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Chinese Character and English Word processing in children's ventral occipitotemporal cortex: fMRI evidence for script invariance

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Abstract

Learning to read is thought to involve the recruitment of left hemisphere ventral occipitotemporal cortex (OTC) by a process of "neuronal recycling", whereby object processing mechanisms are co-opted for reading. Under the same theoretical framework, it has been proposed that the visual word form area (VWFA) within the OTC processes orthographic stimuli independent of culture and writing systems, suggesting that it is universally involved in written language. However, this "script invariance" has yet to be demonstrated in monolingual readers of two different writing systems studied under the same experimental conditions. Here, using functional magnetic resonance imaging (fMRI), we examined activity in response to English Words and Chinese Characters in 1st graders in the United States and China, respectively. We examined each group separately and found the readers of English as well as the readers of Chinese to activate the left ventral OTC for their respective native writing systems (using both a whole-brain and a bilateral OTC-restricted analysis). Critically, a conjunction analysis of the two groups revealed significant overlap between them for native writing system processing, located in the VWFA and therefore supporting the hypothesis of script invariance. In the second part of the study, we further examined the left OTC region responsive to each group's native writing system and found it responded

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equally to Object stimuli (line drawings) in the Chinese-reading children. In English-reading children, the OTC responded much more to Objects than to English Words. Together, these results support the script invariant role of the VWFA and also support the idea that the areas recruited for character or word processing are rooted in object processing mechanisms of the left OTC.

Keywords

Reading; Visual Word Form Area; fMRI; Orthography

Introduction

Learning to read requires mapping of the written, visual form of a language to its spoken, auditory form. Brain models of reading describe a largely left lateralized network including inferior frontal, temporoparietal, and occipitotemporal cortex (OTC; Dehaene, 2009; Martin et al., 2015; Pugh et al., 2000, 2001). The contribution of each these regions to the sub-processes of reading has been established, yet the details are continuously being refined. A specific region of left ventral OTC in the mid-fusiform gyrus termed the "visual word form area," or VWFA (Cohen et al., 2002, 2000; McCandliss et al., 2003), has been of particular interest because of its role in processing written words. It has been shown that the VWFA responds to words more than to other visual stimuli, such as checkerboards (Cohen et al., 2002), scrambled visual stimuli (Szwed et al., 2011), and line drawings of objects (Baker et al., 2007; Szwed et al., 2011). Also, it responds to written words invariantly in regards to size, position, case, or font (Dehaene et al., 2004, 2001). Some investigators also refer to the "visual word form system" (VWFS), recognizing that regions immediately posterior and anterior to the VWFA proper also show some sensitivity to words (Brem et al., 2010, 2009; Olulade et al., 2013a; van der Mark et al., 2009). However, there is an ongoing debate about the characteristics of the VWFA, most notably questioning the specificity of the VWFA to print. Some have argued that this region responds just as much to pictures of objects (Kherif et al., 2011; Mano et al., 2013; Price and Devlin, 2003; Vogel et al., 2012). Independently of this debate on the specificity of the VWFA, it is largely accepted that the VWFA is one of several regions reliably identified during brain imaging studies of reading, in children and adults, as illustrated by a recent meta-analysis (Martin et al., 2015). Interestingly, the posterior portion of the left OTC is engaged more in adults than children (Martin et al., 2015), suggesting an experience/age-dependent increase in the VWFS, consistent with the developmental model of reading advanced by Pugh and colleagues (Pugh et al., 2001, 2000). In adults, training with a novel set of words is associated with increased activity in (Moore et al., 2014) and greater tuning of (Glezer et al., 2015) the VWFA. Further, the left OTC is underactivated in children and adults with the reading disability dyslexia, as demonstrated by several studies and best captured by meta-analyses (Maisog et al., 2008; Richlan et al., 2011).

Of note is that while most studies have been conducted in alphabetic languages, the VWFA is also found to be activated during reading in Chinese, a morphosyllabic (often called "logographic") writing system. This suggests that despite the difference in visual appearance and in the mapping between written units and language units (mapping principles), the brain utilizes a similar region in the left OTC for reading in Chinese (Nakamura et al., 2012; Perfetti and Tan, 2013). Similar to the work examining the brain bases of alphabetic writing systems described above, real Chinese characters elicit a greater response in the VWFA than do artificial characters (Liu et al., 2008) and scrambled characters (Szwed et al., 2014). Together these findings suggest a consistent and universal role of the VWFA in processing written language.

