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Neuropsychologia. Author manuscript; available in PMC 2015 December 01.

Published in final edited form as:
Neuropsychologia. 2014 December ; 65: 156–168. doi:10.1016/j.neuropsychologia.2014.10.019.

Learning to Read Words in a New Language Shapes the Neural Organization of the Prior Languages

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Abstract

Learning a new language entails interactions with one's prior language(s). Much research has shown how native language affects the cognitive and neural mechanisms of a new language, but little is known about whether and how learning a new language shapes the neural mechanisms of prior language(s). In two experiments in the current study, we used an artificial language training paradigm in combination with fMRI to examine (1) the effects of different linguistic components (phonology and semantics) of a new language on the neural process of prior languages (i.e., native and second languages), and (2) whether such effects were modulated by the proficiency level in the new language. Results of Experiment 1 showed that when the training in a new language involved semantics (as opposed to only visual forms and phonology), neural activity during word reading in the native language (Chinese) was reduced in several reading-related regions, including the left pars opercularis, pars triangularis, bilateral inferior temporal gyrus, fusiform gyrus, and inferior occipital gyrus. Results of Experiment 2 replicated the results of Experiment 1 and further found that semantic training also affected neural activity during word reading in the subjects' second language (English). Furthermore, we found that the effects of the new language were

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modulated by the subjects' proficiency level in the new language. These results provide critical imaging evidence for the influence of learning to read words in a new language on word reading in native and second languages.

Keywords

Lexical learning; Reading; Cross-script interaction; Language; fMRI

1 Introduction

Learning new languages, especially how to read them, is essential for social and economic success in this era of globalization. Previous studies on bilingualism have suggested that a native language can shape the cognitive and neural strategies in learning to read a second language (Akamatsu, 1999; Nakada et al., 2001; Nelson et al., 2009; Perfetti et al., 2007; Tan et al., 2003; Wang et al., 2003). For example, Tan and colleagues (2003) found that, compared with English monolinguals, Chinese-English bilinguals showed more activation in the left middle frontal gyrus (a region responsible for addressed phonology when reading Chinese) during word reading in English. The same cross-script effect was also confirmed by another study (Nelson et al., 2009).

Much less attention has been paid to the influence of learning to read words in a new language on word reading in a native language. Thus far, only a few studies have examined how bilinguals and monolinguals differ in the neural processes of their native language. For instance, it has been revealed that the left inferior frontal gyrus is more involved in native language processing for bilinguals than for monolinguals (Kovelman et al., 2008; Parker Jones et al., 2012; Rodriguez-Fornells et al., 2002) and for more proficient bilinguals than for less proficient bilinguals (Nosarti et al., 2010). These results suggest that long-term second language learning can affect the neural basis of native language processing. However, it is unclear whether short-term lexical learning in a new language affects the neural representations of words in prior language(s) (i.e., native language and an already acquired second language) and whether such effects occur at the orthographic, phonological, or semantic level.

Three bilingual memory models are relevant to the discussion on the effect of learning to read words in a new language on word reading in native language. The separation hypothesis (McCormack, 1977; Weinrich, 1953) proposes that words in the two languages are separately represented, and thus learning to read words in a new language is not expected to affect representations of the native language words. In contrast, the integration hypothesis (for reviews, please see Abutalebi and Green, 2007; Kroll and Tokowicz, 2005) postulates that the languages form a single system, although the degree of overlap between the two lexicons may vary (i.e., from partial to complete overlap) across different words. For example, concrete words may share more conceptual features than do abstract words because of the possibility of distributed lexical representations (de Groot, 1992; Finkbeiner et al., 2004). Therefore, words in the two languages would affect each other in all aspects of linguistic features including orthographic, phonologic, and semantic representations. As a compromise between the above two views, the partial integration hypothesis proposes that the languages share a common conceptual system (i.e., semantics), but that their lexical forms (i.e., orthography and phonology) are represented separately (Kroll and Stewart, 1994; Kroll and Tokowicz, 2005; Kroll et al., 2010). Thus, the partial integration hypothesis predicts that learning to read words in a new language affects neural representations of native language words only in terms of the semantic system.

In this study with two experiments, we used an artificial language training paradigm (to be described below) to examine the effect of learning to read words in a new language on the neural mechanisms of word reading in prior languages (i.e., native and second languages) and the modulatory role of proficiency in the new language. This paradigm has at least two major benefits. First, it allows for separate training of the different aspects of lexical learning (i.e., phonological vs. semantic learning) (Xue et al., 2006b) to help to disentangle their effects on the neural representations of words in prior language(s). Second, the artificial language training paradigm also allows us to examine the dynamic process, as the training progresses, of the integration between artificial language words and words in prior language(s). Previous studies have suggested that second language proficiency may be important to the neural representations of the two languages in bilinguals (Abutalebi and Green, 2007; Chee et al., 2004; Perani and Abutalebi, 2005; Perani et al., 2003; Perani et al., 1998; Wartenburger et al., 2003). Specifically, several previous studies have revealed that native and second languages are represented differently in the brain when the proficiency level of the second language is low, but that they share the same neural representations when the proficiency level of the second language is high (Abutalebi and Green, 2007; Perani and Abutalebi, 2005; Wartenburger et al., 2003). All these studies, however, contrasted only low with high proficiency levels without examining the dynamic changes from low to high proficiency. Our literature search did yield one behavioral study that showed a U-shaped modulatory effect of second language proficiency on native language usage. Specifically, Chen (2006) relied on a linguistic difference in the structure of causality sentences between Chinese and English: In Chinese, the typical structure is “because...so...” (called the because-initial structure), whereas in English the “because” subordinate clause can appear either before or after the main clause. To examine the modulatory effect of second language proficiency on native language usage, Chen (2006) compared three groups of Chinese-English bilinguals--native Chinese speakers who had low, medium, and high-proficiency in English--in terms of their usage frequency of the because-initial structure in a Chinese causality sentence task. Results showed that the usage frequency of the because-initial structure was lower for subjects with medium proficiency in English than for either the low- or high-proficiency groups, indicating a U-shaped modulatory effect of second language proficiency. In the current training study, we also examined whether the effects of learning to read words in a new language on word reading in prior languages followed the U-shaped curve as subjects’ proficiency in the new language increased.

Following our previous studies (Chen et al., 2007; Xue et al., 2006b), an artificial language was created by adopting the visual forms and sounds of 60 Korean Hangul characters, which were assigned arbitrary meanings through pictures of 60 different objects (See Fig. 1 for examples). It should be noted that these objects were semantically unrelated to the native and second language materials (i.e., Chinese and English words) used in this study to eliminate the cross-script semantic priming effect as a potential confound. To separate the effect of semantics from that of phonology of a new language on the neural representations of words in native and second languages, two training conditions were used: One involved the training of visual forms, sounds, and meanings of the words (semantic training, in short) and the other involved only the training of visual forms and sounds of the words (phonological training). The present study consisted of two experiments. In Experiment 1, training lasted for eight days. Before and after the eight days of training, subjects were scanned while performing a widely-used reading task (i.e., passive viewing). The effect of learning to read words in a new language on the neural representations of a native language (Chinese) was examined. Experiment 2 aimed to replicate the results of semantic training in Experiment 1 and extend the examination to its effect on a second language (English) and the modulatory effect of the proficiency level of the new language. A new sample of subjects received semantic training for an extended period (13 days) and was scanned while performing the same passive viewing task before training, after eight days of training, and after 13 days of training.

