in Fig. 1, children were asked to take part in a behavioral test on character recognition and an ERP experiment before training so that we could acquire the initial status of these children at both behavioral and neural levels. Next, the two groups of children began the 4 training sessions during 1 month (1 training session per week). Each training session lasted 25-min, and the total training time was about 100 min. To evaluate learning effects, children were submitted to another character recognition test one week after each training session through the training period. After the last training session, participants took part in the post-training behavioral and ERP experiment as in the pre-training session.



**Fig. 1.** Schematic description of study design. “ERP” represented the ERP experiment. “Beh” represented the character-matching test in pre- and post-training sessions. “Rec” represented the character recognition test during training. “Training” represented the training sessions.

**Table 1**  
Characteristics of participants in both training groups.

	Visual learning	Free writing	<i>t</i>	<i>p</i>
<i>N</i>	13	16		
Gender (female)	8	9		
Age (month)	57.77 (3.32)	58.31 (3.42)	0.43	0.67
IQ	105.54 (11.68)	103.97 (11.94)	0.36	0.73
Fine motor(s)	141.77 (37.64)	141.69 (25.65)	0.01	1.00
VMI	17.64 (3.80)	15.92 (3.55)	0.91	0.37
Vocabulary scores	5.92 (5.45)	6.31 (7.44)	0.16	0.88

**Note.** Mean scores for each training group are listed in the table and values in brackets are standard deviation for each group.

### 2.2.2. A battery of behavioral tests

VMI subtest in DTVP-2 (Frostig's Developmental Test of Visual Perception, Second Edition) was used to assess children's visual-motor integration ability. Fine-motor ability was assessed using a 24-hole pegboard in which the children had to insert 24 cylindrical pieces as fast as they could (Martzog et al., 2012). The experimenter recorded the time spent and the hand used when children conducted the test. Non-verbal intelligence was assessed using the Combined Raven's Test (CRT, Chinese version, 1991). According to the performance of these tests, all the participants were assigned to either the VL group or the FW group with all the measures matched (see Table 1).

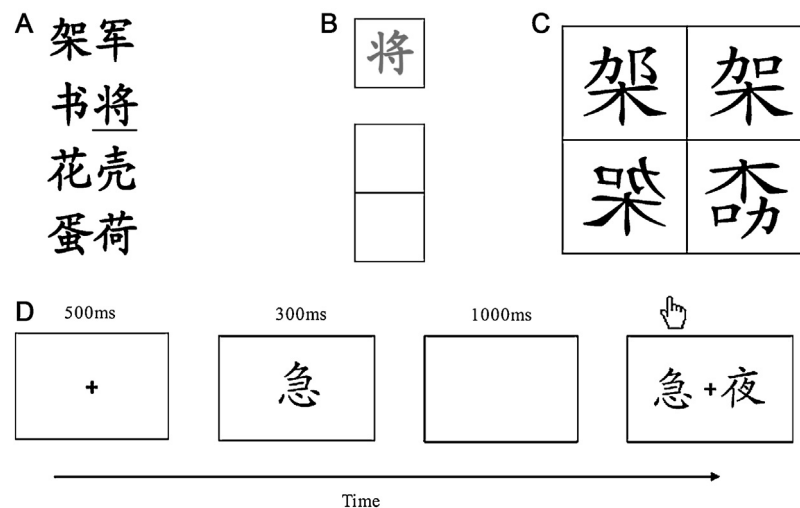
### 2.2.3. Training procedures

Children in both groups were trained to learn 12 Chinese characters in 4 training sessions within one month (one training session per week). The characters were content words selected from the high frequency character list for elementary school in China (China Ministry of Education, 2011). Each character was composed of 3 simple radicals and the number of strokes was less than 10 (For example, 急, 壳, 荷, 夜, 帮). Out of the 12 characters in the learning set, 1 pair of characters shared 1 radical (i.e. 亻 in 荷 and 夜), and another pair of characters shared a radical in different positions (i.e. 木 in 树 and 架). All other radicals in the learning set were unique. None of the participants reported knowing these characters before the training started. All of these 12 Chinese characters were learned twice in each of the training sessions. The orders of the 12 characters were counterbalanced between sessions. Altogether, each

training session took approximately 30 min (including procedural instructions at the beginning and a short break during the session).

Children participated in training in small groups of 4–5 children. At the beginning of each training session, the experimenter showed the learning procedure with an example character to help children understand the procedures. Formal training started after children were familiar with the learning procedure.

For each character to be learned, the experimenter first presented a character, and then told children the pronunciation and meaning of the character. Next, after children could correctly verbally repeat the character and understand the meaning of the character, children in the VL group were asked to identify the character from 8 different characters printed on one page (Fig. 2A). For the 7 distracters, 3 of them were from the learning set, 4 were additional characters. They could do this practice a maximum of four times on four different pages. For children in the FW group, the character was also presented to children firstly but it was printed in gray on the upper side of the page (Fig. 2B). After being told the pronunciation and the meaning of the character, children were instructed to trace over the gray character using a pencil. The trace practice was designed to assist children to write the character at the beginning. Then, they were instructed to copy the character below the sample character on the same page, at least two times. If children identified or copied incorrectly, the experimenter would remind them they had made a mistake. In order to match the print exposure for the two groups, we limited the exposure time for each character each time to 2 min at each training session.



**Fig. 2.** (A) A sample page for learning in the VL group. Children were asked to mark the same character (将) introduced by the experimenter during learning. (B) A sample page for learning in the FW group. Children were required to trace the gray character (将) and copy it twice in the boxes below within the time limit. (C) A sample trial for the character recognition test taken after each training session. Upper left: the radical transformed character (with one radical replaced). Upper right: the correct character (架). Lower left: the mirror image of the character. Lower right: the radical position transformed character. Children were required to circle the correct characters learned in the training sessions. (D) The procedure of the character-matching test in pre- and post-training sessions.

## 2.2.4. Character recognition tests

### 2.2.4.1. Character-matching test in pre- and post-training sessions.

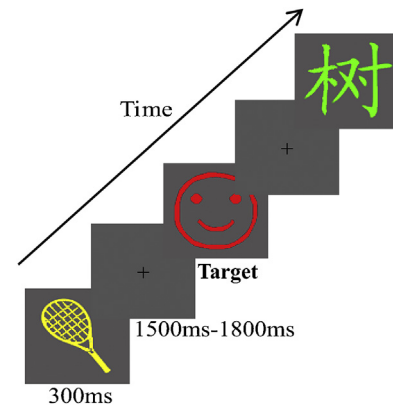
A two-alternative character-matching task was adopted to test the ability to rapidly recognize characters. Following a presented target character (300 ms), children were shown a selection display with both that target and a distracter character, arranged horizontally across the screen. The children were then asked to judge which character was the previously presented target, as quickly and as accurately as possible by pressing keys on the keyboard. They were asked to press “F” if the left character was the previous one and press “J” if the right character was the previous one. The position of the target character in the selection display was counterbalanced across trials. The characters in the training materials were used as stimuli. E-prime 2.0 software was used to present the stimuli. The whole experiment contained 24 trials with each of the 12 characters presented twice as the target. Stimulus order was random across trials. For each trial, following a 500 ms fixation, one stimulus was presented as the target in the center of the screen for 300 ms. Then, after a 1000 ms blank, children chose the target character from 2 different characters presented together in a selection window (Fig. 2D). The accuracy and the response time of matching were recorded by the computer and were analyzed.