Dehaene and colleagues explain this consistency across visually dissimilar scripts via the "neuronal recycling hypothesis" (Dehaene and Cohen, 2007; Dehaene et al., 2005). This theory posits that written language, being a recent cultural invention, has not exerted evolutionary pressure on the brain, unlike spoken language, which has had a much longer time to evolve. Accordingly, when learning to read, the brain must recruit regions previously evolved for another purpose. In the case of ventral visual cortex, word reading adopts cortex previously used for processing other categories of visual stimuli such as faces and/or objects (Dehaene and Cohen, 2007; Dehaene et al., 2005). Strong evidence for this hypothesis comes from a study of ex-illiterates (illiterates who learned to read as adults), who showed greater activation to orthographic stimuli in left ventral temporal cortex compared with illiterates. The illiterates, on the other hand, showed greater activation for objects and faces in this region, suggesting that words take precedence over objects once literacy has been acquired (Dehaene et al., 2010).

Consistency of the VWFA across writing systems plays a significant role in the neuronal recycling hypothesis of the VWFA. Evidence for "script invariance" comes from three sources. The first are meta-analyses of adult studies (Bolger et al., 2005; Tan et al., 2005a). For example, Bolger and colleagues drew on publications that independently studied reading in an alphabetic or logographic writing system and grouped these by writing system to generate activation likelihood maps (Bolger et al., 2005). They found that both writing systems activated left OTC (and Chinese also activated right OTC). However, the overlap in the VWFA across both activation likelihood maps was not statistically tested (this is also true for Tan et al., 2005a).

A second source of evidence comes from studies performed in Chinese L1 speakers who were bilingual in English (Chee et al., 1999; Nelson et al., 2009; Wong et al., 2009). All of these studies showed left OTC activation for English and Chinese. Chee et al. (1999) and Nelson et al. (2009) also showed right hemisphere OTC activation for Chinese characters. Although participants spoke Chinese as their first language, the possibility of bilingual effects on L1 late in life cannot be ruled out. In any case, it is important to have observations of monolingual L1 speakers. In studies designed to assess cross-language bilingual effects, Baker et al. (2007) examined adult English readers with and without experience with written Hebrew. In the group with experience with both scripts, they found greater activation in the VWFA for both Hebrew and English orthographies compared with other visual categories, including Chinese characters (Baker et al., 2007). In the same vein, a study of Japanese Kana, a syllabic system, and Kanji, borrowed from Chinese and thus morphosyllabic, showed overlap in the left VWFA (Nakamura et al., 2005).

The third category of evidence would be studies directly examining native monolingual individuals of logographic and alphabetic writing systems under similar experimental conditions. A recent study (Szwed et al., 2014) of native readers of Chinese and French came close to this, finding that adults demonstrated engagement of the VWFA for both orthographies, despite orthography-specific differences in early visual cortex. However, the Chinese speakers in this study were living in France at the time (for a period of two years or less) and would have been exposed to both spoken and written French, making it more similar to previous studies such as Nelson et al. (2009). Importantly, orthography invariance in VWFA activation has not actually been validated via an empirical study of monolingual beginning readers, which is the ideal situation by which to address this question.

The study of beginning readers affords an opportunity at the early stages of reading acquisition to test for script invariance. Our participants consisted of one group of monolingual (and monoliterate) children in the United States (English Readers) and another group of monolingual (and monoliterate) children in China (Chinese Readers). Both groups performed the same implicit single word reading task for their native writing system in the scanner (using the same model of scanner in each location) under the same experimental conditions and using the same data acquisition and analysis parameters. Both groups also viewed line drawings of objects as well as words in the other (foreign) writing system. We tested for script invariance by searching for spatial overlap of activity during word or character processing, respectively, amongst the English and Chinese Readers (i.e. their native language), quantified by a conjunction analysis conducted (a) at the level of the whole brain and (b) specifically within the OTC. Based on the work conducted in adults and in keeping with the neuronal recycling hypothesis, we expected to find overlap between the two beginning reading groups' brain activity in the OTC, specifically in the VWFA, during the processing of their respective native orthographies.