2. Experiment 1

Experiment 1 aimed to examine whether learning to read words in a new language affected neural representations of words in participants' native language. Two training conditions were used: The semantic training condition involved the training of visual forms, sounds, and meanings of the artificial words; and the phonological training condition involved only the training of visual forms and sounds (Fig. 1). Two groups of participants (one group per condition) were trained for eight days. We measured the neural activity of participants as they read words in their native language (i.e., Chinese) before and after they received artificial language training. Based on the separation hypothesis, we would expect that neither type of training would affect the neural representations of the native language. Based on the integration hypothesis, we would expect that both types of training would result in changes in neural representations of the native language. Finally, based on the partial integration hypothesis, we would expect that semantic training but not phonological training would result in changes in neural representations of the native language.

2.1. Methods

2.1.1. Participants—Participants consisted of 38 native Chinese speakers who had learned English as a second language. 17 participants (8 males; mean age = 20.6 ± 1.37 years old, with a range from 19 to 24 years) received semantic training and 21 participants (10 males; mean age = 22.33 ± 1.85 years old, with a range from 19 to 25 years) received phonological training. The two groups of subjects did not differ in nonverbal intelligence, reading scores of English words (which are more relevant for Experiment 2), and performance on Chinese reading tasks (see Table 1 for mean scores and Table S1 for individual subjects' scores). All subjects had been learning English as second language for about eleven years in school, per Chinese government's educational policies, and achieved medium-level fluency in reading, but were poor in speaking and listening. In addition, subjects had no previous experience with the Korean language. They had normal or corrected-to-normal vision, with no previous history of neurological or psychiatric disease, and were strongly right-handed as judged by Snyder and Harris's handedness inventory (Snyder and Harris, 1993). Informed written consent was obtained from the subjects before the experiment. This experiment was approved by the IRBs of the University of California, Irvine, the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University, and the University of Southern California.

2.1.2. Materials—Sixty Chinese words and 120 artificial language words were used in Experiment 1 (see Fig. 1 for examples). All Chinese words were medium- to high-frequency single-character words according to the Chinese word frequency dictionary (Wang and Chang, 1985). On average, they occurred at the rate of 498.50 per million words. The words consisted of 2-9 strokes (mean = 5.98) and 2-3 units (mean = 2.70) (Chen et al., 1996).

The artificial language words were single Korean Hangul characters constructed using 22 Hangul letters (12 consonants and 10 vowels). We selected the phonemes that are easy to pronounce for native Chinese speakers because this study focused specifically on learning to read words, not on learning new phonemes. To confirm our judgment, three native Chinese-speaking college students were asked to listen to the phonemes one by one and assess the ease of pronouncing the phonemes on a 5-point scale (1: very difficult to pronounce; 5: very easy to pronounce). The average scores across the judges were higher than 3 for each of the phonemes used in this study. The artificial language words consisted of 24 CV and 96 CVC characters. Each consonant appeared 10 times in onset and 8 times in coda, and each vowel was used 10 times. They were matched with Chinese words in visual complexity (mean number of units = 2.67; mean number of strokes = 6.15). The artificial language words were divided into two groups, one for training and the other as control material (not trained). The two groups of artificial language words were strictly matched in number of units and strokes, as well as frequency of each letter.

Artificial language words were read by a native Korean female speaker. Audio recordings of the words were de-noised and normalized to the same length (600 ms) and loudness using Audacity 1.3 (audacity.sourceforge.net).

2.1.3. Training Procedure—Subjects learned 60 artificial language words through a computerized learning program. The semantic training group learned the visual forms, sounds, and meanings of the 60 artificial language words, and the phonological training group learned only the visual forms and sounds of the same 60 artificial language words. Based on our previous study in which subjects successfully learned 60 artificial words after eight days of training (Mei et al., 2014), we also trained subjects for eight days (one hour per day).

Because Korean Hangul has a shallow orthography with consistent correspondence between letters and their pronunciations, participants would have implicitly acquired the grapheme-phoneme correspondence (GPC) rules through learning if we had used the original pronunciations of the letters. To avoid that problem, we assigned each word with a new pronunciation borrowed from one of the 60 artificial language words used for training in the study. Pictures of 60 objects were arbitrarily assigned to the 60 artificial language words for semantic training. To ensure that all pictures were familiar objects, we asked six Chinese college students to assess the familiarity of objects on a 5-point scale (1: very unfamiliar; 5: very familiar). The average scores were higher than 4.3 for all objects. In order to eliminate the cross-script semantic priming effect, a potential confound of the effect of the novel words on native and second languages, we chose pictures of objects that were semantically unrelated to the Chinese or English words (for Experiment 2) used in this study.

Five learning tasks were designed to facilitate the learning of the artificial language words through repeated study and retrieval (please see a detailed description of the learning tasks in Supplementary Materials). There were analogous versions for semantic and phonological training. The tasks included *word learning*, associating each artificial language visual word with its sound (for phonological training) or with both its sound and meaning (for semantic training); *naming with feedback*, reading a word aloud (phonological training) or naming a picture/object aloud (semantic training), followed by feedback with its correct pronunciation/name; *phonological/semantic choice task*, choosing the correct sound out of four to match the target word (phonological training) or choosing the correct picture out of four to match the target word (semantic training); *free learning*, re-learning any words with which subjects had difficulties in the phonological/semantic choice tasks; and *fast naming*, reading ten words (phonological training) or naming ten pictures (semantic training) as fast as possible.

It should be noted that, with the exception of semantics, all other intervening variables such as the number of repetitions and the overall time spent learning were the same in the semantic and phonological training conditions.

2.1.4. Behavioral Task—At the end of each training day, *word naming* was used to test the acquisition of the association between visual forms and sounds in both the semantic and phonological training conditions, and *picture naming* was used to test the acquisition of the association between visual forms and meanings only in the semantic training condition. In both tasks, each artificial language word (in the *word naming* task) or each picture (in the *picture naming* task) was presented for 4 seconds (Days 1-4) or 3 seconds (after Day 4), followed by a 1 second blank. Subjects were asked to read the artificial language word or to name the object on the picture aloud in the artificial language as fast and accurately as possible. The oral responses in those two tasks were recorded and each response's accuracy was evaluated by a research assistant by comparing the subjects' responses with the pronunciations used for training. To ensure the accuracy of the evaluations, we had another research assistant evaluate all of the oral responses of ten subjects. The average agreement rate between the two evaluators was 97%, suggesting a high inter-rater reliability. The accuracy rate (the number of correct responses divided by 60 [total number of items]) was calculated for each task.

2.1.5. fMRI Task—In order to compare the neural activity of word reading before and after training, we used a widely-used reading task (i.e., passive viewing), which emphasized the automatic reading process (e.g., Chen et al., 2007; Cohen et al., 2002; Liu et al., 2007; Nelson et al., 2009; Xue et al., 2006a, b). The passive viewing task was chosen because it could be administered both before and after training, and because it was less likely than other explicit reading tasks (e.g., naming) to be confounded by factors such as task difficulty

(Chen et al., 2007; Cohen et al., 2002; Xue et al., 2006b). The passive viewing task included three types of stimuli, namely Chinese words, trained artificial language words, and untrained artificial language words. Subjects were scanned both before (Scan 1) and after 8 days of training (Scan 2). We used the same stimuli for different scans to ensure that the scans were comparable (i.e., to avoid a potential confound of stimulus differences). Stimulus presentation and response data collection were programmed using Matlab (Mathworks) and Psychtoolbox (www.psychtoolbox.org). Rapid event-related design was used for the passive viewing task, with the stimuli pseudo-randomly mixed. Trial sequences were optimized with OPTSEQ (http://surfer.nmr.mgh.harvard.edu/optseq/) to improve design efficiency (Dale, 1999).

