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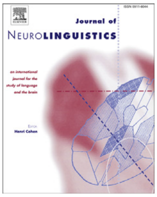

Incremental learning of Chinese orthography: ERP indicators of animated and static stroke displays on character form and meaning acquisition

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ABSTRACT

We examined the hypothesis that encoding Chinese characters through stroke-by-stroke animation produces orthographic learning that is different from conventional static displays. We used behavioral responses and ERPs to index the incremental learning that occurs of character forms, and the attention allocation to dynamic vs. static encodings. Adult, native English speakers learned form-meaning associations for characters displayed either statically or dynamically while ERPs were recorded. During learning, in both conditions, the P600 component decreased over exposures, indexing incremental and episodic learning of characters. Moreover, dynamic displays, relative to static displays, produced a larger P300, indexing attention-based updating of orthographic representations. Furthermore, the P300 predicted retention for dynamically encoded characters. On a form-meaning judgment task immediately following learning, an incongruity N400 effect was found for only the statically-encoded characters, although behavioral accuracy was similar across conditions. Our findings suggest multiple pathways to orthographic learning that result in trade-offs in learning form and meaning lexical constituents.

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1. Introduction

Universally, a skilled reader develops word representations that include strong interconnections among three lexical constituents – orthography, phonology, and semantics (Perfetti, Liu, & Tan, 2005). In order to attain high quality word representations, learners need to establish robust bidirectional connections between these constituents when learning to read (Perfetti & Hart, 2002). However, the ease of establishing these connections differs across writing systems (Aro & Wimmer, 2003; Ellis et al., 2004; Liu, Wang, & Perfetti, 2007), which differ both in the structure of orthographic forms and how these forms map to language.

For learners with an alphabetic language background, the visual complexity of Chinese orthography creates a particularly challenging task. In English, written words are composed from a pool of 26 letters in a simple linear fashion. In contrast, Chinese characters are composed of any or all of five basic strokes and their 44 variants, which are interwoven in stroke patterns to form up to 439 component radicals. The radicals, following more than 11 positional constraints in two-dimensional space, make up the compound characters that account for 80% of 7000 frequent characters (Chinese Language Committee, 2009). The rich number and novel composition of orthographic units create a challenge to learners, who must establish stable links between orthographic forms and meanings. The links from character-level orthography to meaning are necessary for skilled Chinese reading, because the links from phonology to meaning are more unreliable given pervasive homophones in Chinese (Perfetti et al., 2005).

A growing body of research has shown that handwriting is strongly correlated with reading acquisition among native Chinese learners (Chan, Ho, Tsang, Lee, & Chung, 2006; Pak et al., 2005) and that handwriting enhances character learning among Chinese as a foreign language (CFL) learners (Cao et al., 2012, 2013; Guan, Liu, Chan, Ye, & Perfetti, 2011; Xu, Chang, Zhang, & Perfetti, 2013). The CFL studies demonstrate that handwriting strengthens orthographic representations and connections to semantics. For example, Guan et al. (2011) found that CFL learners developed more robust orthographic representations (as seen in a lexical decision task) and had better meaning recall (as seen in a translation production task) when they had encoded such representations through handwriting compared with either passive reading or *pinyin*-typing (*pinyin*: a phonetic system for transcribing the pronunciation of characters into Latin script).

Two mechanisms were proposed for this writing-on-reading effect (Cao et al., 2013; Guan et al., 2011; Tan, Spinks, Eden, Perfetti, & Siok, 2005). First, writing adds additional sensory-motor information to the representations and this motor memory serves visual recognition. Second, writing focuses attention on stroke compositions, eliciting greater visual attention on orthographic representations. A neural basis of the motor mechanism has been explored in several neuroimaging studies (Cao et al., 2012; Longcamp, Anton, Roth, & Velay, 2003). Cao et al. (2012) found that Chinese characters learned through handwriting elicited greater involvement of bilateral sensori-motor cortex during a lexical decision task compared with characters learned through passive viewing. Furthermore, ERP evidence (a larger P100) suggested enhanced visual attention to characters that had been learned through handwriting (Cao et al., 2013), reflecting early, low level attentive processes in visual cortex. Thus, there is evidence consistent with two writing-on-reading mechanisms, enhanced sensory-motor and sequential memories as well as visual-attention allocation.

The present study aims at better understanding the possible role of visual attention in the writing-on-reading effect through an online ERP study of character learning by adult learners of Chinese. The critical manipulation was whether characters were presented dynamically in the correct stroke sequence (a dynamic condition) or statically with the complete character on-screen (a static condition). High-temporal-resolution ERPs provide a window on the unfolding of attention and memory mechanisms that underpin the incremental learning of characters that occurs over multiple exposures.

Our use of dynamic character displays with ERP methods is motivated by three observations. First, theoretically, dynamic character displays can encourage “implicit writing”. Viewing how a character is composed sequentially on a stroke-by-stroke basis resembles writing the character by hand, but without the overt involvement of the motor system. Moreover, dynamic presentation draws attention to the internal composition of characters, emphasizing the development of visual-orthographic representations. Thus, presenting characters dynamically may expose the learner's attention to stroke compositions without explicit motor involvement. Second, practically, dynamic animation affords a simple and economic way to learn characters. Although writing is effective, it is more time-consuming and labor-intensive. The potential value of animation has been manifested in some auxiliary teaching tools (e.g., Chen, Chien, & Chang, 2013) and self-learning programs (e.g., Estroke by Eon Media Ltd) in Chinese pedagogy. Third, methodologically, ERPs are sensitive to the temporal unfolding of cortical processes and often expose processes that go undetected with behavioral measures (Cao et al., 2013; McLaughlin, Osterhout, & Kim, 2004; Tokowicz & MacWhinney, 2005). In our case, ERPs can allow inferences about temporal unfolding of the orthographic learning processes (e.g. separation of attention and memory) and indicators of orthographic-semantic associations.

We investigate the effects of dynamic and static encodings on the development of character orthographic representations and form-meaning associations by focusing on three ERP components: two memory-related components, the P300 and P600, as well as one meaning-related component, the N400. Below we briefly review theoretical bases of these components and relevant findings from word learning studies.

The P300 and P600 ERP components are of interest because prior research has shown that these two components reflect different aspects of encoding and memory (Friederici, 2002; Frisch, Kotz, von Cramon, & Friederici, 2003). These components can reflect processes that are open to differing cognitive descriptors and there is a question about whether the P600 belongs to the P300 family (Coulson, King, & Kutas, 1998; Frisch et al., 2003). However, in our learning paradigm, it is useful to consider the P300 as an indicator of perceptual memory and the P600 as an indicator of episodic memory, consistent with much of the research literature on these components.