**2.2.4.2. Character recognition test during training sessions.** In order to evaluate performance benefits, children were submitted to a character recognition test one week after each training session. The test was performed immediately before the next training session in the following week. The test was on the same day as the training. This test was modeled after a previous study which focused on the effect of writing practice on letter recognition in children (Longcamp et al., 2005). Each time, children were presented with a booklet and a pencil. Four options (including 1 correct character and 3 different distracters) were presented in a box with 4 cells in the booklet (Fig. 2C). Three different distracters were character-like patterns which were adapted from correct characters: the mirror image of the character, a radical transformed character (with a radical replaced) and a radical position transformed character (with each radical position switched). Each of the 12 characters learned during training was tested twice in a random order to minimize the risk of getting a correct response by chance. The positions of the four options in the box were different between trials. The children were asked to find the correct character that they learned during training and draw a circle to mark it with no time requirement. Children’s responses were recorded by counting the number of choices for correct characters after the test. We computed a correct response score (CR) for each child. One CR was given only when the child selected a character twice correctly. Thus, the maximum CR score was 12 in this test. Then, the CR scores were divided by the number of character learned (12) to get the accuracy for the character recognition test after each training session. Four children missed one of the recognition tests because of attending other kindergarten activities. The missing data were replaced with interpolated data, using an expectation-maximization algorithm (Dempster et al., 1977).

## 2.2.5. ERP experiment

**2.2.5.1. Stimuli and procedure.** Three categories of stimuli were used in the ERP experiment. The 12 characters in the training sessions were used as the stimulus in the character condition. Line drawings of faces and tools matched in spatial frequency and contrast were used as the two control conditions. Each category (characters, faces, tools) was presented in one of four colors: red, green, blue and yellow. Thus, there were 48 different items for each category. The size of each image was  $91 \times 90$  voxels.

E-prime 2.0 software was used to present the stimuli. Each time, stimuli in one of the four colors were presented individually on a gray background with the horizontal visual angle 1.36 degree and



**Fig. 3.** Stimulus sample and procedure of the ERP experiment. Stimuli from the left to right were tools, faces, and characters. Red pictures were the targets. Children were instructed to attend to the stimuli and press a key once seeing the targets.

the vertical visual angle 1.38. For each trial, a stimulus appeared for 300 ms and was followed by a 1500–1800 jittered interval. The stimuli of different conditions with different colors were mixed and were presented randomly and continuously (see Fig. 3).

During the experiment, children sat 100 cm away from the screen. Children were instructed to attend to the pictures on the screen and respond to the red ones (targets) by pressing a pre-determined key on the keyboard as quickly and accurately as possible. This target-detection task was content-irrelevant, which can minimize the effects of top-down modulations and attentional biases across stimuli. In addition, this passive viewing task also minimized EEG artifacts induced by the action of key pressing, as we only analyzed the non-target trials. Also, it was easy enough for the young children to understand and perform the task well. Children were given 5 practice trials before starting the experiment to ensure that they understood the instructions and were able to successfully perform the task.

The experiment contained five runs. For each run, the frequency of each non-target color (blue, green, and yellow) was 2 time more than the red target color on average and the ratio of non-target trial to target trial was 6:1. Each run was composed of 27 non-target trials for the 3 conditions (9 for each) and 4.5 target trials on average (the number of target trials was randomized from 3 to 6 for each of the 5 runs). For the 5 runs altogether, there were 45 non-target trials in each category. The children had a break after 31 trials (on average) and received a small gift as a reward after the experiment. The whole experiment took about 10 min.

**2.2.5.2. Data recording and processing.** EEG was recorded with an elastic cap carrying 32 Ag/AgCl electrodes which were placed according to the 10–20 international system (NeuroScanInc., El Paso, TX, USA). Signal was amplified at a sampling rate of 1000 Hz. All channels were filtered with a band pass on-line filter from 0.1 to 100 Hz and 50 Hz noise was notched. Bilateral mastoids were used as the reference and the GND between FPz and Fz electrodes was used as the ground (all data were re-referenced with the grand average in later data analysis). The horizontal EOG was monitored by a bipolar channel using two electrodes placed over the right and left external canthus, and the vertical electrooculogram (EOG) was recorded with two electrodes above and below the left eye. Electrode impedances were kept  $<5$  k $\Omega$ .

Eye blinks were first corrected using the ocular correction function in Scan 4.5 software and the data were digitally filtered by band-pass (0.5–30 Hz). EEG was then segmented into epochs of 900 ms, from 100 ms pre-stimulus to 800 ms post-stimulus onset. Baseline correction was performed (–100 ms to 0 ms). Linear detrending was used for 5 children in Pre-test and 5 children in



**Table 2**  
Response time and accuracy in the character matching task before and after training (SD).

	RT		Accuracy	
	Visual learning	Free writing	Visual learning	Free writing
Pre-test	1574.52 (570.18)	2022.45 (914.38)	0.80 (0.14)	0.75 (0.12)
Post-test	1155.77 (291.72)	1099.35 (196.74)	0.93 (0.05)	0.90 (0.04)

**Note.** Mean scores for each training group are listed in the table and values in brackets are standard deviation for each group.

Post-test to correct too much linear drifting, and baseline correction was applied again after linear detrending. Trials with artifacts exceeding  $\pm 100$  mV in the studied channels were automatically rejected (Because of higher noise level, an amplitude criterion of  $\pm 125$  mV was used in four children's data in Pre-test and three children's data in Post-test.; similarly,  $\pm 150$  mV were used in one child in pretest to reach an acceptable number of trials). Then, EEG signals of no-target trials were averaged to derive ERPs for words, faces and tools, respectively. At least 20 trials were averaged for each category for each child (Mean trial numbers = 33). There were no differences in the number of averaged trials in the three categories of stimuli ( $F(2,56) = 0.10$ ,  $p = 0.89$ ). Channels over the occipital-temporal area (e.g. Maurer et al., 2006; Cao et al., 2011) with the maximum negative amplitude (T5/T6) were selected. The peak values of amplitude and associated latencies were automatically detected between 150 ms and 300 ms after stimulus onset for minima as the N170 segment. The time window was determined in reference to the literature of studies on children at similar ages (S. Li et al., 2013; Maurer et al., 2006) and combined with visual inspection of the individual waveform in the present study. The averaged N170 peak amplitudes were calculated for each stimulus category in Pre-test and Post-test respectively. In addition, the peak amplitude of the P1 component was also detected between 100 ms and 150 ms to verify that changes in N170 component were unique to the time-window associated with high-level expertise.