During each scan, subjects performed two runs of the passive viewing task (Fig. 1C). Each trial lasted for 600 milliseconds, followed by a fixation that varied randomly from 1.4 to 6.4 seconds (mean = 1.9 sec) to improve design efficiency. Subjects were asked to carefully view the stimuli. To ensure that subjects were awake and attentive, we instructed subjects to press a key whenever they saw a word that was underlined, which occurred 6 times per run. Subjects correctly responded to more than 10 of the 12 underlined words across the two runs suggesting that subjects were attentive to the stimuli during the passive viewing task.

2.1.6. MRI Data Acquisition—Imaging data were acquired with a 3.0 T Siemens MRI scanner in the MRI Center of Beijing Normal University. A single-shot T2*-weighted gradient-echo EPI sequence was used for functional imaging acquisition with the following parameters: TR/TE/T = 2000ms/25ms/90°, FOV = 192×192mm, matrix = 64×64, and slice thickness = 3mm. Forty-one contiguous axial slices parallel to the AC-PC line were obtained to cover the whole cerebrum and part of the cerebellum. Anatomical MRI was acquired using a T1-weighted, three-dimensional, gradient-echo pulse-sequence (MPRAGE) with TR/TE/T = 2530ms/3.09ms/10°, FOV = 256×256mm, matrix = 256×256, and slice thickness = 1mm. Two hundreds and eight sagittal slices were acquired to provide a high-resolution structural image of the whole brain.

2.1.7. Image Preprocessing and Statistical Analysis—Initial analyses were carried out using tools from the FMRIB's software library version 4.1.2 (www.fmrib.ox.ac.uk/fsl). The first three volumes in each time series were automatically discarded by the scanner to allow for T1 equilibrium effects. The remaining images were then realigned to compensate for small head movements (Jenkinson and Smith, 2001). Translational movement parameters never exceeded 1 voxel in any direction for any subject or session. All data were spatially smoothed using a 5-mm full-width-half-maximum Gaussian kernel. The smoothed data were then filtered in the temporal domain using a nonlinear high-pass filter with a 60-s cutoff. A 2-step registration procedure was used whereby EPI images were first registered to the MPRAGE structural image, and then into the standard (Montreal Neurological Institute [MNI]) space, using affine transformations with FLIRT (Jenkinson and Smith, 2001) to the avg152 T1 MNI template.

At the first level of analysis, the data were modeled with the general linear model within the FILM module of FSL for each subject and each session. Events were modeled at the time of the stimulus presentation. These event onsets and their durations were convolved with canonical hemodynamic response function (double-gamma) to generate the regressors used in the general linear model. Temporal derivatives and the 6 motion parameters were included as covariates of no interest to improve statistical sensitivity. Null events (i.e., fixation) were not explicitly modeled, and therefore constituted an implicit baseline. Two contrast images (Chinese-baseline and artificial language-baseline) were computed for each run and for each subject.

At the second level of analysis, training effects were calculated across the four runs (two at Scan 1, and the other two at Scan 2) for each condition and for each subject by subtracting Scan 1 from Scan 2. Fixed-effects models were used in the second-level analysis. The data from the second-level analyses were then averaged across the subjects in the third-level analyses using a random-effects model (treating subjects as a random effect) with FLAME stage 1 only (Beckmann et al., 2003; Woolrich et al., 2004). Unless otherwise indicated, statistical images were thresholded using clusters determined by a height threshold of $Z > 2.3$ and a cluster-corrected significance threshold of $p < .05$ (Worsley, 2001).

2.1.8. Regions of Interest (ROI) Analysis—To compare the results across the two training conditions, two regions in the inferior frontal gyrus (IFG) [the left pars opercularis (PO) and pars triangularis (PT)] and six regions in the occipitotemporal areas [the bilateral inferior temporal gyrus (ITG), fusiform gyrus (FG), and inferior occipital gyrus (IOG)] were selected as regions of interests (ROIs). The ROIs were anatomically defined based on Harvard-Oxford probabilistic atlas (Maximal Probability Threshold: 25%) within FSL (for the definition of ROIs, please see Table S2). These regions were selected because of their crucial involvement in word reading (Bolger et al., 2005; Fiez and Petersen, 1998; Price, 2000). It should be noted that the left FG defined in this study covered the so-called “visual word form area” (Cohen and Dehaene, 2004; Cohen et al., 2002). The definition of all ROIs was independent of training conditions. ROI analyses were performed by extracting parameter estimates (betas) of each event type from the fitted model and averaging them across all voxels in the cluster for each subject. Percent signal changes were calculated using the following formula: [contrast image/(mean of run)] × ppheight × 100%, where ppheight was the peak height of the hemodynamic response versus the baseline level of activity (Mumford, 2007).

2.2. Results

Behavioral results showed that both semantic and phonological training significantly improved performance on the artificial language *word naming* task. Semantic training also significantly improved performance on the *picture naming* task. These results suggest that our training was effective. In addition, as would be expected based on the additional component of semantic training, behavioral performance was better after phonological training than after semantic training (reaction time: $t(36) = 1.81$, $p = .079$; accuracy: $t(36) = 3.40$, $p < .01$) (Fig. 2).

We first examined neural activation changes after semantic and phonological training using whole-brain analyses. During the processing of the artificial language words, semantic training resulted in activation increases in the left precentral gyrus (PCG, extending to IFG)

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and right IFG (Fig. 3A), and phonological training resulted in activation increases in the anterior cingulate cortex (ACC), the left IFG (extending to PCG), occipitotemporal areas, and bilateral superior occipital gyrus [SOG, extending to superior parietal lobule (SPL)] (Fig. 3B). No regions showed training-induced decreases. Meanwhile, semantic training resulted in activation decreases when reading Chinese words in several regions of the typical reading network, including the left IFG, angular gyrus (AG), SOG (extending to SPL), and occipitotemporal areas (Fig. 3C & Table 2). In contrast, no regions showed training-induced neural changes for Chinese words after phonological training (Fig. 3D & Table 2).

We then extracted the percent signal change from the eight pre-defined ROIs (Fig. 4). Consistent with the whole-brain analysis, activations during the processing of Chinese words significantly decreased in six of the eight ROIs as a result of semantic learning in the artificial language (the left PO: $t(16) = 3.05$, $p < .01$; left PT: $t(16) = 2.64$, $p < .05$; left ITG: $t(16) = 2.77$, $p < .05$; right ITG: $t(16) = 2.64$, $p < .05$; right FG: $t(16) = 2.72$, $p < .05$; right IOG: $t(16) = 2.95$, $p < .01$). In contrast, no regions showed significant neural activation changes after phonological training (all *p*s > .45). These results suggest that learning to read words in a new language only influences a native language when semantic associations are established for words in the new language.

We further performed a two-way analysis of variance (ANOVA) on training condition (phonological or semantic) and time of test (pre- or post-training) to examine whether the effect of learning to read words in a new language on native language was statistically larger for semantic training than for phonological training. The training-by-test interaction was significant in the left PO ($F(1,36) = 5.24$, $p < .05$) and ITG ($F(1,36) = 5.22$, $p < .05$), which confirmed that neural activities of native language processing in these regions decreased after semantic training to a significantly greater extent than after phonological training.

2.3. Discussion

In this experiment, we found that neural activity during the processing of words in the new language increased in the ACC and bilateral IFG after both semantic and phonological training, and in the left occipitotemporal region after phonological training. The increased activation in the ACC and the left occipitotemporal region may respectively reflect the increased demand for cognitive control during the learning of words in a new language (Abutalebi, 2008; Abutalebi and Green, 2007) and the modulatory effect of phonological learning on visual form processing (Xue et al., 2006b). The increased activation in the bilateral IFG may either represent access to the phonological and semantic representations (Poldrack et al., 1999; Vigneau et al., 2006) or reflect the increased demand for cognitive control in the process of learning to read novel words (Abutalebi, 2008; Abutalebi and Green, 2007).