Next, we characterized each group separately in terms of the functional specialization of the left occipitotemporal pathway for object, word, and character processing. There are reasons to suspect that the invasion or co-opting of object recognition regions in the OTC may be especially noticeable in Chinese: There is a greater reliance on orthographic awareness when learning to read Chinese characters (Tan et al., 2005b), and with this one might expect engagement of the left OTC in Chinese character processing at the expense of regions subserving object processing. Further, since the response of the VWFA is one that is thought to come about by experience, one would not expect to see VWFA activity during the processing of a writing system with which the participant is not familiar (Baker et al., 2007; Szwed et al., 2011). As such, we examined the activity in response to the other, foreign script (that is, English Words in the Chinese children and vice versa), with the expectation that it will not elicit as much of a response as the native orthography.

The study allowed us to address the following two questions: (1) Is there spatial convergence of the brain regions activated during single word or character processing by English and Chinese Readers respectively, and does this convergence fall specifically within the VWFA in support of the neuronal recycling hypothesis? (2) In each group, English and Chinese Readers separately, how does signal change in the left OTC during word processing in the native writing system compare with signal change during other types of object processing?

We expected to find that left OTC regions dedicated to the native writing system would also respond to objects, thus showing signs of object processing cortex being co-opted by print, but to find little response in the left OTC to the non-native writing system.

Methods

Subjects and Behavioral Profile

Twenty-six monolingual English Readers (mean age 7 years, 3 months) from the greater Washington, D.C., area in the United States and twenty-three Mandarin-speaking, monolingual Chinese Readers (mean age 7 years, 1 month) from Beijing, China, completed the behavioral and imaging protocol for this study. After removing subjects for excessive in-scanner motion (see below), seventeen subjects (7 boys, 10 girls) were included in the English-reading group and seventeen subjects (6 boys, 11 girls) were included in the Chinese-reading group. To be eligible for the study, English-reading children needed to score 85 or above on the Matrix Reasoning portion of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999). Chinese Readers needed to score 85 or above on the Chinese version of Raven's Standard Progressive Matrices (Zhang and Wang, 1985). This non-verbal IQ measure was used both as a selection criterion and to ensure matching of the two groups. For study participation, subjects from both groups also needed to score within the normal range for reading. For the English-reading children, single real word reading was measured using the Woodcock Reading Mastery Test–Revised Word Identification subtest (Woodcock, 1987). Since standardized reading measures are not available in China, for the Chinese-reading group, the Beijing Graded Reading Test was used to determine that reading was in the normal range. This test was developed for the purpose of this study and is based on the reading distribution of 313 Chinese children in a public school in Beijing. It includes 200 characters taught during 1st through 3rd grade in Beijing, which children are asked to read aloud. This process of determining normal reading is similar to that previously employed to capture reading ability in Chinese readers (Hu et al., 2010; Tan et al., 2005b). Children from both groups had to score within or above the normal range (the normal range being one standard deviation from the norm on their respective reading tests). Additionally, all children were determined to be free of developmental disabilities, congenital or acquired neurological and psychological disorders, and any major medical conditions. There was no known history of birth complications, and all subjects were free of metallic implants and severe claustrophobia. Demographic information for both groups can be found in Table 1.

fMRI Acquisition and In-Scanner Task

fMRI data acquisition was performed at the Center for Functional and Molecular Imaging (CFMI) at Georgetown University and the Beijing MRI Center for Brain Research on identical 3 Tesla Siemens Trio whole-body MRI systems. Functional scans were acquired using the following parameters: 134 images consisting of 30 slices obtained in interleaved descending order, 3.3 x 3.3 x 4.0mm^3 voxels, 210mm field of view, TR = 2s, TE = 30ms, flip angle = 90°.

In the scanner, all subjects in both countries viewed English Words, Chinese Characters, and line drawings of Objects in separate block-design runs. Each run consisted of blocks of whole stimuli alternating with blocks of scrambled stimuli (visual control condition), separated by blocks of fixation (Figure 1). Two blocks of each stimulus type were presented in each run, with ten stimuli presented per block. Two runs of each stimulus type (for a total of six runs) were obtained, and the order of presentation (whole stimuli first or scrambled stimuli first) was counterbalanced.