**2.2.5.3. ERP data analyses.** Three parts of analyses were performed on the N170 amplitudes of each category. First, in order to confirm the initial statuses of two groups were matched before training, an ANOVA was performed in the Pre-test data with between-subject factor of Training Group (VL vs. FW) and the within-subject factors of Category and Hemisphere. Second, in order to compare the effect of different learning conditions on the N170 amplitudes for each stimulus category across times, a mixed designed ANOVA on the N170 amplitudes with between-subject factor of Training group, and within-subject factors of Time, Category, and Hemisphere was conducted within each group. Third, in order to investigate changes in N170 lateralization after training, pairwise comparisons were performed between left and right hemisphere for all categories and in pre-test and post-test for each group. In addition to the N170 peak amplitude, the peak latency of N170 was assigned to ANOVAs with between-subject factor of Training group and within-subject factors of Time, Category and Hemisphere. In order to further verify the changes in category difference in N170 amplitude was not lead by changes in P1 component, which reflected the basic visual processing, we also performed similar ANOVA with the P1 amplitude of T5 and T6 channels.

### 3. Results

#### 3.1. Behavioral results

##### 3.1.1. Character-matching test in pre- and post-training sessions

The accuracy of the character matching task showed an increase with training but it was not affected by the different ways of training. The analysis of ANOVA with repeated factor Time (Pre-test,

Post-test) and between-participants factor Training group (VL vs. FW) only revealed a significant main effect of Time ( $F(1,27) = 34.62$ ,  $p < 0.01$ ,  $\eta^2 = 0.56$ ) with increasing accuracy in the post-training test ( $p < 0.01$ ) (see Table 2 for the results of each group). The Training group main effect ( $F(1,27) = 2.19$ ,  $p = 0.15$ ,  $\eta^2 = 0.07$ ) and the interaction between Time and Training group ( $F(1,27) = 0.26$ ,  $p = 0.62$ ,  $\eta^2 = 0.01$ ) were not significant. Similar with the accuracy result, the analysis of the response time by ANOVA with repeated factor Time and between-participants factor Training group only revealed a significant main effect of Time ( $F(1,27) = 19.76$ ,  $p < 0.01$ ,  $\eta^2 = 0.42$ ), with the response time in the Post-test was faster than that in the Pre-test ( $p < 0.01$ ) (Table 2). While the interaction between Time and Training group were not significant ( $F(1,27) = 2.79$ ,  $p = 0.11$ ,  $\eta^2 = 0.09$ ).

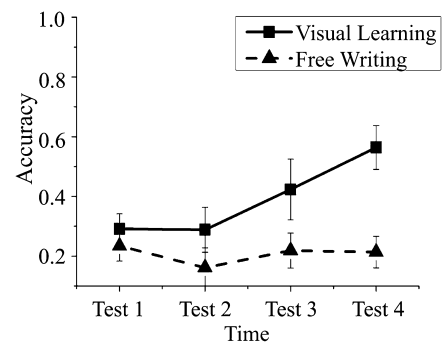
##### 3.1.2. Character recognition test during training

In order to analyze the relatively long effects of different training methods on recognizing the learned characters, the accuracy for the character recognition test was submitted to a  $4 \times 2$  mixed design ANOVA with Time serving as the repeated measures and training group serving as the between-subject factor. The main effect of Time was significant ( $F(3,81) = 9.14$ ,  $p < 0.01$ ,  $\eta^2 = 0.25$ ) and the interaction between Time and Training group was significant ( $F(3,81) = 7.08$ ,  $p < 0.01$ ,  $\eta^2 = 0.21$ ). As can be seen in Fig. 4, the score in the VL group was significantly higher than that in the FW group after the 4th training session (Test 4) ( $p < 0.01$ ). The accuracy of the VL group increased significantly after 3 weeks training (Test 3 vs. Test 2,  $p < 0.01$ ) and continued to increase after the 4th week of training (Test 4 vs. Test 1 & Test 4 vs. Test 2,  $p < 0.01$ , Test 4 vs. Test 3,  $p = 0.06$ ). However, the FW group did not show significant changes among the four testing times during training sessions (all  $p$ -values  $> 0.10$ ).

#### 3.2. ERP results

##### 3.2.1. N170 peak amplitude

**3.2.1.1. Pre-training results of two groups.** No significant group differences were found in the Pre-test for either characters or none-character categories (all  $p$ -values  $> 0.10$ ). Also, no main effects

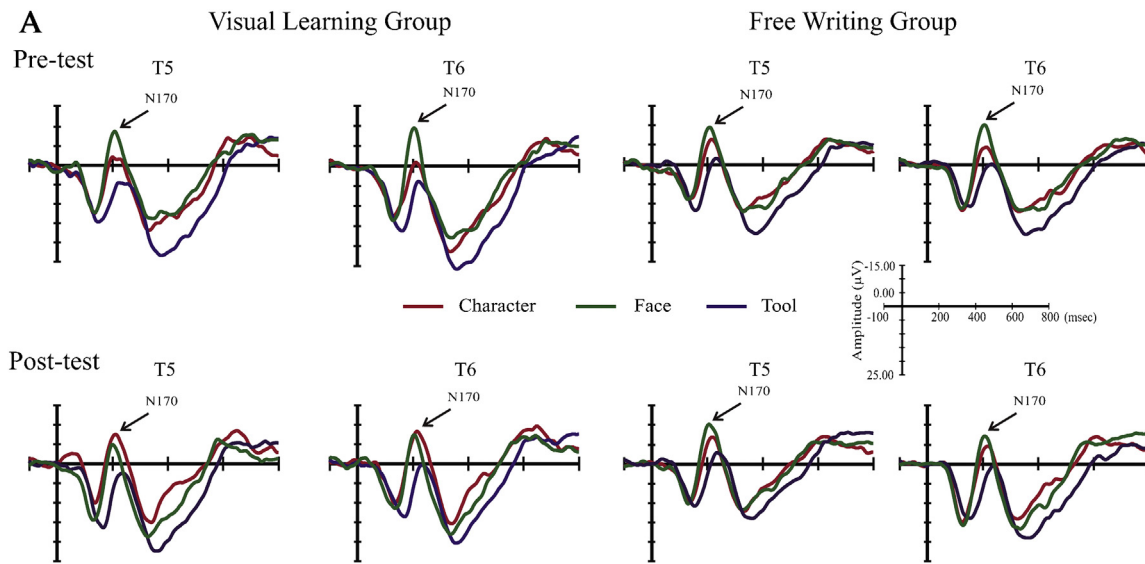


**Fig. 4.** Accuracy in the character recognition tests across 4 training sessions. "Test 1" for the test after training session 1, "Test 2" for the test after training session 2, "Test 3" for the test after training session 3 and "Test 4" for the test after training session 4.