More importantly, we found that learning to read words in a new language changed neural processes of word reading in the native language. Specifically, neural activity during word reading in the native language decreased in several reading-related regions after semantic learning, but not after phonological learning. These regions included not only brain regions for semantic processing (i.e., the left PT and bilateral ITG), but also regions for visual form processing (the right FG and bilateral IOG) and for phonological processing (the left PO)

(Binder et al., 2009; Poldrack et al., 1999; Vigneau et al., 2006). Although we cannot rule out the possibility that these regions played a role in semantic processing, a more likely explanation is that activation decreases in these regions were due to their interconnections with the semantic system, which serves as a bridge to link the new language with the native language (i.e., a shared semantic system) whose orthographic and phonological representations are automatically activated in the process of reorganization (e.g., Humphreys et al., 1982; Marí-Beffa et al., 2000). In other words, learning to read words in a new language affected word reading in the native language through the semantic system.

Nevertheless, there are several important limitations in the experimental design. First, although semantic training and phonological training were matched in terms of the overall time for learning, subjects had achieved lower proficiency after semantic training relative to phonological training because subjects in the semantic training condition learned one more linguistic component (e.g., semantics) than those in the phonological training condition. Thus, our results might be confounded by the differences in proficiency between subjects in the semantic training and phonological training conditions. Second, if learning to read words in a new language affects word reading in the native language through the semantic system, such an effect would occur not only for the native language but also for any other language(s) the subject speaks or reads, and for words but not for pseudowords which lack semantics. Therefore, an experiment that includes words and pseudowords in subjects' second language would provide additional tests of the cross-script effect at the semantic level. Finally, previous studies have suggested that the proficiency in a new language is an important factor in brain organization of languages (Abutalebi and Green, 2007; Perani and Abutalebi, 2005; Wartenburger et al., 2003) and may modulate the new language's effect on the native and other previously acquired languages (Chen, 2006). A longer period of training than that used in this experiment would allow us to examine the role of the proficiency of the artificial language in modulating its effect on the native language and other previously acquired languages.

3. Experiment 2

Experiment 2 aimed to overcome the three limitations of Experiment 1 described above. First, because subjects achieved lower proficiency after semantic training than after phonological training in Experiment 1, we needed to rule out the possibility that differences in proficiency levels confounded our results. In Experiment 2, we prolonged the semantic training sessions from 1 hour to 1.5 hours per day in hopes that subjects' proficiency in the artificial language from semantic training in Experiment 2 would at least match that from phonological training in Experiment 1. If activation decreases in the native language after eight days of training were replicated in Experiment 2, we would rule out proficiency differences as a potential confound. Second, to further test the partial integration hypothesis, we investigated whether learning to read words in the new language affected the processing of participants' existing second language (English) and native language (Chinese). In the functional scans, we added English words and alphabetic pseudowords (i.e., letter strings that comply with English orthographic rules). If learning to read words in the new language affected the processing of the native language through the semantic system, the effects would also occur for any other language(s) that the subjects knew, but not for pseudowords which lack semantics. Finally, to examine whether proficiency in the new language modulated its effect on word reading in native and second languages, we prolonged the training from 8 days to 13 days and scanned the participants three times (Scan1: before training; Scan 2: after 8 days of training; and Scan 3: after 13 days of training).

3.1. Methods

In this experiment, a new sample of subjects received the same semantic training as in Experiment 1, except that the training lasted for 13 days instead of eight, 1.5 hours instead of one hour per day, and the scanning tasks included English words and alphabetic pseudowords.

3.1.1. Participants—A new sample of 22 subjects (12 males; mean age = 21.59 ± 1.22 years old, with a range from 20 to 24 years) participated in this experiment. As in Experiment 1, all subjects had been learning English as second language for about eleven years in school. Subjects in this experiment did not differ from those in Experiment 1 in nonverbal intelligence, reading scores of English words, and performance on Chinese reading tasks (see Table 1 for mean scores and Table S1 for individual subjects' scores). All subjects had normal or corrected-to-normal vision, with no previous history of neurological or psychiatric disease, and were strongly right-handed as judged by Snyder and Harris's handedness inventory (Snyder and Harris, 1993). All subjects had no previous experience with the Korean language. Informed written consent was obtained from the subjects before the experiment. This experiment was approved by the IRBs of the University of California, Irvine, the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University, and the University of Southern California.

3.1.2. Materials—In addition to the 60 Chinese words and the 120 artificial language words that were used in Experiment 1, 60 English words and 60 pronounceable alphabetic pseudowords (i.e., letter strings that comply with English orthographic rules, such as *hilk* and *bime*) were included to examine whether learning to read words in a new language would affect the neural organization of subjects' second language (English).

Monosyllable English words were selected from the MRC psycholinguistic database: machine usable dictionary, version 2.00 (Wilson, 1988). They were high-frequency (i.e., more frequent than 12 per million words) with a mean frequency of 530.80 per million words, and consisted of 3-6 letters (mean = 4.38). Monosyllable alphabetic pseudowords, which matched the real words in number of letters (mean = 4.38), were selected from the ARC nonword database (Rastle et al., 2002). To ensure that Chinese subjects could read the English materials, we asked five Chinese college students to evaluate the familiarity of the English words (1: very unfamiliar; 5: very familiar) and to assess the ease of pronouncing the alphabetic pseudowords (1: very difficult to pronounce; 5: very easy to pronounce) on a 5-point scale. The average scores were higher than 4 for all English words and 3 for all pseudowords.

3.1.3. Training Procedure—Subjects learned the visual forms, phonologies, and semantics of 60 artificial language words for 13 days, 1.5 hours per day. The semantic training procedure in Experiment 2 was the same as that in Experiment 1 except the length of training.

3.1.4. Behavioral Task—At the end of each training day, the *word naming* and *picture naming* tasks (the same as those used in Experiment 1) were used to assess how well the subjects had learned the artificial words.

3.1.5. fMRI Task—As in Experiment 1, Experiment 2 used the passive viewing task to collect fMRI data. This task included five types of stimuli, namely, Chinese words, English words, alphabetic pseudowords, trained artificial language words, and untrained artificial language words. Rapid event-related design was used, with the stimuli pseudo-randomly mixed. Subjects were scanned before training (Scan 1), after 8 days of training (Scan 2), and after 13 days of training (Scan 3). On the passive viewing task, subjects correctly responded to more than 10 of the 12 underlined words across the two runs for all three scans, suggesting that subjects were attentive to the stimuli during the task.

3.1.6. MRI Data Acquisition and Analysis—Imaging data were acquired with the same MRI scanner and with the same parameters as in Experiment 1. Image preprocessing and the first-level analysis were also the same as in Experiment 1 except for the inclusion of two additional contrasts (i.e., English word-baseline and alphabetic pseudoword-baseline). At the second level of analysis, training effects were calculated across the six runs (two at Scan 1, two at Scan 2, and two at Scan 3) for each condition and for each subject by subtracting Scan 1 from Scan 2 and subtracting Scan 2 from Scan 3. Fixed-effects models were used in the second-level analysis. The data from the second-level analyses were then averaged across the subjects in the third-level analyses using a random-effects model (treating subjects as a random effect) with FLAME stage 1 only (Beckmann et al., 2003; Woolrich et al., 2004). Unless otherwise indicated, statistical images were thresholded using clusters determined by a height threshold of $Z > 2.3$ and a cluster-corrected significance threshold of $p < .05$ (Worsley, 2001).

3.1.7. ROI Analysis—The same eight regions (i.e., the left PO, PT, bilateral ITG, FG, and IOG) as in Experiment 1 were defined as ROIs in Experiment 2. The percent signal changes in the eight ROIs were extracted using the same procedure as in Experiment 1 for each condition, scan, and subject.