One influential account of the P300 is the context updating hypothesis (Donchin, 1981), which interprets the P300 as reflecting the updating of mental representations, which occurs through an attention-driven comparison of stimulus attributes that produces a reaction to differences. In processing sensory stimuli, the P300 has been shown to reflect attention: Greater P300 amplitudes are elicited to target stimuli relative to other stimuli (Kok, 1997; Polich, 1989; Rushby, Barry, & Doherty, 2005). At higher levels, distinctive words (Fabiani, Karis, & Donchin, 1986, 1990) and more attended words elicit larger P300 responses (Curran, 2004; Curran & Cleary, 2003). In line with this attention interpretation, we expect the P300 to be an indicator of attention allocation during character learning. More specifically, and consistent with the updating interpretation, this component should be associated with stroke by stroke dynamic displays, which explicitly update a previous stimulus by adding a stroke.

In contrast, we take the P600 component as an index of episodic memory. In a classic recognition paradigm, greater P600 amplitudes occur during recognition of “old” (previously presented) items relative to “new” items (Curran, 1999; Rugg, Allan, & Brich, 2000; Rugg et al., 1998; Rugg, Schloerscheidt, Doyle, Cox, & Patching, 1996). Applied to word learning, larger P600 components have been associated with the viewing of newly learned words relative to both unknown words and familiar words (Balass, Nelson, & Perfetti, 2010; Perfetti, Wlotko, & Hart, 2005). These findings can be explained by an episodic, recollection-based account of the P600.

The N400 component has largely been associated with meaning retrieval or meaning integration (Brown & Hagoort, 1993; Federmeier & Kutas, 1999; Kutas & Hillyard, 1980a, 1980b; for a review, see Kutas & Federmeier, 2011). In previous word learning studies, N400 effects have been observed during meaning judgments to words learned in sentence contexts (Mestres-Misse, Rodriguez-Fornells, & Munte, 2007), with synonym-like definitions (Perfetti, Liu, et al., 2005; Perfetti, Wlotko, et al., 2005), or as incomplete lexical entries, with new words associated with meaning or phonology but not both (Balass et al., 2010).

In summary, our study addresses two research questions. First, what is the influence of two different character encodings – dynamic and static – on the establishment of robust orthographic representations? Second, to what extent do dynamic and static encodings strengthen form-meaning associations? Specifically, we hypothesize that dynamic encoding of characters will lead to better form recognition than static encoding, given that the dynamic presentation will draw learners' attention to the internal composition of the characters. We expect this dynamic learning mechanism will lead to larger P300 responses to dynamically encoded characters relative to statically encoded ones. We also expect incremental learning to be reflected by P600 responses to the newly-learned characters over exposures. Furthermore, if dynamic displays lead to better orthographic learning, we would predict that they would lead to stronger form-meaning associations, which depend on orthographic form representations. This would lead to reduced N400 in response to dynamically encoded characters relative to statically encoded characters on a meaning-based task. Finally, we are interested in examining whether the hypothesized encoding effect can be seen in a long-term retention. By designing a delayed test two weeks after the learning, we expect that brain responses which are sensitive to encoding manipulation would be predictive to retention scores for characters learned by different encodings.

Our predictions are based on the visual-attention allocation hypothesis: By drawing learners' attention to the visual forms, dynamic encoding will lead to the establishment of robust orthographic representations. When attention is directed to the orthographic constituent, the resulting higher quality form representations may allow associations to be more readily made from to the semantic constituent, leading to strong form-meaning memory traces. To test these predictions, we adopted a combined behavioral (explicit) and ERPs (implicit) approach, recording ERPs during learning as well as testing. To the best of our knowledge, this study is the first to examine on-line processing during the incremental learning of Chinese orthography.

2. Methods

2.1. Participants

Nineteen adult CFL learners (10 male) enrolled in 2nd-year Chinese classes at the University of Pittsburgh participated. Ages ranged from 18 to 30 years (mean = 20.73 years, *SD* = 3.09). All participants met the following criteria, based on an informational interview: (1) native English speaking, (2) no Chinese-heritage background, (3) normal or corrected-to-normal vision, (4) right handed, (5) no history of neurological or psychiatric impairment, and (6) no learning disorder. During the learning and testing phases, participants continued their Chinese class.

2.2. Materials

Sixty Chinese characters that had not been taught at the time of the experiment were selected as learning materials from the participants' Chinese textbooks. Half of the characters have a left-right configuration and the other half have an up-down configuration. In addition to configuration, the characters were matched by (1) number of strokes, (2) number of chunks as defined by the Chinese Orthography Database (Chen, Chang, Chiou, Sung, & Chang, 2011), and (3) frequency of the English translation (Brysbaert & New, 2009). Detailed information of each character can be retrieved from the Appendix. All the characters have identical forms in the traditional and the simplified systems.

2.3. Procedure

This study used a within-subject design that included pretest, learning, immediate testing, and delayed testing phases. The independent variables are presentation type (dynamic vs. static) and number of exposure (first vs. average across second and third exposures); the dependent variables are behavioral performance (accuracy and reaction time) and ERP components (P300, N400, and P600). The ERP recordings were made during the learning and immediate testing phases.

In the pretest phase, the participants were asked to write the *pinyin* and meaning of the 60 characters used in the learning phase. Immediately after the pretest, the participants moved to a sound-attenuated and electrically insulated booth equipped with a computer and a 15-in (38.1 cm) CRT display with a 60 Hz refresh rate to begin learning and testing. At a set viewing distance of 60 cm, both dynamic and static displays subtended a vertical and a horizontal visual angle of 2°. All computerized tasks were programmed and carried out on E-Prime software (Psychology Software Tools, Inc., Pittsburgh, PA).

In the learning phase, the participants were instructed to pay attention to the form and the English translation of each character and to try to associate the form with its meaning. Each character learning trial proceeded as follows (in order of display): a 500 ms fixation point, a blank display for 300 ms, a character presented statically for 1000 ms, another blank display for 300 ms, either a dynamic or a static presentation of the character (the presentation times were equated), the character presented statically for 1000 ms, the character's English translation presented for 1000 ms, and finally, an eye image presented for 1000 ms to indicate to participants that they were able to blink freely. For the dynamic display, each stroke smoothly appeared over 300 ms to present its writing sequence (average number of strokes = 10); for the static display, each character remained complete over the same presentation time as it did in the dynamic presentation. Fig. 1 provides an overview of the trial sequence for the two conditions of the same character. 30 characters were learned using a dynamic presentation and 30 characters were learned using a static presentation. For each condition, there were three blocks and 30 characters appeared randomly within a block. Thus, the participants experienced three exposures to the learning trial of each character. Both the learning materials and the sequence of encodings were counterbalanced. The learning phase lasted approximately 25 min.

Immediately after the learning phase, the participants completed an old/new judgment task and a form-meaning matching task. In the old/new judgment task, the participants were exposed to the 60 characters from the learning phase and 60 novel characters. Following a fixation point for 500 ms, a character was presented for 1000 ms, followed by a “yes-no” judgment presented for 1000 ms. The participants were instructed to judge whether the character presented on the screen was a previously-presented character. In the form-meaning matching task, the participants saw characters followed by English translations that were learned during the learning session. Half of the 60 translations semantically matched with the characters, and half semantically mismatched with the character. Following a fixation point for 500 ms, a character was presented for 1000 ms, followed by an English word for 1000 ms, and then a “yes-no” judgment for 1000 ms. The participants were instructed to judge whether the English word was the correct meaning of the character. For both judgment tasks, the participants used their index fingers to press a button for a “yes” or a “no” response. This delayed judgment design excluded ERP contamination from a readiness potential. The “yes” and “no” buttons were counterbalanced across participants. The presentation of stimuli in each task was randomized.