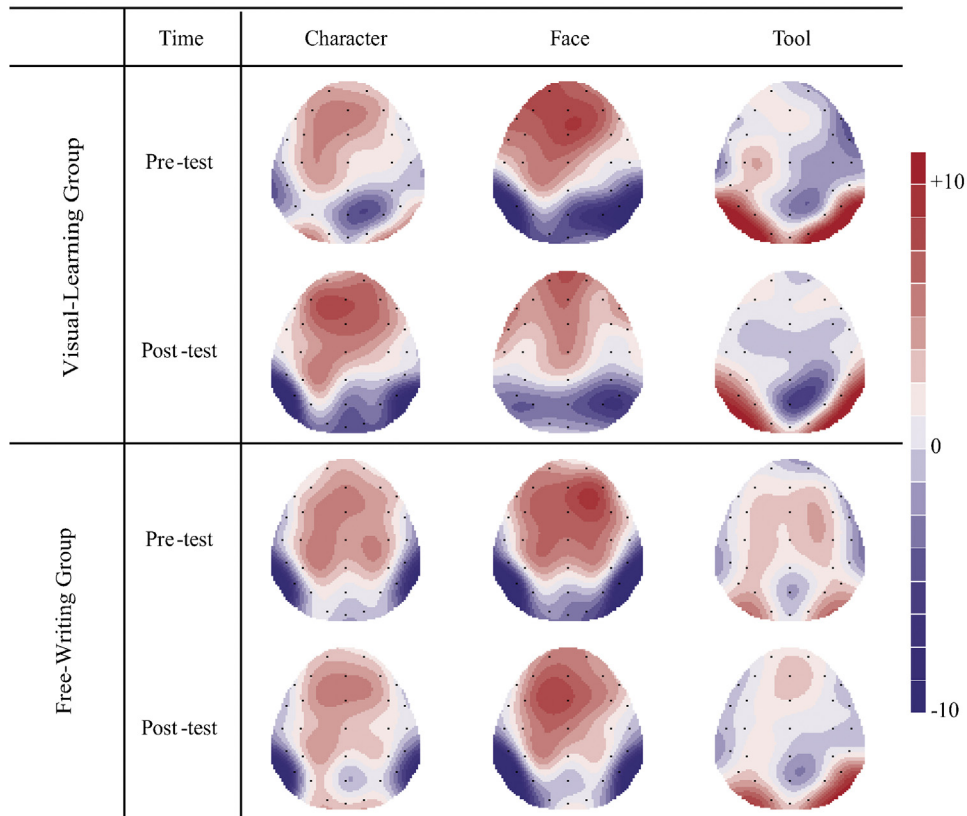
or interactions with group or hemisphere were significant (all  $p$ -values  $> 0.10$ ). The ANOVA analysis revealed only a significant main effect of Category ( $F(2,64) = 51.31, p < 0.01, \eta^2 = 0.61$ ). Before training, the N170 amplitudes induced by characters **were** smaller than that by faces and were larger than that by tools ( $p < 0.01$ ). And

the N170 amplitudes for faces were also larger than that of tools ( $p < 0.01$ ).

3.2.1.2. *Effects of visual learning and free writing.* N170 peak amplitudes **were** assigned to ANOVA with between-subject factor



**B**



**Fig. 5.** N170 waveform at T5/T6 and scalp voltage maps in the VL group and the FW group. (A) N170 waveform at T5/T6 in the VL group and the FW group. Waveforms of characters were plotted with red lines, faces with green lines and tools with blue lines. The upper row presented waveforms in the Pre-test and the lower row presented waveforms in the Post-test. Left two columns showed the N170 waveforms of the VL group, the right two columns for the FW group. For each group, the left columns showed the N170 waveform at T5 channel, and the right for T6 channel. (B) The scalp voltage maps at 200–219 ms in the VL group and the FW group before and after training. Columns from left to right: Characters, Faces, Tools. Upper block presented scalp maps of VL group in the Pre- and the Post-test and lower block presented scalp maps of the FW group in the Pre- and the Post-test. Red color represented positive voltage.

**Table 3**  
Peak amplitude differences ( $\mu\text{V}$ ) of N170 at T5/T6 before and after training in VL and FW group.

		Left				Right			
		C-F		C-T		C-F		C-T	
Visual learning	Pre	4.75	$t=3.21$ $p<0.01$	-5.84	$t=2.01$ $p=0.07$	7.86	$t=3.38$ $p<0.01$	-4.36	$t=1.98$ $p=0.07$
	Post	-2.76		-10.32		3.38		-9.14	
Free writing	Pre	3.19	$t=-0.20$ $p=8.43$	-4.59	$t=-0.55$ $p=0.59$	5.05	$t=1.00$ $p=0.33$	-4.13	$t=1.10$ $p=0.29$
	Post	3.55		-3.87		2.55		-5.98	

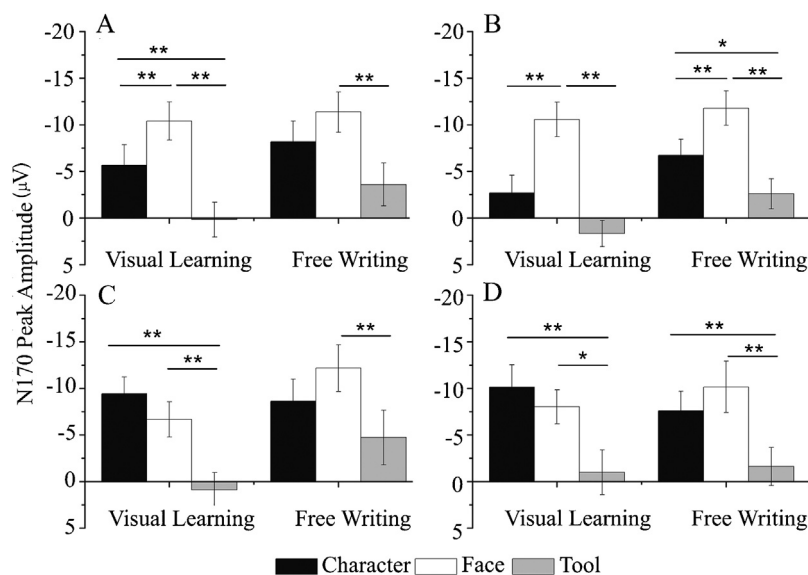
**Note.** C-F represented the N170 peak amplitude difference between character condition and face condition, C-T represented the N170 peak amplitude difference between character condition and tool condition. The  $t$  &  $p$  values were the results of paired sample  $t$ -test between Pre-tests and Post-tests for each pair of difference.

of Training group and within-subject factors of Time, Category and Hemisphere. The ANOVA revealed significant main effect of Category ( $F(2,54)=65.96$ ,  $p<0.01$ ,  $\eta^2=0.71$ ) and significant interaction between Time and Category ( $F(2,54)=8.42$ ,  $p<0.01$ ,  $\eta^2=0.24$ ). Most importantly, the 3-way interactions of Training group  $\times$  Time  $\times$  Category ( $F(2,54)=45.15$ ,  $p=0.02$ ,  $\eta^2=0.16$ ) and Training group  $\times$  Time  $\times$  Hemisphere ( $F(1,27)=5.10$ ,  $p=0.03$ ,  $\eta^2=0.16$ ) were significant. None of the other main effects or interactions were significant ( $p>0.10$ ). The two 3-way interactions indicated that, in the two groups, there could be different changes for the N170 amplitude of each category in each hemisphere after training. Thus, we further performed ANOVAs with factors of Training group, Time and Category within each hemisphere respectively.

In the left hemisphere, the Category main effect was significant ( $F(1,27)=42.64$ ,  $p<0.01$ ,  $\eta^2=0.61$ ). The interaction between Time and Category was significant ( $F(2,54)=3.52$ ,  $p=0.04$ ,  $\eta^2=0.12$ ). The 3-way interaction of Training group  $\times$  Time  $\times$  Category was significant ( $F(2,54)=4.41$ ,  $p=0.02$ ,  $\eta^2=0.14$ ). Post hoc test revealed that, in the VL group, the N170 amplitudes of characters and tools did not change significantly ( $p>0.10$ ). However, the face N170 amplitude decreased significantly after training compared to before training ( $p=0.03$ ). While in the FW group, the N170 amplitudes of characters, faces, and tools did not change significantly after training compared to before training (Character,  $p=0.84$ ; Faces,  $p=0.61$ ; Tools,  $p=0.55$ ) (Fig. 5).