3.2. Results

Behavioral data showed that after 8 days of training, subjects in Experiment 2 (with more intensive semantic training) attained the same level of proficiency in the artificial language as those receiving phonological training in Experiment 1(all ps > .1). After 13 days of training, subjects in Experiment 2 reached a higher level of proficiency than those in the semantic training condition in Experiment 1, who received only 8 days of training (all ps < .01) (Fig. 2).

As in Experiment 1, we first examined training effects by comparing neural activity during Scan 1 and Scan 2. Results replicated the findings in Experiment 1 that semantic training induced increases during the processing of artificial language words and decreases during the processing of Chinese words. Specifically, training-induced increases during the processing of artificial language words were found in the ACC, the left PCG, and bilateral IFG (Fig. S1A & Table 3), and training-induced decreases during the processing of Chinese words were found in the right PCG, middle temporal gyrus (MTG), and the bilateral occipitotemporal areas (Fig. S1C & Table 4). No region showed decreased activation during the processing of artificial language words or increased activation during the processing of Chinese words.

Mirroring our findings regarding subjects' native language (Chinese), training-induced decreases were found during the processing of words in subjects' second language (English) in several regions, including the left IFG, the bilateral SPL (extending to SOG), and occipitotemporal areas (Fig. S1E & Table 5). No region showed increased activation during the processing of English words. As expected, no region showed neural changes from Scan 1 to Scan 2 during the processing of alphabetic pseudowords (Fig. S1G). These results further confirmed the hypothesis that the influence of learning to read words in a new language on existing languages only occurs at the semantic level.

We then examined how proficiency in the new language affects native language processing by comparing neural activity between Scan 2 and Scan 3. Results showed that further training on the artificial language also resulted in neural activation changes during the processing of words in both new and existing languages. Specifically, during the processing of artificial language words, training-induced increases were found in the precuneous cortex [extending to posterior cingulate cortex (PCC)], right middle frontal gyrus (MFG), left cerebellum, and bilateral SOG [extending to right angular gyrus (AG)] (Fig. S1B & Table 3). More interestingly, during the processing of Chinese words, several regions, including ACC, PCC, bilateral IFG, temporal pole (TP), SOG (extending to AG), and occipitotemporal areas, showed higher activation in Scan 3 compared with Scan 2 (Fig. S1D & Table 4). Similar increases in activation were also found during the processing of English words in the left IFG, the bilateral SOG (extending to SPL) and occipitotemporal areas (Fig. S1F & Table 5). We further compared neural activity during the processing of Chinese and English words in Scans 1 and 3 and found no significant differences, suggesting that neural activity during the processing of words in existing languages follow a U-shaped curve with increasing proficiency in the new language. In contrast, there were no changes in activation during the processing of alphabetic pseudowords, which lacked semantics (Fig. S1H).

The cross-script effect at the semantic level was further confirmed by ROI analysis. In this analysis, we first performed one-way repeated measures ANOVAs (scan: Scans 1, 2, and 3) on the activities in the eight ROIs for Chinese words, English words, and alphabetic pseudowords separately. Across the three scans, the U-shaped pattern (i.e., neural activity decreased initially and recovered after further learning) was evident in all ROIs for Chinese words, and in the left PO, PT, ITG, and bilateral IOG for English words. In contrast, none of the ROIs showed significant activation changes for alphabetic pseudowords (please see Table S3 for a summary of the statistics). Further two-way ANOVAs on material (Chinese words, English words, or alphabetic pseudowords) and time of test (Scan 1, 2, or 3). revealed significant material-by-time-of-test interactions in the left PO ($F(4,84) = 3.48$, $p < .05$), PT ($F(4,84) = 3.39$, $p < .05$), and FG ($F(4,84) = 4.15$, $p < .01$)(Fig. 5).

3.3. Discussion

In this experiment, we first replicated activation decreases in reading-related regions (i.e., the left PO, PT, bilateral ITG, FG, and IOG) for subjects' native language (Chinese) after 8 days of semantic training when proficiency in the new language was matched between semantic training in this experiment and phonological training in Experiment 1. This result suggests that the differential effects of phonological and semantic training on the native language found in Experiment 1 could not be attributed to subjects' differences in proficiency in the new language.

Second, we found that learning to read words in a new language affected not only word reading in subjects' native language (Chinese), but also word reading in subjects' second language (English). In addition, such effects occurred only for real words, but not for pseudowords which lack semantics. These results extended Experiment 1's finding of the cross-script effect from a native language to a second language, and further confirmed that learning to read words in a new language affected word reading in prior languages through the semantic system.

Finally, we found that subjects' proficiency in the new language modulated the effect of learning to read words in the new language on word reading in prior languages such that the effect manifested during the initial acquisition of words in the new language and diminished when subjects reached a high level of proficiency. This result is consistent with one previous behavioral study which revealed that the effect of a second language on a native language followed a U-shaped curve (Chen, 2006). It is also consistent with the view that proficiency in a new language is an important factor in brain organization of languages (Abutalebi and Green, 2007; Perani and Abutalebi, 2005; Wartenburger et al., 2003).

4. General Discussion

Using an artificial language training paradigm, the present study examined the effect of learning to read words in a new language on the processing of native and second languages. Specifically, we examined the effects of semantic as opposed to phonological training, as well as the possible modulatory role of proficiency in the new language. We found that neural activity during word reading in native and second languages decreased in several reading-related regions (i.e., the left PO, PT, bilateral ITG, FG, and IOG) after semantic learning, but not after phonological learning. Furthermore, subjects' proficiency level in the new language modulated the effect of the new language on native and second languages. Specifically, the effect manifested during the initial acquisition of words in the new language and diminished when subjects reached a high level of proficiency. It should be noted that although the same stimuli were used across the scans, our results cannot be explained by the familiarity effect, as activation decreases were specific to the early stage of semantic training. Moreover, we did not find any neural changes across scans for alphabetic pseudowords. In sum, the two experiments provided convergent and strong evidence to suggest that learning to read words in a new language affects neural activity during the processing of native and second languages at the semantic level, and that this effect is modulated by proficiency level in the new language.

Our results make several significant contributions to the understanding of neural organizations of multiple languages and their interactions. First, our results provide evidence for the influence of learning to read words in a new language on word reading in previously acquired languages. Our results also suggest that the influence of the new language on existing language(s) can occur at an early stage of learning, at least in the reading-related brain areas. Consistent with our findings, one behavioral study reported that six hours of learning a second language could affect reading performance in a native language (Yelland et al., 1993). By revealing the effect of learning to read words in a new language on word reading in prior languages, our results complemented previous findings regarding a native language's influence on the cognitive and neural mechanisms involved in learning a second language (Akamatsu, 1999; Nakada et al., 2001; Nelson et al., 2009; Perfetti et al., 2007; Tan et al., 2003; Wang et al., 2003).

Second, our study provides imaging evidence for the modulatory role of proficiency in the new language. Specifically, it has been proposed that the influence of a second language on a native language follows a U-shaped curve as proficiency in the second language increases (Chen, 2006). As Chen (2006) speculated, during the early stage of learning a second language, the existing language system (i.e., the native language) is changed to accommodate the second language. However, the effects of the second language diminish when proficiency in the second language becomes high and the accommodation process is completed (Chen, 2006). Our results were consistent with this U-shaped effect. It should be noted that, although our results were limited to temporary activation changes of the existing languages to accommodate the newly acquired language, long-term interactions between these languages are likely to continue, as shown by the comparisons between bilinguals and monolinguals (Kovelman et al., 2008; Rodriguez-Fornells et al., 2002) and brain changes in bilinguals (Mechelli et al., 2004; Mohades et al., 2012).