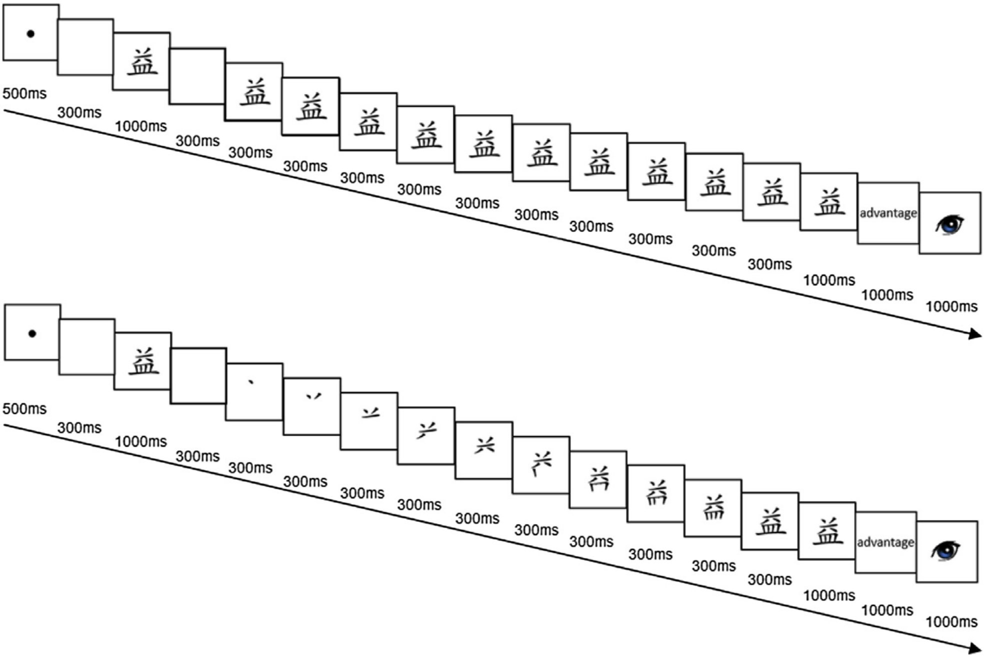

Fig. 1. Example trials for static (top panel) and dynamic (down panel) presentations of the same character 益 (English translation: advantage).

Two weeks after the learning session, the participants completed a paper-and-pen form-meaning matching task as a retention test. The test presented the same 60 character-English word pairs that appeared at immediate test. The participants were instructed to judge whether the character have the same meaning as the English words or not (write "Y" for "Yes" and "N" for "No").

2.4. ERP data acquisition and pre-processing

ERP data were recorded during the learning the immediate testing phases. Participants were fitted with a 128 electrode Geodesic sensor net (Tucker, 1993) with Ag/AgCl electrodes (Electrical Geodesics, Inc., Eugene, OR). Scalp potentials were recorded with a sampling rate of 500 Hz and a hardware bandpass filter of 0.01–200 Hz. Impedances were kept below 40 kΩ, a good threshold with this system (Ferree, Luu, Russell, & Tucker, 2001). During the recording, a vertex reference was used; later, the data was referenced offline using an average reference. Six electrodes were monitored for artifacts related to eye-blinks and eye-movements.

Preprocessing was done using both EEGLAB (Delorme & Makeig, 2004) and NetStation software (Electrical Geodesics, Inc., Eugene, OR). Offline, data were re-referenced to the average reference. Independent components were extracted utilizing the Extended Informax algorithm (i.e., the binica function; Delorme & Makeig, 2004). The components related to eye movement were identified using ADJUST (Mognon, Jovicich, Bruzzone, & Buiatti, 2011) and then removed. Data were further analyzed in NetStation where segments were created based on the event of interest of each task. In the learning task, segments started 200 ms before the onset of the first static display of a character on each trial, and extended 800 ms (1000 ms in total). In the old/new judgment task, trials were segmented into 1000 ms epochs, starting 200 ms before onsets of characters. In the form-meaning matching task, trials were also segmented into 1000 ms epochs, starting 200 ms before onsets of English words. Segmented data were digitally filtered with a 30-Hz lowpass finite impulse response (FIR) filter. Within a segment, differential voltages greater than ±75 μV, and ±140 μV on two separate pairs of electrodes were considered eye movements and eye blinks, respectively. Moreover, any electrodes displaying variation less than ±0.5 μV within 150 ms or variation more than ±200 μV across the entire segment were considered bad channels. Segments that contained either eye movements, eye blinks, or more than 12 bad channels were rejected. After bad channels were removed and replaced by interpolation using data from surrounding channels (Ferree, 2006). Participants with more than 12 bad channels were removed from data analyses; only one participant in the form-meaning matching task was excluded due to excessive artifacts. After eliminating bad trials, mean number of trials per condition was 28.4 in the learning phase, 27.9 in the old/new judgment task, and 14.8 in the form-meaning matching task.

2.5. ERP data analyses

The ERP analysis focused on the P300, N400, and P600 components. We followed the conventions of prior research (Hoormann, Falkenstein, Schwarzenau, & Hohnsbein, 1998; Jeon & Polich, 2001; Picton et al., 2000; Polich, 2007) in examining both mean amplitudes and peak latencies for these components. The mean amplitude is defined as the average voltage of the ERP waveform within a certain time window. The peak latency is defined as the time to reach the greatest absolute amplitude within a specified time window.

Fig. 2 shows the schematic of the electrode net used in this study, including notations indicating the approximate locations of the international 10–20 system (Jasper, 1958). For the P300, potentials were analyzed within the time window of 270–380 ms using values averaged across frontal, central, and parietal areas (F3, Fz, C3, C4, P3, and P4 clusters). For the N400, potentials were analyzed within the time window of 350–500 ms using values averaged across central and right parietal areas (Pz and P4 clusters). For the P600, potentials were analyzed within the time window of 480–760 ms using values averaged across central-parietal areas (Cz and Pz clusters). Repeated-measures analyses of variance (ANOVAs) were performed to examine the effect of condition on the ERP components. When applicable, critical values were adjusted using the Greenhouse and Geisser (1959) correction for violation of the assumption of sphericity. When appropriate, differences were examined using the pairwise comparisons with Bonferroni correction.