In order to verify the changes in the N170 amplitude of characters relative to the other non-character categories, we further performed paired-sample  $t$ -tests for the changes in amplitude differences of character-face (C-F) and character-tool (C-T) between Pre- and Post-test (Table 3). In the VL group, the N170 amplitude difference between characters and faces (C-F) decreased significantly in the Post-test ( $p<0.01$ , Table 3). Additionally the N170 amplitudes differences between characters and tools (C-T) showed an increasing trend in the Post-test ( $p=0.07$ , Table 3). In the FW group, the C-F and C-T N170 amplitudes differences showed no significant effects in the Post-test (all  $p$ -values  $>0.10$ , see Table 3).

In the right hemisphere, the Category main effect was significant ( $F(1,27)=43.78$ ,  $p<0.01$ ,  $\eta^2=0.62$ ). The interaction between Time and Category was significant ( $F(2,54)=6.89$ ,  $p<0.01$ ,  $\eta^2=0.20$ ). The 3-way interaction of Training group  $\times$  Time  $\times$  Category was marginally significant ( $F(2,54)=2.51$ ,  $p=0.097$ ,  $\eta^2=0.09$ ). Post hoc test revealed that, in the VL group, the N170 amplitude of characters increased significantly after training compared to the before training ( $p<0.01$ ) and the N170 amplitudes of faces and tools did not change significantly in the Post-test ( $p>0.10$ ). In the FW group, the N170 amplitudes of characters, faces, and tools did not change significantly after training compared to the before training (Character,  $p=0.69$ ; Faces,  $p=0.48$ ; Tools,  $p=0.65$ ). However, the planned comparisons between N170 amplitude of characters and non-character categories revealed that the N170 amplitude of characters was smaller than that of faces ( $p=0.01$ , Fig. 6B) in the Pre-test. While



**Fig. 6.** Amplitudes of N170 component at T5/T6. (A) N170 peak amplitudes over the left hemisphere (T5) in the Pre-test. (B) N170 peak amplitudes in the right hemisphere (T6) in the Pre-test. (C) N170 peak amplitude in the left hemisphere (T5) in the Post-test. (D) N170 peak amplitudes in the right hemisphere (T6) in the Post-test. For each figure, the left clusters of bars represented the amplitudes of the VL group, the right for the FW group. The amplitudes of characters in the Pre-test were plotted with black, faces with gray and tools with white. \*\* Significant differences at  $p<0.01$ ; \* Significant differences at  $p<0.05$ .

**Table 4**  
Peak latency (ms) of N170 component at T5/T6 before and after training in Visual leaning group and Free writing group.

	Training group	Character		Face		Tool	
		T5	T6	T5	T6	T5	T6
Pre-test	Visual Learning	208(20)	216(15)	210(14)	205(12)	247(31)	235(30)
	Free Writing	223(15)	211(22)	209(16)	207(16)	238(25)	233(26)
Post-test	Visual Learning	212(16)	221(18)	209(17)	210(14)	232(30)	239(17)
	Free Writing	222(21)	218(20)	211(16)	205(17)	250(26)	233(31)

**Note.** Peak latency for each training group is listed in the table and values in brackets are standard deviation for each group in each condition.

the N170 amplitude of characters did not significantly differ from that of faces in the Post-test ( $p=0.52$ , Fig. 6D). This result indicated an increased N170 amplitude of characters relative to that of faces after training compared to the before training in the FW group.

Similar with the paired-sample t-test in the left hemisphere, in the VL group, the N170 amplitude difference between characters and faces (C-F) decreased significantly (Table 3). Since the N170 amplitude of characters became significantly larger than that of tools in the right hemisphere in the Post-test ( $p<0.01$ , Fig. 6B and D), the N170 amplitudes differences between characters and tools (C-T) also showed an increasing trend in the right hemispheres too (Table 3). In the FW group, the C-F and C-T N170 amplitudes differences showed no significant changes in the Post-test (all  $p$ -values  $>0.10$ , see Table 3).

Generally, in visual identification groups, although the N170 amplitude for characters was larger than that of tools before training, a training effect reflected by larger amplitude of characters in the right hemisphere was observed. Regarding the free writing group, the very strong learning effects on N170 character amplitudes were not found compared with that in the visual identification group. However, in the right hemisphere, the N170 amplitude difference between characters and faces disappeared.

**3.2.1.3. N170 lateralization.** The pairwise comparisons between the left and right hemisphere for all categories and in Pre-test and Post-test for each groups respectively showed that none of the hemispheric differences among these categories reached significance in either Pre-test or Post-test in any group (all  $p$ -values  $>0.10$ ).

### 3.2.2. N170 peak latencies

The ANOVA for the N170 peak latencies revealed that only the main effect of Category was significant ( $F=102.70$ ,  $p<0.01$ ,  $\eta^2=0.80$ ). The N170 latency of faces was shorter than that of characters and tools ( $p<0.01$ ) and the N170 latency of characters was shorter than that of tools ( $p<0.01$ ) (Table 4). The N170 peak latencies were not significantly different between groups in both Pre- and Post-test (Group main effect:  $F=0.07$ ,  $p=0.80$ ,  $\eta^2=0.003$ ; Group  $\times$  Time:  $F=0.40$ ,  $p=0.53$ ,  $\eta^2=0.02$ ). And the changes of peak latency between pre-test and post-test did not reach significant

level, either (Time main effect:  $F=0.74$ ,  $p=0.40$ ,  $\eta^2=0.03$ ). No other significant main effect or interactions were found (all  $p$ -values  $>0.10$ ).

### 3.2.3. P1 amplitude

P1 peak amplitudes of three categories were assigned to ANOVA with between-subject factor of Training group and within-subject factors of Time, Category and Hemisphere. The Time  $\times$  Training group ( $F(1,27)=4.66$ ,  $p=0.04$ ,  $\eta^2=0.15$ ) and the Time  $\times$  Hemisphere  $\times$  Training group interactions were significant ( $F(1,27)=4.30$ ,  $p=0.05$ ,  $\eta^2=0.14$ ). The post hoc analysis revealed that the P1 amplitude was only significantly enhanced in the FW group in the right hemisphere in the Post-test ( $p=0.01$ ) (Table 5). The Category main effect or any Category related interactions were not significant (all  $p$ -values  $>0.05$ ).

## 4. Discussion

The current study is the first study to examine the ERP effects of short-term reading and writing training on the emergence of visual word expertise processing in Chinese preschool children. We focused on whether the N170 markers for visual word expertise emerge very quickly in young Chinese children after short-term word learning and whether early writing experience could prompt the early acquisition of word expertise processing.