Twenty one-syllable English Words and twenty one- or two-character Chinese Character stimuli were selected for early age of acquisition. English Words ranged from three to four letters and Chinese Characters used between three and twelve strokes. Objects were selected from a set of simple line drawings that were all one syllable, and also shown to have an early age of acquisition (Snodgrass and Vanderwart, 1980). Words, characters, and objects were chosen to be simple and easy for the children to read. Post-scanner recognition tests showed that children were easily able to recognize all of the stimuli observed in the scanner, validating this point (see Results section). Scrambled stimuli were generated by scrambling the real images within the same visual space using in-house software.

For the blocks of real and scrambled stimuli, each trial began with a fixation cross in the center of the screen. The fixation cross then disappeared and the stimulus appeared with the inside edge on or just adjacent to where the fixation cross was located. Subjects responded via button press to indicate which side the stimulus was located (relative to the previously presented fixation cross). This decision on horizontal placement of the stimuli was chosen because the response was easy for children to map onto their left and right hands touching the button box. The stimuli were presented sufficiently close to the center of the screen to avoid hemifield bias during processing of the stimuli. Similarly to other tasks (Turkeltaub et al., 2004, 2003), this implicit processing paradigm allows for subjects to visually process the stimuli without explicitly naming the word, character, or object. Each block contained ten trials followed by an 18-second fixation period. Each stimulus was presented for 1200ms followed by a 3000-ms response period, totaling 4200 ms per trial and 42 seconds per stimulus block. Two blocks of each stimulus type (real and scrambled) plus the four fixation periods equals 240 seconds. With additional fixation added to the beginning (to account for saturation effects) and end of the run, each run lasted 268 seconds and resulted in 134 acquisitions. Stimuli were presented using Presentation software (www.neurobs.com) and back-projected onto a screen mounted behind the scanner. All participants performed a practice session outside the scanner to ensure they understood the task.

Pencil-and-paper post-tests were administered following the fMRI protocol, outside of the scanner, to gauge if the children had been paying attention to the stimuli. Each test consisted of a list of forty stimuli (one test for each type of run: Objects, Words, or Characters), half of which had been presented during the scan and the other half of which had not. Subjects indicated using a checkmark whether they believed they had seen the stimulus in the scanner or not (Turkeltaub et al., 2003).

fMRI Preprocessing and Single-Subject Analysis

All analyses were carried out in SPM8 (Wellcome Trust Centre for Neuroimaging, UCL). All runs for each subject were pre-processed together. Prior to pre-processing, the first eight scans of each run were removed to account for T1 saturation effects. Preprocessing was then performed: motion correction by realigning to the mean functional image, normalization to the standard Montreal Neurological Institute (MNI) EPI template, and smoothing using an $8mm^3$ Gaussian kernel. While there have been some concerns for normalization of pediatric data to adult templates (Wilke et al., 2003, 2002), this has primarily been for T1-weighted images used for tissue classification. Our current study's use of normalization to the MNI EPI template for fMRI data was consistent with our prior pediatric studies (Evans et al., 2014; Olulade et al., 2015, 2013a, 2013b) based on the feasibility of transforming pediatric brains into adult stereotactic space (Burgund et al., 2002; Kang et al., 2003). The data was examined for excessive head motion, and subjects were excluded based on inter-scan movement and total movement during a run. Subjects who moved over a threshold of 0.75mm/scan in more than 30% of the scans of any run, or who moved more than 1cm from the origin (x, y, or z direction) during the course of any run were excluded from further analysis. Following this quality-control procedure, seventeen subjects from each group remained in the study and were submitted to the following analyses.

Head motion parameters in all six dimensions and global mean signal were entered as regressors of no interest for the generation of all individual subject maps (i.e. English Words, Chinese Characters, and Objects vs. Fixation or vs. scrambled stimuli, as described below). Stimulus onsets were modeled using the canonical hemodynamic response function and high-pass filtered at 128s. Both runs were included in the analyses for all subjects for all stimulus types.

fMRI Group Analyses

1. (a) Script Invariance: Whole-Brain Analysis—First we conducted whole-brain analyses for each group, contrasting English Words versus Fixation (English Readers), and Chinese Character versus Fixation (Chinese Readers), and used these maps in a conjunction null test to identify common regions of activity between the two groups. This analysis in SPM returns all voxels where both conditions have met the statistical height threshold indicated. The purpose here was to determine the locations where both groups were displaying activation during reading of their native script. A whole-brain approach allowed us to observe the specificity of any overlap in the context of any other overlap in the brain.