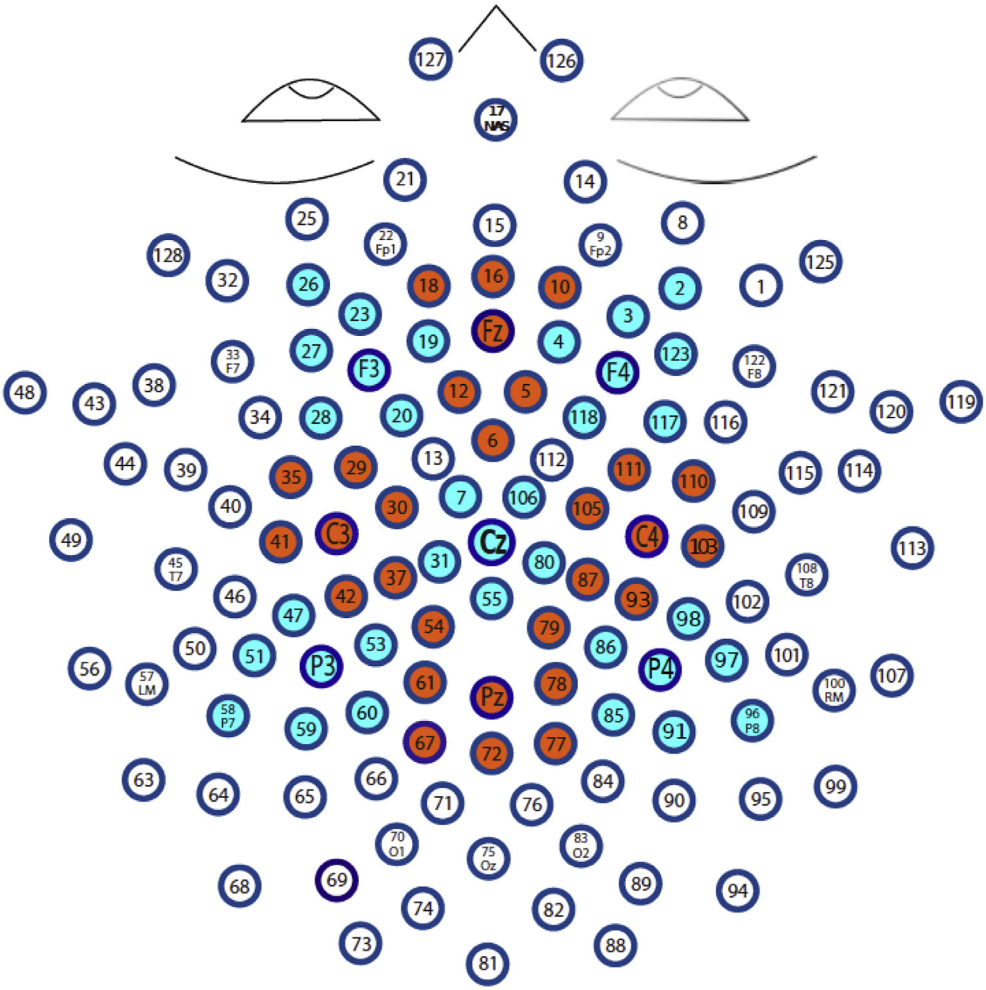

Fig. 2. Schematic flat representation of the 128 electrode positions (the front of the head is at the top). Electrode clusters that were used in data analysis are highlighted (red and blue are used to distinguish electrode clusters) and these 9 clusters correspond to the international 10–20 systems (F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Behavioral measures

Behavioral measures did not reveal any difference between dynamic and static conditions. Table 1 presents the descriptive statistics of participants' accuracy and reaction time (RT) on the correct responses in each task. In the pretest, none of the participants wrote the *pinyin* and meaning of the characters correctly. In the old-new judgment task, there was no condition difference on accuracy, $F(1,18) < 1$, whereas there was a significant difference on RT, $F(1,18) = 5.51$, $p = .03$, with the static presentation leading to faster RTs than the dynamic condition ($p = .03$). However, given that the RTs were retrieved from delayed responses where the participants were asked to respond when they saw a judgment probe, the faster RT on the static condition should be interpreted with a caution. In the form-meaning matching task, no difference between conditions was found either for the accuracy,

Table 1
Means and standard deviations (shown in parentheses) of accuracy and reaction time for the dynamic and static conditions in the immediate test and the retention test.

	Old/New Judgment task ($n = 18$)		Form-meaning Matching task ($n = 17$)		Retention task ($n = 18$)	
	Dynamic	Static	Dynamic	Static	Dynamic	Static
Accuracy (%)	88.00 (10.57)	88.32 (9.05)	86.72 (8.96)	87.89 (8.22)	70.35 (9.36)	71.40 (11.83)
Reaction time (ms)	342.90 (106.48)	327.07 (98.90)	319.74 (95.73)	328.25 (89.44)	–	–

$F(1,17) < 1$, or RT, $F(1,17) = 1.09$, $p = .31$. In the delayed paper-and-pencil retention test, no difference between the dynamic and static conditions was found, $F(1,18) < 1$.

3.2. ERP measures

ERP measures revealed significant difference between conditions. We summarize the major findings first and then present the results by tasks. In the learning phase, the results show (1) an increased P300 for the dynamic presentation, (2) for both static and dynamic presentations, an earlier P600 after repeated exposures to the characters. In the testing phase, the results show (3) a greater P300 for the new items over the old items, (4) a greater P600 for the old items versus the new items, and (5) a larger N400 on the semantically mismatched items than the semantically matched items for characters learned by static presentation, but not by dynamic presentation. Additionally, brain-behavior correlations show that (6) the amplitude difference of P300 (dynamic minus static) in the learning phase predicted two-week retention for characters learned by dynamic presentation.

3.2.1. Dissociation between P300 and P600 in the learning phase

In the learning phase, one critical question was whether dynamic presentation of characters would facilitate orthographic learning, compared with static presentations, as indexed by two memory-related ERP components: P300 (an indicator of perceptual memory) and P600 (an indicator of episodic memory). We carried out two types of analyses to answer this question. The first analysis examined the difference between dynamic and static conditions over exposures; the second analysis evaluated the difference across exposures to characters in the learning phase regardless of presentation condition (dynamic or static).

For the first analysis, we found an effect of learning condition on the P300 component but not on the P600 component. For the mean amplitude analysis, in the time window of the typical P300 (270–350 ms), the very first exposure, which preceded the display manipulation, produced no difference between conditions, $F(1,18) = 1.80$, $p = .20$, as expected. However, following the onset of the display manipulation, the average across the second and third exposures produced P300 amplitudes that were larger for the dynamically presented characters than for the statically presented characters, $F(1,18) = 5.16$, $p = .04$. For the P600 mean amplitude (time window: 480–760 ms), no difference was found between dynamic and static presentations either at the first exposure: $F(1,18) = 1.30$, $p = .27$ or for the average of second and third exposures: $F(1,18) < 1$. For the latency analysis, using the same time window and scale distribution, no differences between conditions were found.