We found that Chinese characters induced the bilateral N170 component in the occipital-temporal channels in preschool children before training, consistent with previous findings for alphabetic scripts (Maurer et al., 2005b, 2006; Brem et al., 2010). Importantly, our data, for the first time, showed that the word-related N170 expertise emerged very quickly in very young preliterate Chinese children (4 to 5 years old) after short-term word learning (about 100 min), especially in visual identification groups. Although the N170 amplitude for characters was larger than that of tools before training, we still observed a training effect reflected by larger amplitude of characters in the right hemisphere. Furthermore, such changes in the character N170 amplitude at the neural level were coordinated with the behavioral performance changes in the character-matching test, which reflects a fast character-processing ability enhanced after training sessions. Thus, combined with the

**Table 5**  
Peak amplitudes ( $\mu V$ ) of P1 component at T5/T6 before and after training in VL and FW group.

	Training group	Character		Face		Tool	
		T5	T6	T5	T6	T5	T6
Pre-test	Visual learning	13.54 (4.73)	13.58 (5.92)	13.70 (4.40)	15.04 (8.07)	15.36 (3.67)	16.24 (6.19)
	Free writing	10.42 (6.45)	13.56 (9.12)	10.40 (4.29)	13.02 (9.23)	11.69 (6.52)	11.73 (7.00)
Post-test	Visual learning	11.85 (6.79)	11.72 (4.91)	15.68 (8.76)	13.28 (7.02)	15.32 (8.35)	12.25 (6.84)
	Free writing	11.81 (7.87)	16.87 (5.70)	11.65 (6.47)	17.89 (8.56)	11.35 (7.09)	14.93 (7.96)

**Note.** Mean amplitudes for each training group is listed in the table and the values in the bracket is a standard deviation for each group in each condition.



findings in children who learn to read alphabetic script (Brem et al., 2010), our findings indicate that the fast emergence of visual word N170 expertise after learning to read is independent of the type of script young children learn. It is worth mentioning that the pronunciation and semantic meaning of the specific characters were provided to children when we visually presented the characters at the beginning of each training session in both groups. Such a learning method is similar to that in Brem et al. (2010)'s study, which asked children to learn letter-sound correspondences (Brem et al., 2010). Thus, the enhanced N170 effect for visual words by short-term training suggests that visual-speech correspondences (character-syllable correspondence in Chinese) are essential for the emergence of N170 word expertise processing regardless of the differences in visual and linguistic features that make up different scripts.

In order to ensure the children had little literacy experience before training, we specifically selected children with low reading ability. Also, we investigated the home literacy environment of these children. According to the questionnaires, about 70% of the parents occasionally instructed their child to read Chinese characters and over 80% of their homes had less than 5 Chinese character recognition books. Moreover, it is not necessary for teachers to teach children to learn to read and write in kindergarten according to the Early Childhood Education Guideline from China Ministry of Education. Thus, we can assume that the participants didn't have much reading experience, perhaps only from passive print exposure in their environment. And passive print exposure in children's daily life is not likely to have a strong influence on the emergence of word expertise processing in the preschool period. Explicit word learning may be crucial to the fast emergence and development of the word N170 expertise.

Our other interesting finding is the different training effects of visual identification and writing learning on the visual word N170 expertise processing. The visual identification task made the neural activities of character processing change differently in both hemispheres. The N170 amplitudes to characters did not change significantly after training in the left hemisphere, whereas the N170 amplitudes of characters enhanced remarkably in the right hemisphere. Regarding the free writing group, we did not observe very strong learning effects on N170 character amplitudes compared with that in the visual identification group. However, although writing training did not produce significant increases in N170 character amplitude, in the right hemisphere, the amplitude difference between characters and faces disappeared (Fig. 6B and D). Since the pattern of N170 amplitudes of the three categories was similar in both groups before training, different learning effects may reflect different impacts of different literacy inputs on the N170 word expertise processing.

The current study did not show that writing experience produces significant improvements of reading ability either in terms of the behavioral performance in the character recognition tests, or the N170 amplitude for characters in Chinese preschool children. We did not find any significant correlations between the character recognition score after 4 weeks training and the N170 amplitude of characters before or after training (all  $p$ -values  $>0.10$ ) as well. These results appear to be inconsistent with the results obtained with children learning to read English letters (James, 2010). For example, James (2010) trained 4–5 years old children with limited letter knowledge (7.5 letters) to copy English letters. During learning sessions, words that contained letters highlighted in the story text were learned. The experimenter read the story and then children copied the highlighted letters and words. After four 30-min writing practice sessions (2 h in total), they found an enhanced fusiform gyrus response to the letters in both hemispheres while the response to pseudoletters and shapes remained unchanged. However, it should be noted that in the study of James (2010), children in visual learning groups were

offered the pronunciations of the whole words which consisted of the letters to be learned. In other words, the children in that study were presented with the whole word in learning sessions but tested with the recognition of letters instead of words after training. This procedure might lead less effective visual learning since the grapheme-phoneme correspondences would be less likely to be encoded (Morrison et al., 1995).

One explanation of the small learning effects of free writing in our study is that the task of writing Chinese characters is more cognitive-resource consuming than writing a letter. Writing characters involves greater demands on visual-spatial working memory, and writing ability itself is constrained by the individual's working memory (Swanson and Berninger, 1996). Constrained by limited cognitive resources in this way, young children in the FW group may not be able to spare more resources during character learning, thus resulting in poorer learning throughout the training period (Van Merriënboer and Sweller, 2005). This is in line with the finding of Longcamp et al. (2005), which suggests that only children in an appropriate age can benefit from writing learning. To our knowledge, the crucial role of writing in reading Chinese has only been found in school age children who have advanced working memory ability (Tan et al., 2005, 2013); no study has been reported in preliterate children. However, importantly, a failure to enhance the N170 amplitude to Chinese characters in the writing group does not mean a failure to enhance any skill that might be useful for expertise processing. For example, writing-training did improve children's performance in the character-matching test. Thus, neural markers of expertise such as the N170 might be modulated by only a subset of the perceptual skills that might benefit from familiarity, and domain-specific expertise.

Another possibility is that writing training does have a role in improvement of word N170 expertise processing but we could not detect it due to the stimuli we used in the present study. Faces and tools are two visual categories that are highly dissimilar in appearance to Chinese characters. A stronger effect of writing training on N170 selectivity might be seen in a task that requires finer processing of Chinese characters. Recent studies have found that children and adults learning Chinese as a second language with higher writing ability were reduced in holistic processing of Chinese characters (Tso et al., 2012, 2014). It suggested that writing experience may enhance the local processing of Chinese characters over the more global and category level selection. It seems that the children in the visual identification group were likely to pay more attention to the global information of the character since they needed to choose one character from many other characters, while children in the writing learning group may attend more to the local information. The different training effects we found in the current study may reflect different approaches or processing strategies taken by the children in the two groups. Therefore, additional studies are needed to test this hypothesis by use of stimuli sharing certain orthographic patterns with Chinese characters (e.g. Lin et al., 2011).

Although the exposure time of characters was controlled between the two training groups, it seems that a greater number of Chinese characters were exposed to the children in the visual learning group since children in that group were required to search the learning characters among other characters. In addition, the visual learning groups were presented with additional characters as distracters when they identified the learnt characters during training sessions. It is likely that the changes in character N170 amplitude in the visual learning group could be affected by the more frequent exposure to characters in general; though these extra distracters were probably not attended to as often or as strongly as the target characters. However, mere passive print exposure might not be the direct reason of the different training effects in both groups. As stated in James study (2010), children do not learn from the

environment by passively sampling. Rather, they “move through our environment voluntarily, and attend, explore, manipulate and handle the pieces of our environment that we choose.” In short, we are “active perceivers”.