1. (b) Script Invariance: OTC Analysis—Because we expected to observe significant conjunction results in the left OTC, we next tested this *a priori* hypothesis by restricting the analysis to a spatially constrained region, including only the bilateral inferior temporal and fusiform gyri using the Wake Forest University Pick Atlas (Maldjian et al., 2004, 2003). The analysis examined ventral OTC activation in each group separately (English Readers and Chinese Readers). Again, English Readers' Words vs. Fixation contrast maps, and Chinese Readers' Characters vs. Fixation contrast maps (we later refer to this area as the "native script reading cluster" for each group) were generated. We then statistically tested for spatial overlap between the two groups using the conjunction null analysis, thereby providing another opportunity to examine spatial overlap indicative of script-invariance, this time, however, constrained to the ventral OTC.

2. Activity for Word or Character Stimuli in Relationship to other Object Classes—We extracted fMRI signal from the native script reading clusters generated in each group (used for the conjunction analysis above, that is, one left ventral OTC cluster per group, found to be responsive to native script reading) using the MarsBaR toolbox (Brett et al., 2002). This was conducted separately in each group (English Readers and Chinese Readers) in order to calculate the modulation of the signal (percent change) in response to each stimulus type (English Words, Chinese Characters, and Objects) in comparison to the respective scrambled control conditions. Specifically, one-way repeated measures ANOVAs were run on Stimuli vs. Scrambled Stimuli signal for each stimulus type in each group. This allowed us to compare the signal increases for the native writing system OTC region with signal increases observed for objects as well as the writing system with which the group had no familiarity. Since the objective was to focus on the stimulus type within each group, no between-group comparisons were made; therefore, it did not matter that the regions over which percent signal change (PSC) was calculated were not of the same size in the English and Chinese Readers. It should be noted that the PSC analysis was on the subtler comparison of whole versus scrambled stimuli, and different from the word/character versus fixation contrast applied at the voxel-wise level to generate the native script reading cluster in the ventral OTC.

Results

Behavioral Data: In-Scanner Performance

The task in this study was implicit: Children were not asked to explicitly read the words or characters, or name the objects; rather, they pressed buttons in their left and right hands in response to the relative horizontal position of the stimuli on the screen. As expected based on the nature of the tasks, in-scanner performance accuracy was high for both groups on all stimulus types, all averaging above 93% accuracy. Details for average accuracy (% correct for answered trials) and reaction times (RT) for each group for each stimulus type can be found in Table 2. Statistical comparisons were made for accuracy and RT in ways to parallel the neuroimaging analysis. Specifically, the first analysis, the conjunction map (examining script invariance), did not involve a comparison between any two conditions and hence did not motivate analysis of the corresponding behavioral data. The second analysis warranted analyses of the in-scanner data to parallel the fMRI analysis addressing object and non-native script processing. One-way repeated measures ANOVAs were performed on the accuracy and RT data while viewing whole stimuli and scrambled stimuli. As with the fMRI data, these were carried out for each stimulus type (English Words, Chinese Characters, and Objects) in each group (English Readers and Chinese Readers). In the English Readers there was an effect for RT for whole stimuli (F=7.753, p=0.002), and post-hoc paired t-tests revealed these to be between English Words and Chinese Characters (t=3.929, p=0.001), as well as between English Words and Objects (t=2.691, p=0.016). For Chinese Readers, there was a significant effect of accuracy for whole stimuli (F=5.068, p=0.012), with post-hoc paired t-tests revealing differences between English Words and Objects (t=2.777, p=0.013) as well as between Chinese Characters and Objects (t=2.406, p=0.029). For RT in the Chinese Readers, there was a significant effect for the scrambled stimuli (F=9.100, p=0.001): post-hoc paired t-tests identified differences between the scrambled stimuli generated from English Words and from Objects (t=3.600, p=0.002) as well as between scrambled stimuli generated from Chinese Characters and Objects (t=3.683, p=0.002). No other comparisons were significant.