For the second analysis, we found a general learning effect on the P600 component not the P300 component. Fig. 3 shows ERP waves illustrating the P600 difference across trials. In the 480–760 ms time window, a main effect of exposure was found by an ANOVA on the peak latencies, $F(2,36) = 5.98$, $p < .01$, but not mean amplitude, $F(2,36) < 1$. Averaging across the dynamic and static conditions, we found that the peak latency of the P600 was earlier during the second ($p = .02$) and third exposures ($p = .02$), than during the first exposure, with no further difference between the second and third exposures ($p = .99$). This main effect of exposure, however, was not apparent in the 270–350 ms time window of the P300, neither in peak analysis, $F(2,36) = 2.62$, $p = .12$, nor in amplitude analysis, $F(2,36) < 1$.

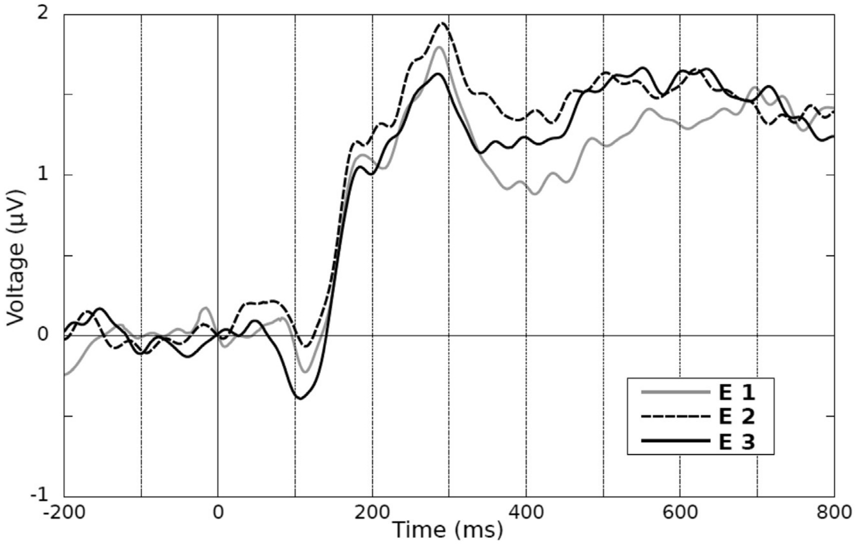

Fig. 3. ERP waves corresponding to 1st, 2nd, and 3rd exposures (E1/E2/E3) of P600 (time window: 480–760 ms) in the learning task, where electrodes are selected for analyses and corresponding to Cz of the 10–20 systems. P600 latency is longer for 1st exposure than for 2nd and 3rd exposures. Negative voltages are plotted down.

Overall, the dynamic presentation elicited larger P300 responses than did the static presentation, while both conditions produced an earlier amplitude peak in the P600 after the first exposure.

3.2.2. P300 and P600 effects in the old-new judgment task

In the testing phase, we continued to examine the P300 and P600 to observe the relationship between the perceptual and episodic memories. For each ERP component, two analyses were carried out. One analysis focused on the mean amplitude of the waveform when the participants encountered novel items (i.e., the "new" condition) relative to newly-learned items (i.e., the "old" condition). The other analysis focused on the mean amplitude of the waveform when the participants encountered items learned in the dynamic and static conditions of the learning phase. For the P300 component (time window: 280–380 ms), there was a difference between the new and old conditions, $F(1,18) = 18.26$, $p < .01$, with the new condition eliciting a greater positivity than the old condition ($p < .01$). However, no P300 difference was found between the dynamic and static conditions, $F(1,18) < 1$. For the P600 component (time window: 500–600 ms), there was also a difference between the new and old conditions, $F(1,18) = 5.61$, $p = .03$. The pattern of responses was the inverse of that in the P300, with characters in the old condition eliciting a greater positivity than those in the new condition ($p = .03$). No P600 difference was found between the dynamic and the static conditions, $F(1,18) < 1$.

In summary, during the old-new task, new characters elicited greater P300 responses than the old (newly learned) characters, whereas the old characters elicited larger P600 responses than the new characters. Fig. 4 shows the ERP mean amplitudes for the P300 and P600 effects in the old/new comparisons. No differences on either component were found between characters learned in the dynamic and static conditions.

3.2.3. N400 effect in the form-meaning matching task

Another critical question in the study was whether a dynamic presentation would strengthen the association between two lexical constituents – orthography and semantics. We answered this question by investigating the N400 component. In the time window surrounding the typical N400 (350–500 ms), a 2 (learning condition: dynamic and static) × 2 (stimuli type: semantically matched and semantically mismatched) ANOVA revealed a significant interaction, $F(1,17) = 7.94$, $p = .01$. Simple main effect tests found that characters presented dynamically showed no significant N400 differences between

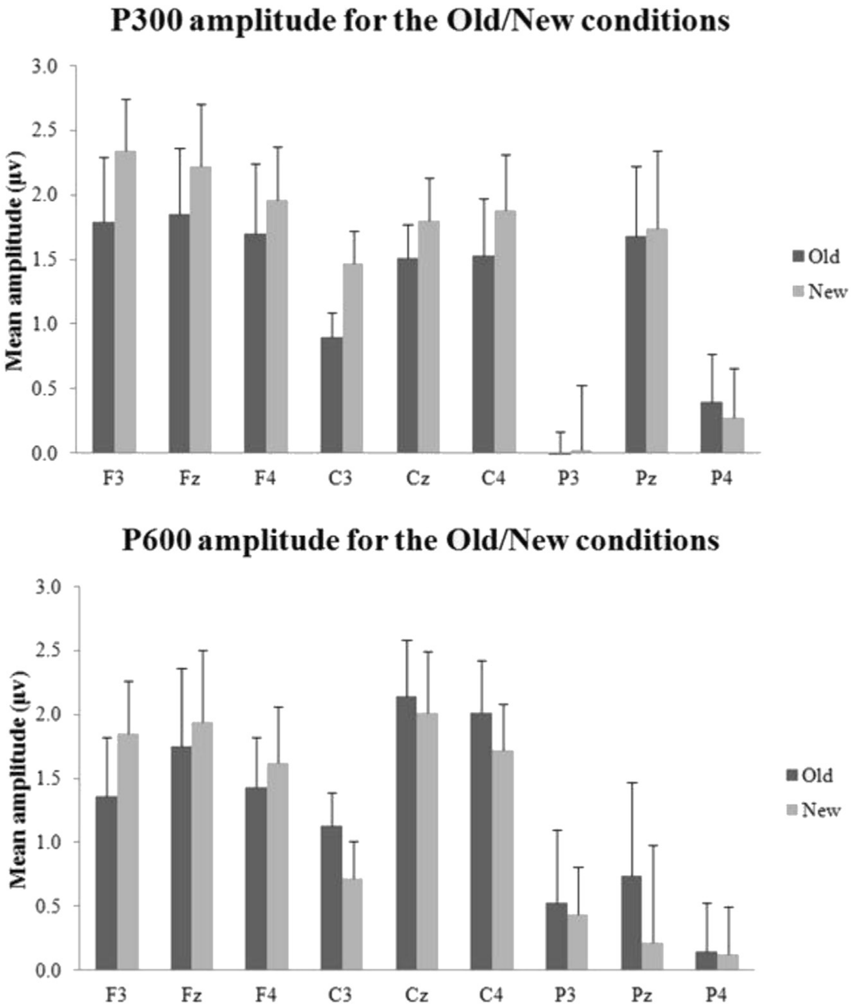

Fig. 4. P300 and P600 mean amplitudes for the “Old” and “New” conditions at clusters corresponding to the international 10–20 system. At the frontal and central areas, P300 is significantly greater for the new items than the old items. At the parietal area, P600 is significantly greater for the old items than the new items.