Third, our results have important implications for our understanding of lexical memory organization in bilinguals. Three rival hypotheses (the separation, integration, and partial integration hypotheses) have been proposed regarding how bilinguals or multilinguals represent words in their two or more languages. Natural language materials are not ideal for testing the three hypotheses because word reading in natural languages usually elicits co-activations of several language components such as phonology and semantics (e.g., Humphreys et al., 1982; Marí-Beffa et al., 2000). Our study disentangled the effects of these components by using an artificial language training paradigm. First, we found that the effect of learning to read words in the new language on the native language only occurred when semantics were linked to words in the new language. Second, learning to read words in a new language could affect both words in the native language (i.e., Chinese) and those in the previously-acquired second language (i.e., English), which differ in visual form and orthography. Finally, these effects were only found when using words with semantics, as opposed to pseudowords, suggesting that learning to read words in a new language affected word reading in existing language(s) through the semantic system. Consistent with our results, previous neuroimaging studies have revealed shared neural mechanisms for bilinguals' two languages when semantic tasks were used (Illes et al., 1999; Klein et al., 1995; Xue et al., 2004). These results suggest that bilinguals' two languages share a

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common semantic system, which lends support to the partial integration hypothesis (Kroll and Stewart, 1994; Kroll and Tokowicz, 2005; Kroll et al., 2010).

Fourth, in addition to contributing theoretically to models of lexical representation of bilinguals, our results have important implications to the methodology of neuroimaging studies about language learning. Previous studies on language learning often used native language materials as the high-level baseline to control for the test-retest variability in fMRI or PET signals (Raboyeau et al., 2004; Xue et al., 2006b). The basic rationale underlining those studies is that neural activity during the processing of native language materials is constant across the scans. Contrary to this idea, but consistent with cognitive models, our results suggest that neural activity during the processing of native language materials is affected by the learning of a new language. Although it might be acceptable to use native language materials as the control when there is no semantic training or when the training is long enough for subjects to acquire relatively high proficiency in the new language, caution is needed when using native language materials as the control during new language learning. Either a nonlinguistic condition, or a condition with pseudowords, or both, may provide better contrasts.

Four limitations of this study should be discussed. First, compared to natural languages, learning materials used in this study were limited in their vocabulary size and morphology, and were lacking syntax. These limitations might have impeded the acquisition of inherent structures of words such as letter combinations (i.e., bigram, trigram) and the acquisition of nonnative phonological categories (Best and Tyler, 2007). Future studies on language training should enlarge the vocabulary size and include syntax to improve ecological validity.

Second, even though both the artificial language and the Chinese language are logographic, they still differ in visual forms and form-sound mapping, which might have led to less cross-script influence at the orthographic and phonological levels in this study. Indeed, this possibility is indirectly supported by the finding of cross-language competition and interference at the phonological level when bilinguals' two languages have similar visual forms and form-sound mapping (Hoshino and Thierry, 2011; Rodriguez-Fornells et al., 2005; van Heuven et al., 2008). Future studies should test the partial integration hypothesis by including artificial languages that are orthographically the same as the native language. Furthermore, differential effects of semantic and phonological training could have been a result of differential familiarity with the linguistic features: Semantic training required subjects to associate *familiar* concepts with *unfamiliar* sounds and symbols, whereas phonological training required subjects to associate *unfamiliar* sounds with *unfamiliar* symbols. To complement our studies, future studies should examine the cross-script effect at orthographic and phonological levels by using *familiar* symbols and sounds in phonological training, and examine the cross-script effect at the semantic level by using *unfamiliar* semantics (i.e., novel meanings/objects for the artificial language words) in semantic training.

Third, in addition to subjects' level of proficiency in a new language, their age of acquisition (AOA) may also play a role in the effects of a new language on neural representations of the native language. For example, it has been suggested that early bilinguals show more activation in the right hemisphere than late bilinguals (Hull and Vaid, 2007). Semantic priming effects are also found in early, but not late bilinguals (Silverberg and Samuel, 2004). Subjects in this study were all college students with small variations in age and AOA of their second language (English), precluding us from investigating age-related or AOA-related effects. Future research should compare subjects of different age groups (e.g., children versus adults) as well as subjects with different AOAs (early vs. late bilinguals).

Finally, in this study, we only used an implicit reading task (i.e., passive viewing), which did not require explicit phonological and semantic access. Thus, it is not clear whether the same cross-script effect can be obtained when an explicit reading task (e.g., a naming task) is used. There is evidence that the reading network is more involved in explicit reading tasks than implicit reading tasks (Vogel et al., 2013). Future research should include explicit reading tasks to address this question.

In summary, by using an artificial language training paradigm, our study provided evidence for the effect of learning to read words in a new language on the neural organization of prior languages. It further revealed that learning to read words in a new language affected word reading in prior languages through the semantic system during the initial acquisition of words, thus supporting the partial integration hypothesis about the bilingual brain.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (31400867, 31130025), the 973 Program (2014CB846102), the National Institute of Health (HD057884-01A2), and the 111 Project (B07008). We would also like to thank Karen Wu for her comments and suggestions.

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Highlights

- We examined the effect of new language learning on the existing languages.
- The effect occurred only at the semantic level.
- The effect manifested initially and diminished after further learning.

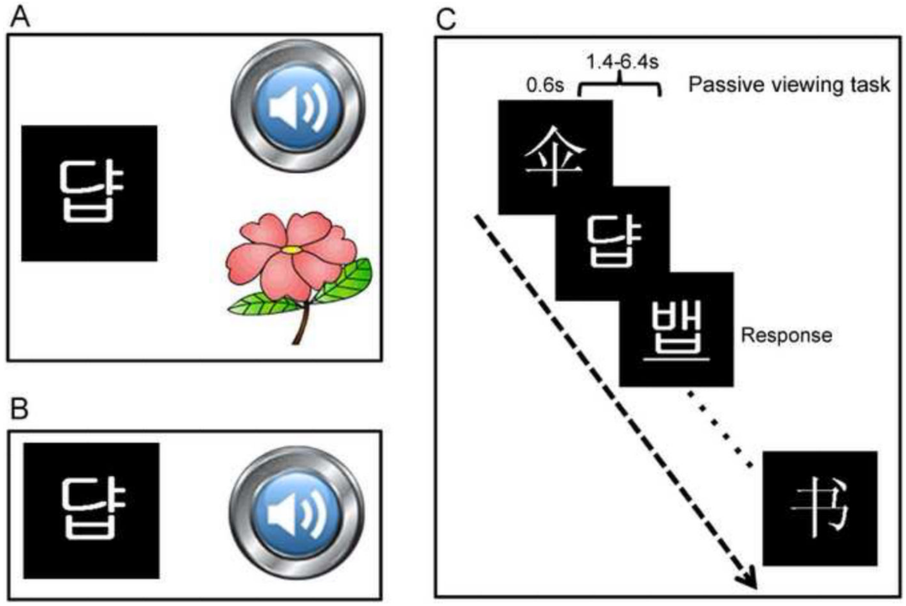

Fig. 1.
Experimental design and examples of materials. Two groups of participants in Experiment 1 received 8 days of either semantic training (A, learning the visual forms, sounds, and meanings of the words simultaneously) or phonological training (B, learning the visual forms and sounds). Participants in Experiment 2 received semantic training for 13 days. fMRI scans were performed before training and after 8 days and 13 days of training. During the scan, participants performed a passive viewing task (C), in which subjects were asked to carefully view the stimuli and to respond if the stimulus was underlined.