Although we found different training effects in VL and FW groups, both training approaches led to changes in N170 selectivity in the right occipito-temporal sites. In a study of German young children, 6.5 year old children with high letter knowledge also showed marginal N1 word-symbol differences in right occipito-temporal sites (Maurer et al., 2005b). N1 effects in both alphabetic and logographic scripts indicate that the right hemisphere plays an important role in the early development of word expertise processing. Given a small degree of early literacy experience, word N170 expertise processing can start to develop at early age, but still differs from the mature, more left-lateralized N170 in adults (Maurer et al., 2005b).

In terms of N170 latency, we found that the peak latency of faces and characters were shorter than that of tools but the peak latency of characters were still longer than that of faces. The shorter face N170 latency suggests that the expert processing of faces starts to develop earlier (Itier and Taylor, 2004) whereas the longer N170 peak latency of characters indicates that the neural specialization of characters was still in the developmental process. The development of such an expertise still requires more extensive learning and the further development and maturation of the neural system (Rossion et al., 2003).

Another interesting finding of our study is that with the increasing N170 amplitude for characters, the amplitude of faces decreased at the same time especially in the left hemisphere after visual learning Chinese characters. Li et al.'s study finds that young children's reading ability has a negative effect on N170 right lateralization for faces (S. Li et al., 2013). The current results provides further and direct evidence to support the competition hypothesis of the development of visual word expertise (Dehaene and Cohen, 2007), which proposes that there is competition between culturally or environmentally shaped visual processing and perhaps the more hard-wired visual processes like face perception that may be more shaped by evolution. Explicitly teaching children to read may induce children to devote more neural resources to process words at the expense of the neural resources for face processing (S. Li et al., 2013). More importantly, devoting more neural resources to the development of word processing does not necessitate competition with neural development in other domains. As we found in the current study, the object (tools) N170 amplitude did not change significantly after training.

Our study is the first to find that the word-related N170 expertise emerges very quickly in young Chinese children (4 to 5 years old) after only short-term word learning. Visual and writing learning have different effects on visual word N170 expertise processing. These results suggest that different experiences with the same stimuli (Chinese characters) can exert different effects on a child's developing brain. However, due to the limitation of our sample size in the present study, the underlying mechanism of experience-brain interactions during development still needs to be investigated. The experience-brain interactions during development are very complex. Child behavior and cognition emerge from dynamic neural connectivity in developing brains. Actually, in developing brains, there are two modes of networks: structural networks and functional networks. Each mode shapes and constrains the other across multiple timescales and each shows age-related changes as well (Byrge et al., 2014). The intrinsic brain dynamics, extended brain-behavior networks and developmental process construct a very complex dynamic system. Visual word expertise processing, as one of the important aspects of brain specialization correlated with multiple experience (reading and writing), emerges and develops from such a dynamic system. For

example, visual and motor experience integration across sensory and motor systems can contribute to functional visual word specialization (James and Atwood, 2008). Thus, future studies need to explore the changes of brain connectivity under different types of literacy experience, and in children with different ages. Evidence from these studies, we hope, will eventually answer the question of why different environmental inputs results in different effects on children's brain activity and their behavior.

## References

- Allison, T., McCarthy, G., Nobre, A., Puce, A., Belger, A., 1994. Human extrastriate visual cortex and the perception of faces, words, numbers, and colors. *Cereb. Cortex* 4 (5), 544–554.
- Baker, C.I., Liu, J., Wald, L.L., Kwong, K.K., Benner, T., Kanwisher, N., 2007. Visual word processing and experiential origins of functional selectivity in human extrastriate cortex. *Proc. Natl. Acad. Sci.* 104 (21), 9087–9092.
- Bentin, S., Mouchetant-Rostaing, Y., Giard, M., Echallier, J., Pernier, J., 1999. ERP manifestations of processing printed words at different psycholinguistic levels: time course and scalp distribution. *J. Cogn. Neurosci.* 11 (3), 235–260.
- Brem, S., Bach, S., Kucian, K., Guttorm, T.K., Martin, E., Lyytinen, H., Richardson, U., 2010. Brain sensitivity to print emerges when children learn letter–speech sound correspondences. *Proc. Natl. Acad. Sci.* 107 (17), 7939–7944.
- Brem, S., Bach, S., Kujala, J.V., Maurer, U., Lyytinen, H., Richardson, U., Brandeis, D., 2013. An electrophysiological study of print processing in kindergarten: the contribution of the visual N1 as a predictor of reading outcome. *Develop. Neuropsychol.* 38 (8), 567–594. <http://dx.doi.org/10.1080/87565641.2013.828729>.
- Brem, S., Bucher, K., Halder, P., Summers, P., Dietrich, T., Martin, E., Brandeis, D., 2006. Evidence for developmental changes in the visual word processing network beyond adolescence. *Neuroimage* 29 (3), 822–837.
- Brem, S., Halder, P., Bucher, K., Summers, P., Martin, E., Brandeis, D., 2009. Tuning of the visual word processing system: distinct developmental ERP and fMRI effects. *Hum. Brain Mapp.* 30 (6), 1833–1844.
- Byrge, L., Sporns, O., Smith, L.B., 2014. Developmental process emerges from extended brain–body–behavior networks. *Trends Cogn. Sci.* 18 (8), 395–403.
- Cao, X., Li, S., Zhao, J., Lin, S.E., Weng, X., 2011. Left-lateralized early neurophysiological response for Chinese characters in young primary school children. *Neurosci. Lett.* 492 (3), 165–169.
- Chan, D.W., Ho, C.S.-H., Tsang, S.-M., Lee, S.-H., Chung, K.K., 2006. Exploring the reading–writing connection in Chinese children with dyslexia in Hong Kong. *Read. Writing* 19 (6), 543–561.
- Chan, L., Zi Juan, C., Lai Foon, C., 2008. Chinese preschool children's literacy development: from emergent to conventional writing. *Early Years* 28 (2), 135–148.
- Chow, B.W.-Y., McBride-Chang, C., Cheung, H., Chow, C.S.-L., 2008. Dialogic reading and morphology training in Chinese children: effects on language and literacy. *Dev. Psychol.* 44 (1), 233–244.
- Cohen, L., Dehaene, S., 2004. Specialization within the ventral stream: the case for the visual word form area. *Neuroimage* 22 (1), 466–476.
- Cohen, L., Dehaene, S., Naccache, L., Lehéricy, S., Dehaene-Lambertz, G., Hénaff, M.-A., Michel, F., 2000. The visual word form area: spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. *Brain* 123 (2), 291–307.
- Curriculum Development Council, 1996. *Guide to the Pre-primary Curriculum*. Hong Kong, China.
- Dempster, A.P., Laird, N.M., Rubin, D.B., 1977. Maximum likelihood from incomplete data via the EM algorithm. *J. Roy. Stat. Soc. Ser. B (Methodological)*, 1–38.
- China Ministry of Education, 2001. *Early Childhood Education Guideline*. Beijing Normal University Press, Beijing.
- China Ministry of Education, 2013. *Calligraphy Education Guideline for Middle School and Primary School*.
- China Ministry of Education, 2011. *Language Curriculum Norm for Compulsory Education*. Beijing Normal University Publishing Group, Beijing.
- Dehaene, S., Cohen, L., 2007. Cultural recycling of cortical maps. *Neuron* 56 (2), 384–398.
- Itier, R.J., Taylor, M.J., 2004. N170 or N1? Spatiotemporal differences between object and face processing using ERPs. *Cereb. Cortex* 14 (2), 132–142.
- James, K.H., 2010. Sensori-motor experience leads to changes in visual processing in the developing brain. *Develop. Sci.* 13 (2), 279–288.
- James Karin, H., Atwood Thea, P., 2008. The role of sensorimotor learning in the perception of letter-like forms: tracking the causes of neural specialization for letters. *Cognit. Neuropsychol.* 26 (1), 91–110.
- Li, H., Shu, H., McBride-Chang, C., Liu, H., Peng, H., 2012. Chinese children's character recognition: visuo-orthographic, phonological processing and morphological skills. *J. Res. Reading* 35 (3), 287–307.
- Li, S., Lee, K., Zhao, J., Yang, Z., He, S., Weng, X.C., 2013. Neural competition as a developmental process: early hemispheric specialization for word processing delays specialization for face processing. *Neuropsychologia* 51 (5), 950–959.
- Lin, S.-E., Chen, H.-C., Zhao, J., Li, S., He, S., Weng, X.C., 2011. Left-lateralized N170 response to unpronounceable pseudo but not false Chinese characters—the key role of orthography. *Neuroscience* 190, 200–206.