semantically mismatched and semantically matched stimuli ($p = .99$); for the characters that were presented statically, semantically mismatched stimuli elicited a greater negativity than semantically matched stimuli ($p < .01$). The restriction of the N400 effect to characters learned in the static condition diverges from the behavioral data, which show that meaning judgment accuracy and reactions times were comparable for static and dynamic presentations. The N400 difference between the two conditions may reflect the strength of the form-meaning association beyond what is indexed by RTs. The grand average waveforms and topographic maps for the dynamically and statically presented characters in semantically matched and semantically mismatched conditions are shown in Fig. 5 and Fig. 6, respectively.

3.3. *Brain-behavioral correlation over time*

Finally, we examined whether a brain indicator found to be sensitive to the dynamic vs. static manipulation in the learning phase (i.e., the P300 component) predicted form-meaning recall on the retention

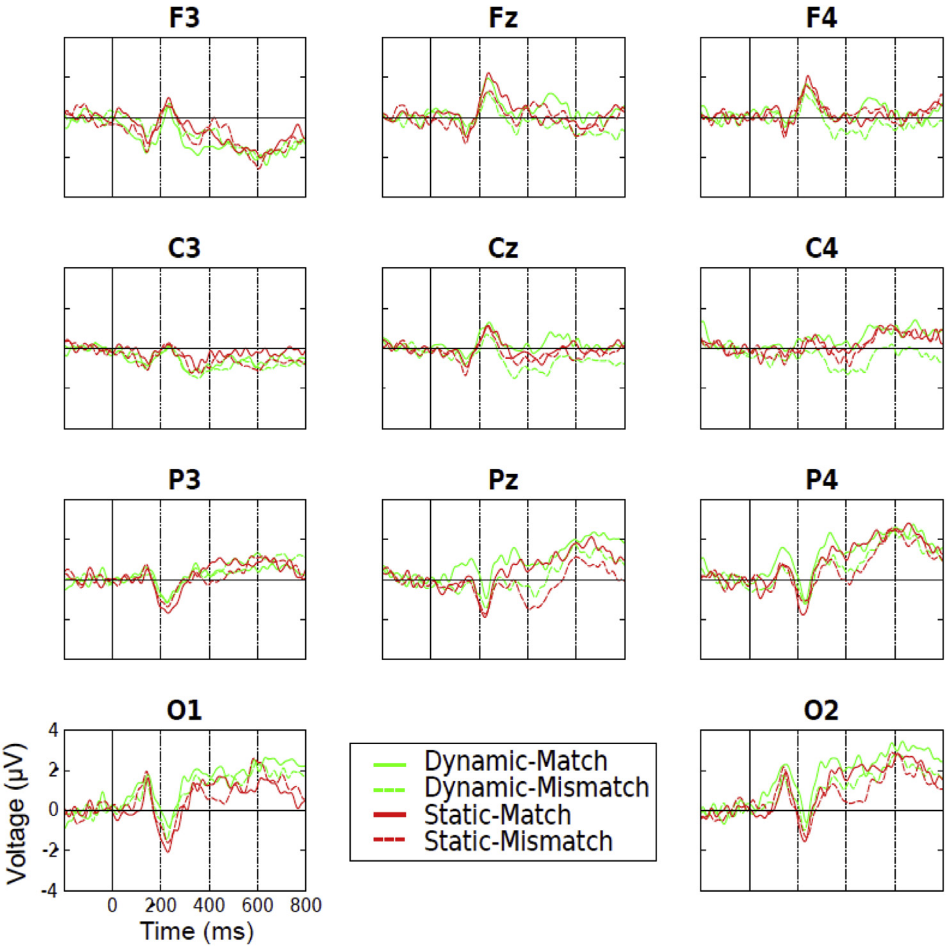

Fig. 5. ERP waves corresponding to the N400 effect (time window: 350–500 ms) in the form-meaning matching task. At the parietal area, N400 is significantly greater for static mismatched condition than for static matched condition.

test. We conducted two brain-behavior correlation analyses. First, because P300 amplitude differences were found between the dynamic and static presentations, we created amplitude difference scores by subtracting each participant's mean P300 amplitude in the static condition from that in dynamic condition. We correlated the P300 amplitude difference scores with the retention scores for the characters learned in the dynamic and static conditions. Larger P300 difference scores (dynamic minus static) were significantly and positively correlated with retention scores for characters learned in the dynamic condition ($r = .58$, $p < .01$, two-tailed). The P300 difference scores were negatively but not significantly correlated with retention scores for characters learned in the static condition ($r = -.27$, $p = .27$, two-tailed). Fig. 7 shows the brain-behavior correlation.

4. Discussion

This study investigated how dynamic and static encodings differentially support the development of orthographic representations and form-meaning associations in learning Chinese characters. Based on the visual-attention allocation hypothesis, we predicted that dynamic encoding would lead to better form recognition and further affect form-meaning mapping. The results diverged somewhat

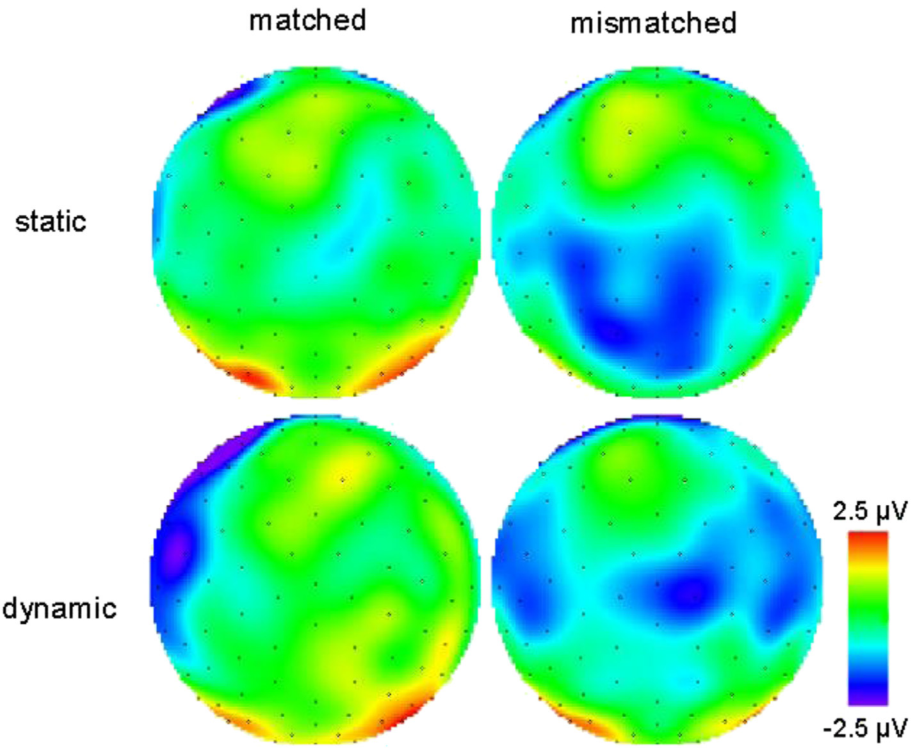

Fig. 6. Topographical maps of the N400 effect (time window: 350–500 ms) in the form-meaning matching task. At the parietal area, N400 is significantly greater for the static and mismatched condition than for the static and matched condition.

across behavioral and ERP measures: The behavioral measures did not reveal a reliable difference between dynamic and static encodings, but the ERP measures did.