Behavioral Data: Post-Scan Stimuli Recognition Tests

Paper-and-pencil tests were given to the children after exiting the scanner to gauge if they had attended to the stimuli during the scan. For each stimulus type (English Words, Chinese Characters, and Objects) the tests included 20 items the child saw in the scanner intermixed with another 20 items they did not see in the scanner. Children responded by checking a box *yes* or *no* as to whether they thought they had seen the item in the scanner. English Readers averaged (SD) 69.1% (± 16.8%) correct for English Words, 84.6% (±11.9%) correct for Objects, and 53.6% (± 7.9%) correct for Chinese Characters. Chinese Readers averaged 73.4% (± 9.1%) correct for Chinese Characters, 73.5% (± 10.5%) correct for Objects, and 55.3% (± 8.3%) correct for English Words. This demonstrates that the children were attending to the stimuli in the scanner, yet, as expected, both groups were much closer to chance for their non-native writing systems.

fMRI Data 1(a): Script Invariance: Whole-Brain Analysis with Conjunction

In order to identify brain regions showing overlap for reading in the two different native languages used by each group, we conducted an SPM analysis at the level of the whole brain, followed by a conjunction analysis. Maps of English Words vs. Fixation were generated for the English Readers and Chinese Characters vs. Fixation for the Chinese Readers (p<0.001 uncorrected height threshold, p<0.05 cluster threshold FWE corrected). English Readers showed four left hemisphere clusters including inferior occipital gyrus (extending into fusiform gyrus), middle frontal gyrus (extending into precentral gyrus), insula (extending into inferior frontal gyrus), and superior frontal gyrus (extending into right cingulate gyrus) (Table 3). Chinese Readers showed two left hemisphere clusters: one with peak location in the cuneus (extending into the inferior and middle occipital gyri), and one in the supramarginal gyrus. They also had one right hemisphere cluster in the cuneus (extending into inferior occipital gyrus and cerebellum) (Table 3). We then used the conjunction null test in SPM to return all voxels surviving the height threshold of p<0.001. Five clusters were identified with at least 10 contiguous voxels. In the left hemisphere: lingual gyrus (extending into cuneus), inferior occipital gyrus (extending into fusiform gyrus), middle frontal gyrus, and medial frontal gyrus. There was also one right hemisphere cluster located in inferior posterior fusiform gyrus (Table 3, Figure 2).

fMRI Data 1. (b): Script Invariance: OTC Analysis with Conjunction

Similarly to the whole-brain analysis described above, we first computed separate within-group maps for the English Readers and the Chinese Readers using the word/character processing condition from each group’s respective native script (i.e. English Words, Chinese Characters, each compared with Fixation in a single SPM model; height threshold p<0.001 uncorrected, FWE cluster-corrected p<0.05). However, this time the analyses were restricted to the bilateral fusiform and inferior temporal gyri as noted in the Methods section. For English Word processing, the English Readers had one cluster in the left hemisphere, as did the Chinese Readers for Chinese Character processing (Figure 3, Table 4). We refer to these areas as the each group's respective "native script reading cluster" (see later analyses below).

Next, we once again statistically tested for spatial overlap between these two separate sets of group data by using a conjunction analysis ($p<0.001$ uncorrected in both groups; $k > 10$ voxels). This revealed a left hemisphere cluster located at MNI coordinates −42, −52, −14 (Talairach coordinates −42, −51, −9; Table 5, Figure 4) very close to the reported average location of the VWFA at Talairach (Talairach and Tournoux, 1988) coordinates −42, −54, −12 (±5) (Cohen et al., 2002; Kronbichler et al., 2004; McCandliss et al., 2003). This region was located within the left inferior occipital gyrus cluster reported in the whole group analysis, above. This result demonstrates that the location of the VWFA is indeed the same for the alphabetic (English) and logographic (Chinese) orthographies studied here, lending direct support for script-invariant engagement of this region and the neuronal recycling hypothesis.