- Liu, H.C., Jiang, Y., Zhang, B., Ma, L.F., He, S., Weng, X.C., 2013. The orthographic sensitivity to written Chinese in the occipital-temporal cortex. *Exp. Brain Res.* 227, 387–396.
- Longcamp, M., Zerbato-Poudou, M.-T., Velay, J.-L., 2005. The influence of writing practice on letter recognition in preschool children: a comparison between handwriting and typing. *Acta Psychol. (Amst.)* 119 (1), 67–79.
- Martzog, P., Chen, W., Stoeger, H., Shi, J., Ziegler, A., 2012. Specifying relations between fine motor skills and cognitive abilities: a cross-cultural study. In: Stoeger A.A., H., Harder, B. (Eds.), *Talent Development and Excellence*. LIT, Münster, Germany, pp. 135–154.
- Maurer, U., Brandeis, D., McCandliss, B.D., 2005a. Fast, visual specialization for reading in English revealed by the topography of the N170 ERP response. *Behav. Brain Function* 1 (1), 1–13, <http://dx.doi.org/10.1186/1744-9081-1-13>.
- Maurer, U., Brem, S., Bucher, K., Brandeis, D., 2005b. Emerging neurophysiological specialization for letter strings. *J. Cogn. Neurosci.* 17 (10), 1532–1552.
- Maurer, U., Brem, S., Kranz, F., Bucher, K., Benz, R., Halder, P., Brandeis, D., 2006. Coarse neural tuning for print peaks when children learn to read. *Neuroimage* 33 (2), 749–758.
- Maurer, U., Zevin, J.D., McCandliss, B.D., 2008. Left-lateralized N170 effects of visual expertise in reading: evidence from Japanese syllabic and logographic scripts. *J. Cogn. Neurosci.* 20 (10), 1878–1891.
- McBride-Chang, C., Chung, K.K., Tong, X., 2011. Copying skills in relation to word reading and writing in Chinese children with and without dyslexia. *J. Exp. Child Psychol.* 110 (3), 422–433.
- McCandliss, B.D., Cohen, L., Dehaene, S., 2003. The visual word form area: expertise for reading in the fusiform gyrus. *Trends Cogn. Sci.* 7 (7), 293–299.
- Morrison, F.J., Smith, L., Dow-Ehrensberger, M., 1995. Education and cognitive development: a natural experiment. *Dev. Psychol.* 31 (5), 789–799.
- Rossion, B., Joyce, C.A., Cottrell, G.W., Tarr, M.J., 2003. Early lateralization and orientation tuning for face, word, and object processing in the visual cortex. *Neuroimage* 20 (3), 1609–1624.
- Shu, H., 2003. Chinese writing system and learning to read. *Int. J. Psychol.* 38 (5), 274–285.
- Siok, W.T., Fletcher, P., 2001. The role of phonological awareness and visual-orthographic skills in Chinese reading acquisition. *Dev. Psychol.* 37 (6), 886–899.
- Swanson, H.L., Berninger, V.W., 1996. Individual differences in children's working memory and writing skill. *J. Exp. Child Psychol.* 63 (2), 358–385.
- Tan, L.H., Laird, A.R., Li, K., Fox, P.T., 2005. Neuroanatomical correlates of phonological processing of Chinese characters and alphabetic words: a meta-analysis. *Hum. Brain Mapp.* 25 (1), 83–91.
- Tan, L.H., Xu, M., Chang, C.Q., Siok, W.T., 2013. China's language input system in the digital age affects children's reading development. *Proc. Natl. Acad. Sci.* 110 (3), 1119–1123.
- Tso, R.V.Y., Au, T.K.-f., et al., 2012. Writing facilitates learning to read in Chinese through reduction of holistic processing: a developmental study. *J. Vis.* 12 (9), 530.
- Tso, R.V.-y., Au, T.K.-f., et al., 2014. Perceptual expertise: can sensorimotor experience change holistic processing and left-side bias? *Psychol. Sci.*, 0956797614541284.
- Tong, X., Yip, J., 2015. Cracking the Chinese character: Radical sensitivity in learners of Chinese as a foreign language and its relationship to Chinese word reading. *Read. Writing* 28 (2), 159–181.
- Van Merriënboer, J.J., Sweller, J., 2005. Cognitive load theory and complex learning: Recent developments and future directions. *Educ. Psychol. Rev.* 17 (2), 147–177.
- Wong, A.C.-N., Bukach, C.M., Hsiao, J., Greenspon, E., Ahern, E., Duan, Y., Lui, K.F., 2012. Holistic processing as a hallmark of perceptual expertise for nonface categories including Chinese characters. *J. Vis.* 12 (13), 1–15.
- Wong, A.C., Gauthier, I., Woroch, B., Debuse, C., Curran, T., 2005. An early electrophysiological response associated with expertise in letter perception. *Cognit. Affect. Behav. Neurosci.* 5 (3), 306–318.
- Wu, X., Li, W., Anderson, R.C., 1999. Reading instruction in China. *J. Curriculum Stud.* 31 (5), 571–586.
- Zhao, J., Kipp, K., Gaspar, C., Maurer, U., Weng, X., Mecklinger, A., Li, S., 2014. Fine neural tuning for orthographic properties of words emerges early in children reading alphabetic script. *J. Cogn. Neurosci.* 26 (11), 2431–2442, [http://dx.doi.org/10.1162/jocn\\_a.00660](http://dx.doi.org/10.1162/jocn_a.00660).
- Zhao, J., Li, S., Lin, S.-E., Cao, X.-H., He, S., Weng, X.-C., 2012. Selectivity of N170 in the left hemisphere as an electrophysiological marker for expertise in reading Chinese. *Neurosci. Bull.* 28 (5), 577–584.