Behaviorally, accuracies did not differ in the form-meaning matching task. Although reaction times favored static encoding, implications are limited given the design of delayed response probes. Interestingly, the ERP measures yielded significant differences between conditions: (1) although during learning, multiple exposures supported Chinese orthographic learning in both conditions equally (e.g., P600 was sensitive to exposures for both dynamic and static conditions), dynamic encoding induced more distinct orthographic representations than static encoding (e.g., P300 was sensitive to manipulations of attention allocation); (2) at immediate testing, N400 effects appeared only for statically encoded characters, suggesting that static encoding was better at establishing form-meaning links during beginning exposures to new characters; and (3) at a two week delay, greater character retention for characters encoded dynamically was positively associated with greater P300 responses during learning.

Taken together, the results suggest that an intervention designed to draw attention to details of orthographic form does not have a simple effect on all aspects of orthographic (character) learning; instead its effects are specific to the cognitive processes that are sensitive to the features of the intervention. Here, the dynamic sequencing of strokes had its effect on incremental attention to form, which in turn had an effect on long-term character recognition, but not on the association of form and meaning.

We ground these conclusions by reference to the dissociation between the P300 and P600 components during the learning phase. During learning, the P300 amplitude was greater for the dynamically encoded characters than the statically encoded characters. We suggest that the P300 effects reflect the attention-mediated updating attracted by the incremental addition of strokes during the dynamic display of a character. This interpretation is consistent with context updating theory

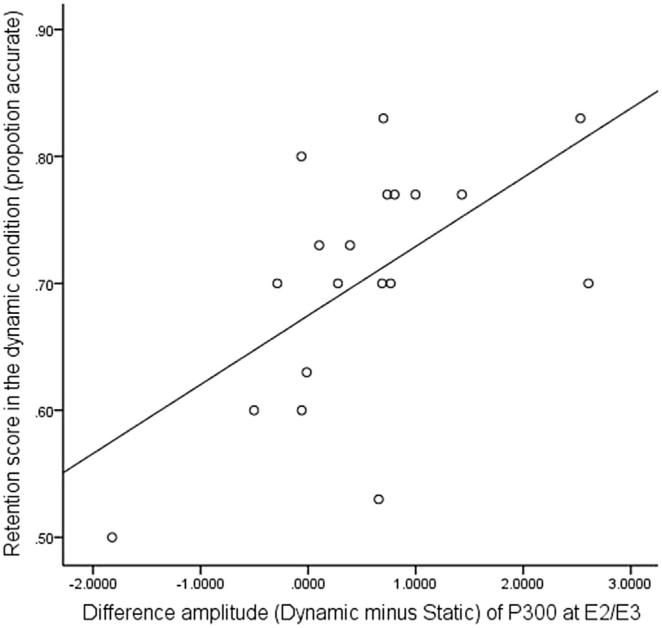

Fig. 7. Brain behavior correlations. The difference amplitude of P300 across 2nd and 3rd exposures (E2/E3) where electrodes are selected for analyses and corresponding to P3 and P4 of the 10-20 system is positively correlate with participants' retention scores in the dynamic condition.

(Donchin, 1981), which postulates an attention-driven comparison of a representation with a continuing stream of stimuli. The P300 is produced when a distinct stimulus or stimulus characteristic is detected. For example, words with distinctive features relative to other words (e.g., different font size) elicit larger P300 components during encoding and are more likely to be recalled (Karis, Fabiani, & Donchin, 1984).

The amplitude of the P300 thus may index an updating process associated with encoding operations (e.g., Fabiani, Karis, & Donchin, 1990; Paller, McCarthy, & Wood, 1988) that is facilitative of memory storage and retrieval (e.g., Azizian & Polich, 2007). We found that larger average P300 amplitudes for the dynamic condition relative to the static condition were associated with increased recognition after two weeks, as revealed by the positive correlation between P300 amplitude differences and retention scores for words learned in the dynamic condition. We reason that the participants may have more attentively encoded the dynamic characters, resulting in more highly-specified orthographic representations; these highly-specified representations later contribute to recognition.

While the P300 reflects attention and perceptual memory, the P600 indicates a different memory mechanism, reflective of episodic memory, or recollection-based memory. The P600 distinguishes repeated from unrepeated stimuli (e.g., Curran, 1999; Guillem, N'Kaoua, Rougier, & Claverie, 1995; Rugg & Nagy, 1989; Smith & Halgren, 1989). In word learning studies, the P600 has been demonstrated to be greater for recently learned words than “old” familiar words in English (Frishkoff, Perfetti, & Collins-Thompson, 2011; Perfetti, Wlotko, et al., 2005) and in Chinese (Cao et al., 2013). In the present study, we observed an earlier P600 peak following the second and third exposures to a character and this effect was indifferent to whether the display was static or dynamic. This implies a rapid neural response to a recognition event, as additional exposures reactivate previous word learning episodes. The disassociation between the P300 and P600 suggests that the P300 is sensitive to the amount of attentional resources engaged during dynamic encoding, while the P600 is sensitive to the number of exposures to the characters, regardless of the encoding method.

The second question of the present study was which method of encoding new characters, dynamic or static, better establishes form-meaning associations. We focused on an N400 effect (i.e., a greater negativity on semantically mismatched trials than on semantically matched trials) given that N400 has been shown as an indicator of strengthened form-meaning link (Mestres-Misse et al., 2007; Perfetti, Wlotko, et al., 2005). This N400 effect was elicited by characters learned in the static condition, but not the dynamic condition. This superficially appears in contradiction to Guan et al.'s (2011) study, which found that handwriting, a dynamic encoding method, lead to better meaning recall than a static encoding method (i.e., passive reading).