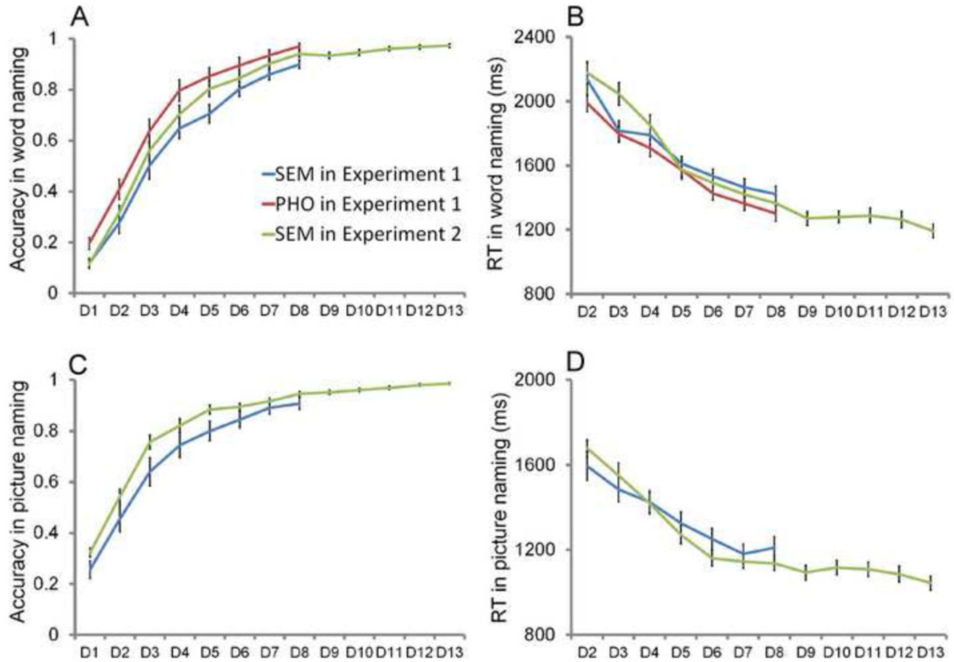

Fig. 2.

Behavioral performance in the two experiments. Accuracies (A) and reaction times (B) on the artificial language naming task (reading each artificial language word aloud) are shown in the upper panels. Accuracies (C) and reaction times (D) on the picture naming task (naming each picture in artificial language aloud) are shown in the lower panels. The reaction times in the first training day are excluded due to the relatively low accuracy. Error bars represent the standard error of the mean. SEM = semantic training; PHO = phonological training; and D = day.

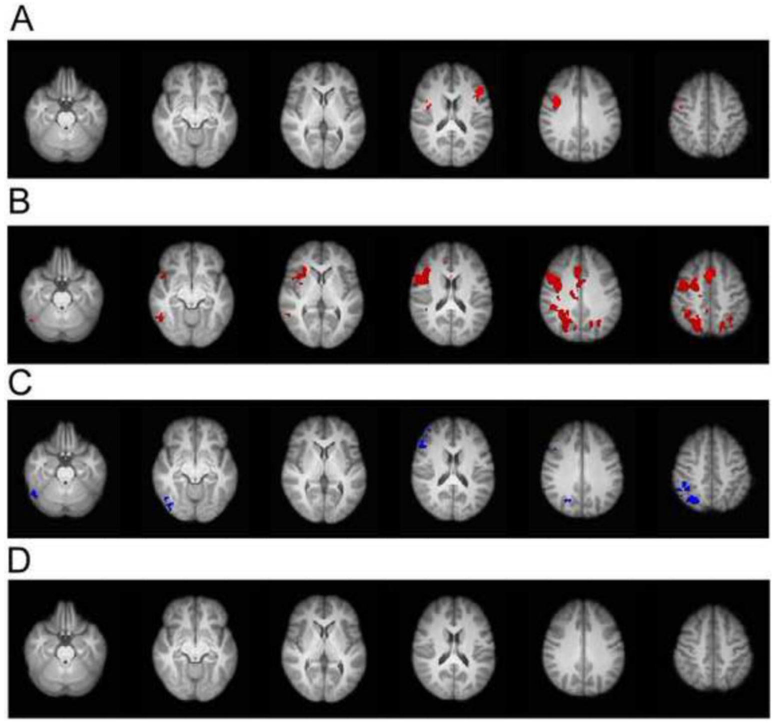

Fig. 3.

Brain regions showing training-related neural activation changes in Experiment 1: (A) activations increased for artificial language words after semantic training; (B) activations increased for artificial language words after phonological training; (C) activations decreased for Chinese words after semantic training; and (D) activations decreased for Chinese words after phonological training. The activation increases were computed by subtracting neural activity before training from that after eight days of training, and the activation decreases were computed using the reverse subtraction. All activations were thresholded at $z > 2.3$ (whole-brain corrected) and overlaid onto the group-averaged anatomical map. Red color represents regions showing activation increases for artificial language words and blue color represents regions showing activation decreases for Chinese words. R = right.

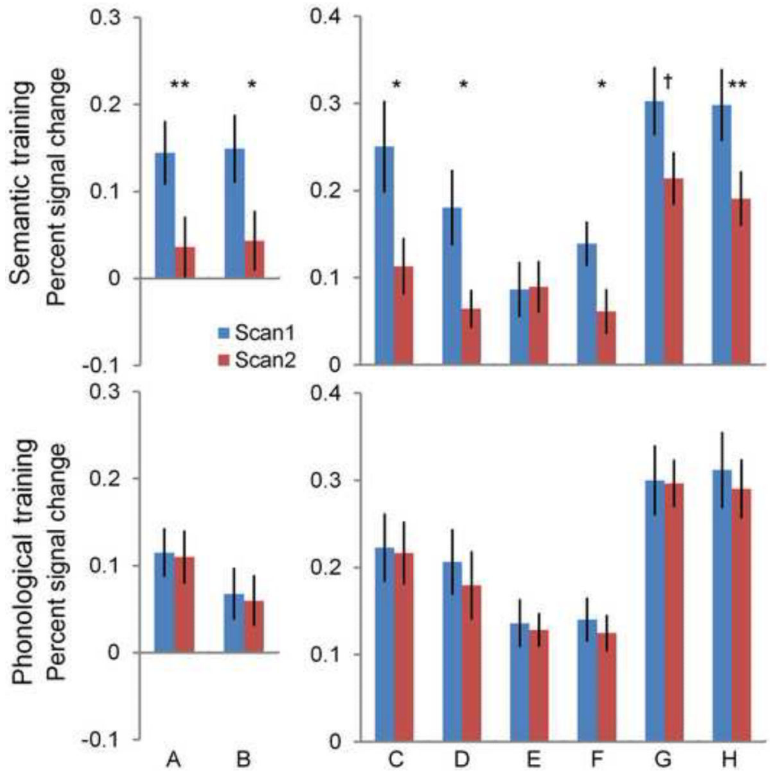

Fig. 4.

Neural activity for Chinese words at the pre- (Scan 1) and post-training (Scan 2) stages in Experiment 1. For both semantic and phonological training, percent signal change was extracted from the eight pre-defined structural ROIs, including (A) the left pars opercularis (PO), (B) the left pars triangularis (PT), (C) the left inferior temporal gyrus (ITG), (D) the right ITG, (E) the left fusiform gyrus (FG), (F) the right FG, (G) the left inferior occipital gyrus (IOG), and (H) the right IOG. All ROIs, except the left FG, showed decreased activations for Chinese words after semantic training, but no significant changes after phonological training. Error bars represent the standard error of the mean.* $p < .05$, † $p < .10$.