While both handwriting and viewing animation encourage greater visual attention to the orthographic constituent, these two interventions differ in how they introduce dynamic encodings. Viewing how characters are composed stroke-by-stroke guides learners' attention to the sequence of strokes that build to a visual-orthographic form, but without active motor encoding by the learner. The writing-on-reading effect (Cao et al., 2013; Guan et al., 2011; Tan et al., 2005), according to the fMRI study by Cao et al. (2013), has neural correlates in greater activation of sensori-motor and visual spatial brain areas, compared with passive viewing. Passively viewing dynamic displays may not produce these neural correlates, although we lack direct imaging comparisons between writing and animations effects. Instead, our results suggest that dynamic animations affect the allocation of visual attention, compared with static displays that represent normal reading. The difference we observe between static and dynamic displays may reflect cortical activity patterns that are influenced by visual attention in more subtle ways that the contrast produced by handwriting vs. reading. Thus, animated displays that enhance visual attention alone may not support the links from form to meaning that seem to be strengthened by writing. To put it another way, handwriting strengthens the representation of character forms and thus the formation of meaning connections to these forms. Animated displays strengthens the perception of building blocks of character forms – the sequence of specific strokes – rather than the character as whole functional unit, which is thus less accessible for meaning connections.

In this context, the ERP effects are relevant for considering display effects. Taking into account both the N400 results from the form-meaning matching task and the P300 effects during the learning phase, we see a trade-off in the learning of different lexical constituents. Greater P300 responses during learning were associated with greater retention of orthographic form learning over two weeks for the dynamically encoded characters. We attribute this effect to the dynamic encoding condition attracting attention (and thus perceptual memory) to the processing of the characters' visual forms. However, while this visual attention to form – the orthographic constituent – may establish a strong form representation, it may do so at a cost in establishing initial form-meaning links. In the form-meaning matching task, N400 effects were found only for characters encoded statically, suggesting that the form-meaning link was better strengthened by the relatively passive observation of the characters, which perhaps resulted in more equally allocated attention to both form and meaning. Thus, although dynamic exposure recruited greater attentional resources to encoding the character forms, this may have drawn attention away from the form-meaning link between the characters and their English translations. This resulted in the absence of an N400 effect for dynamically encoded characters in the form-meaning matching task and the presence of such an effect for statically encoded characters.

The trade-off interpretation of the results of this ERP study is consistent with previous behavioral studies (Xu, Chang, & Perfetti, 2014; Xu et al., 2013). In the most relevant study (Xu et al., 2013), compared the effectiveness of reading (i.e., static encoding), animation, and handwriting (i.e., dynamic encoding) in learning Chinese characters. Animation and handwriting led to better form recognition (i.e., faster reaction times), while reading lead to superior meaning recall (i.e., higher accuracy). The authors suggested a trade-off in different encoding methods: a dynamic encoding advantage for the orthographic constituent and a static encoding advantage for the form-meaning link. Their arguments resonate with the lexical quality hypothesis (Perfetti, 2007; Perfetti & Hart, 2002), which stresses that the lexical constituents (e.g., orthography, semantics, and phonology) can be learned to a higher level of quality at different rates for different individuals at different points during learning. Thus, these researchers proposed that characteristics of learners (e.g., vocabulary size), as well as interventions, may play a role in the development of lexical representations. Future studies involving individuals with different vocabularies and interventions with varied learning trials are needed to clarify these interpretations.

These studies combine with the present one in emphasizing the learning specificity of instructional procedures. In the case of orthographic learning, this specificity applies to the constituents of lexical representations. Thus, dynamic encoding (e.g., handwriting, animation, and visual chunking) draws attentional resources toward the incremental establishment of high-quality orthographic representations in which all strokes and radicals are fully specified (Perfetti, 2007; Perfetti & Hart, 2002). Static encoding (e.g., passive reading) may produce less fully specified representations, but until the character vocabulary becomes large and reduces the discriminability among the representations, these less complete representations are sufficient to make reliable links to meaning. That is, with the static display, the learner can allocate attention to associating semantic or phonological constituents to the orthographic representation (Perfetti, Liu, et al., 2005), even if it is not fully specified. These observations suggest that the use of multiple encoding methods may be effective for promoting high levels of learning that establish both fully specified forms and their associations to semantic constituents.

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Appendix

Learning Materials: 60 characters.

	Chinese character	S#	C#	Configuration	English translation	English translation frequency
1	引	4	2	left-right	to make	70,775
2	扔	5	2	left-right	to throw	6570
3	汗	6	2	left-right	sweat	1115
4	改	7	3	left-right	to change	12,258
5	股	8	2	left-right	share	3545
6	注	8	3	left-right	record	4365
7	咕	8	3	left-right	to rumble	139
8	呼	8	4	left-right	to call	43,931
9	括	9	2	left-right	to include	568
10	砍	9	2	left-right	to cut	11,718
11	拜	9	3	left-right	to bow	1034
12	俗	9	2	left-right	common	2275
13	修	10	4	left-right	study	2501
14	倒	10	3	left-right	to fall	6044
15	缺	10	2	left-right	to lack	905
16	值	10	3	left-right	to cost	2801
17	推	11	2	left-right	to push	3598
18	偶	11	2	left-right	even	44,672
19	剩	12	4	left-right	remains	890
20	握	12	3	left-right	to hold	22,273
21	硬	12	2	left-right	hard	15,700
22	跌	12	2	left-right	to drop	6661
23	傲	13	4	left-right	proud	4265
24	塔	13	5	left-right	tower	1165
25	煤	13	3	left-right	coal	335
26	殿	13	5	left-right	hall	2649
27	搞	13	2	left-right	to do	312,915
28	源	13	4	left-right	source	1437
29	福	14	4	left-right	happiness	1249
30	境	14	4	left-right	area	3821
31	互	4	2	up-down	mutual	368
32	充	5	2	up-down	full	8512
33	秀	7	2	up-down	beautiful	14,266
34	兵	7	2	up-down	arms	3050

(*continued*)

	Chinese character	S#	C#	Configuration	English translation	English translation frequency
35	命	8	4	up-down	life	40,629
36	妻	8	2	up-down	wife	17,795
37	奇	8	4	up-down	surprise	4534
38	享	8	3	up-down	to enjoy	4222
39	炎	8	2	up-down	hot	9682
40	皇	9	2	up-down	royal	1185
41	某	9	2	up-down	some	88,089
42	冠	9	4	up-down	hat	3273
43	染	9	3	up-down	to catch	6911
44	苦	9	3	up-down	bitter	15,700
45	突	9	2	up-down	suddenly	2854
46	宵	10	3	up-down	night	44,168
47	益	10	4	up-down	advantage	1125
48	盒	11	4	up-down	case	14,403
49	悉	11	2	up-down	to know	291,780
50	晨	11	2	up-down	morning	22,389
51	寄	11	5	up-down	to send	9169
52	袋	11	3	up-down	bag	4796
53	基	11	3	up-down	base	1804
54	曾	12	4	up-down	ever	36,170
55	善	12	4	up-down	good	133,117
56	筒	12	4	up-down	pipe	989
57	筷	13	3	up-down	chopsticks	93
58	聚	14	5	up-down	to collect	1020
59	熊	14	5	up-down	bear	2928
60	墓	14	4	up-down	grave	1340

Note. "S#" and "C#" refer to the number of strokes and the number of chunks in a character, respectively.

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