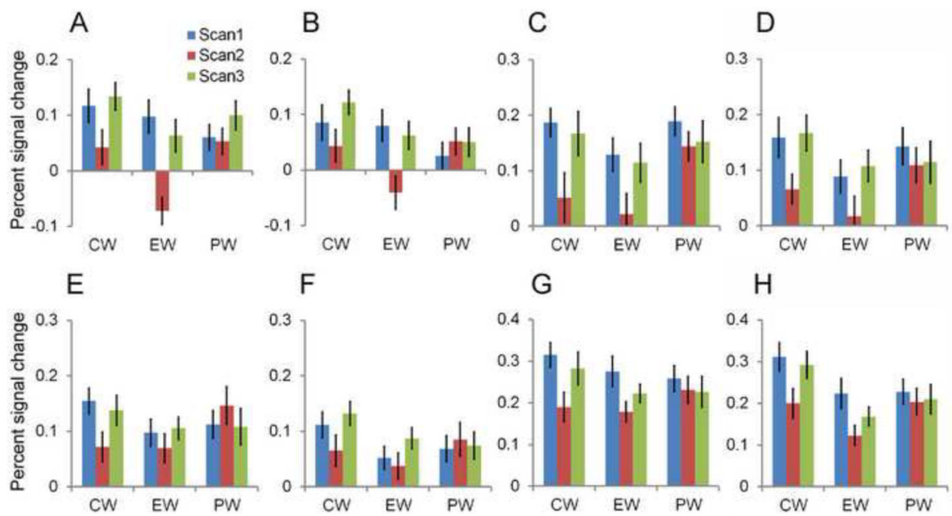

Fig. 5.
Neural activities for Chinese words (CW), English words (EW), and alphabetic pseudowords (PW) in the eight pre-defined structural ROIs in Experiment 2. Scans 1, 2, and 3 were performed before training and after 8 days and 13 days of training, respectively. The eight bar graphs show percent signal change in (A) the left pars opercularis (PO), (B) the left pars triangularis (PT), (C) the left inferior temporal gyrus (ITG), (D) the right ITG, (E) the left fusiform gyrus (FG), (F) the right FG, (G) the left inferior occipital gyrus (IOG), and (H) the right IOG. Across the three scans, the U-shaped pattern was evident in all ROIs for Chinese words, and in the left PO, PT, ITG, and bilateral IOG for English words. In contrast, none of the ROIs showed significant activation changes for alphabetic pseudowords (please see Table S3 for statistics). Error bars represent the standard error of the mean.

Table 1

Mean scores on reading scales and a nonverbal intelligence test for the subjects in the two experiments

Variables	Experiment 1: Semantic training	Experiment 1: Phonological training	Experiment 2: Semantic training	F	p
Chinese word efficiency	88.41 (11.72)	83.33 (12.88)	81.91 (14.94)	1.21	.306
Chinese word identification	25.53 (5.48)	25.14 (5.76)	23.59 (6.04)	0.64	.532
Visual-auditory learning	125.29 (7.61)	123.43 (9.17)	122.77 (10.66)	0.36	.697
English word identification	84.12 (13.20)	88.14 (11.48)	91.14 (10.05)	1.77	.177
Sight word efficiency	69.59 (6.65)	74.29 (7.40)	73.73 (8.89)	1.98	.148
Phonemic decoding efficiency	42.94 (6.79)	43.48 (7.31)	43.48 (8.09)	0.03	.969
Raven advanced matrix	29.24 (3.35)	27.95 (4.55)	26.64 (3.79)	2.08	.135

Note: Numbers inside the parentheses represent standard deviations. The scores are the number of correct items. The Chinese word efficiency and identification tasks were designed by authors of this study; the visual-auditory learning and English word identification were subtests of Woodcock Reading Mastery Tests - Revised (WRMT-R); the sight word efficiency and phonemic decoding efficiency were subtests of the Test of Word Reading Efficiency (TOWER).

Table 2

Brain regions showing training-related neural changes for artificial language words and Chinese words in Experiment 1

Brain regions	Increases for artificial language words				Decreases for Chinese words			
	x	y	z	Z	x	y	z	Z
Semantic training								
Left inferior frontal gyrus/precentral gyrus	−36	8	28	3.62	−52	24	22	3.23
Right inferior frontal gyrus	46	24	18	3.72				
Left angular gyrus					−40	−52	42	3.43
Left inferior occipital gyrus/inferior temporal gyrus					−48	−76	−14	3.67
Left superior occipital gyrus/superior parietal lobule					−32	−66	44	3.91
Phonological training								
Left inferior frontal gyrus/precentral gyrus	−42	10	26	4.64				
Anterior cingulate cortex	−2	16	46	5.44				
Left inferior occipital gyrus/inferior temporal gyrus	−50	−72	−16	3.55				
Left superior occipital gyrus/superior parietal lobule	−30	−64	52	4.24				
Right superior occipital gyrus	28	−72	54	4.23				

Note: Regions showing neural increases were computed by subtracting the neural activity before training from that after 8 days of training, and regions showing neural decreases were computed using the reverse subtraction.

Table 3

Brain regions showing training-related neural increases for artificial language words in Experiment 2

Brain regions	Scan 2 > Scan 1				Scan 3 > Scan 2			
	x	**y**	**z**	**Z**	**x**	**y**	**z**	**Z**
Left precentral gyrus/inferior frontal gyrus	−52	12	18	3.72				
Right inferior frontal gyrus	42	20	6	3.63				
Right middle frontal gyrus					38	26	48	3.66
Anterior cingulate cortex/supplemental motor cortex	2	6	56	4.19				
Left superior occipital gyrus					−32	−86	28	3.32
Right superior occipital gyrus/angular gyrus					44	−76	36	3.63
Precuneous/posterior cingulate cortex					−4	−68	54	3.89
Left cerebellum					−38	−74	−44	3.71

Note: Scans 1, 2, and 3 were performed before training, and after 8 days and 13 days of training, respectively.

Table 4

Brain regions showing training-related neural changes for Chinese words in Experiment 2

Brain regions	Scan 1 > Scan 2				Scan 3 > Scan 2			
	x	y	z	Z	x	y	z	Z
Right precentral gyrus	32	−6	62	3.55				
Left inferior frontal gyrus					−56	16	14	3.16
Right inferior frontal gyrus/temporal pole					62	8	0	3.68
Left temporal pole					−58	6	−12	3.74
Anterior cingulate cortex					0	2	38	4.29
Posterior cingulate cortex					0	−26	42	3.65
Right middle temporal gyrus	46	−54	14	3.37				
Left superior occipital gyrus/angular gyrus					−48	−74	24	3.74
Right superior occipital gyrus/angular gyrus					30	−76	46	3.88
Left inferior occipital gyrus/inferior temporal gyrus	−48	−74	−14	3.86	−34	−78	−18	4.08
Right inferior occipital gyrus/inferior temporal gyrus	42	−68	−4	3.62	52	−58	−24	3.71

Note: Scans 1, 2, and 3 were performed before training and after 8 days and 13 days of training, respectively.

Table 5

Brain regions showing training-related neural changes for English words in Experiment 2

Brain regions	Scan 1 > Scan 2				Scan 3 > Scan 2			
	x	y	z	Z	x	y	z	Z
Left inferior frontal gyrus/precentral gyrus	−54	12	22	4.11	−54	14	−2	3.57
Left superior parietal lobule/ superior occipital gyrus	−32	−50	40	3.91	−48	−74	28	3.55
Right superior parietal lobule/superior occipital gyrus	26	−66	46	3.45	26	−74	50	3.25
Precuneous cortex/posterior cingulate cortex					4	−58	52	3.18
Left fusiform gyrus					−26	−68	−16	3.41
Left fusiform gyrus					28	−76	−18	3.01
Left inferior occipital gyrus/inferior temporal gyrus	−52	−68	−4	3.54				
Right inferior occipital gyrus/inferior temporal gyrus	46	−68	−6	3.38				

Note: Scans 1, 2, and 3 were performed before training and after 8 days and 13 days of training, respectively.