For visualization purposes only, the PSC for each condition in each group was extracted from the conjunction analysis cluster and displayed in the right panel of Figure 4. It reveals that both groups show low signal change in response to the scrambled control stimuli and a strong signal change in response to their native script (Chinese Readers to Chinese characters, English Readers to English Words). The only difference in response profile is that while Chinese Readers showed little signal change in response to English Words, English Readers showed a strong signal increase in response to Chinese Characters.

fMRI Data: (2) Activity Underlying Word or Character Stimuli in Relationship to other Object Classes

Lastly, we addressed how areas involved in reading (identified above) behave in response to other visual stimulus classes. To this end, PSC was extracted from the native script reading clusters identified separately in the readers of English and readers of Chinese (as described above). PSC for English Words, Chinese Characters, and Objects versus their respective scrambled conditions (Stimuli-Scrambled Stimuli PSC) were submitted to 3x1 repeated measures ANOVAs (One ANOVA per group). We found that in the readers of English, there was a main effect of Stimulus Type ($F=4.548$, $p=0.018$). Post hoc t-tests showed that the response to English Words was dwarfed by the activity elicited by Objects ($p=0.039$, see Figure 5). Likewise, the response to Objects was greater than that to Chinese Characters ($p=0.007$). There was no difference in the response to English Words and Chinese Characters. For the Chinese Readers there was a main effect of Stimulus Type ($F=3.561$, $p=0.04$, see Figure 3B). Post hoc t-tests revealed that Chinese Characters elicited a stronger response than did English Words ($p=0.015$). There was no difference in the signal for Chinese Characters and Objects ($p=0.766$).

For visualization of the data, Figure 5 depicts the PSC values plotted for all three types of whole and scrambled stimuli versus Fixation.

In summary, our whole-brain conjunction analysis and the conjunction analysis constrained to the ventral OTC revealed overlap in activity between the two groups of children in the VWFA, providing evidence of script invariance in further support the neuronal recycling hypothesis. Secondly, we also found that when examining signal change in ventral OTC, for English Readers the Objects were still the dominant stimulus category at this point in development, even though the region itself was identified based on a response to words. Surprisingly, English Readers did not show a stronger response to English Words compared with Chinese Characters. On the other hand, Chinese Readers' response to their native writing system reflects the nature of the orthography, in that the response was similar to that shown for objects, and at the same time, significantly higher than that for the non-native English Words.

Discussion

Left mid-fusiform gyrus has been shown to consistently respond to word reading across cultures, orthographies, and writing systems (Baker et al., 2007; Bolger et al., 2005; Nakamura et al., 2005; Szwed et al., 2014), suggesting a consistent recruitment of ventral visual cortex when learning to read (Dehaene and Cohen, 2007). However, this consistency has yet to be shown within the context of a single study of typically developing, monolingual readers of different writing systems. In this study, we investigated English word and Chinese character processing in 1st grade children monolingual and monoliterate in English or Chinese, respectively, who were scanned on identical scanners in the United States and China. First, our main goal was to test the neuronal recycling hypothesis (Dehaene and Cohen, 2007) by investigating whether children from both groups activated the same region of ventral OTC during word processing in their respective native scripts. Our conjunction analysis results from both a whole-brain analysis as well as one that was restricted to the OTC demonstrated that both groups recruited an overlapping region of left OTC located in the classical VWFA, as previously described in adults (Cohen et al., 2002; Kronbichler et al., 2004; McCandliss et al., 2003), providing the first evidence for script invariance in monolingual children and further support for the neuronal recycling hypothesis. Secondly, within each group, as we anticipated, activation to native script encroached on object processing regions (both groups' native reading clusters showed strong signal increase to objects). We also expected to find in each group relatively little signal increase during the processing of the other, non-native writing system. This was confirmed for the Chinese-reading but not the English-reading children. Together, our results show for the first time in purely monolingual (and monoliterate) subjects under the same experimental conditions that there is overlap between English and Chinese reading activation in the VWFA. Furthermore, Chinese Readers showed equal activation between their native writing system and Objects, while English Readers showed less activation for their native writing system compared with Objects. This is likely to reflect differences in the nature of the individual script and in how these writing systems are learned.

A recent study of adult French and Chinese readers provides an interesting comparison with the current study, since it also focused on the issue of script invariance (Szwed et al., 2014). While not a purely monolingual study, both groups were presented with their native writing system and non-native writing system. The task was similar to the current study in that it did not explicitly involve reading, but it involved an oddball detection task during rapid presentation of Chinese characters, French words and nonwords, objects, and scrambled stimuli. Overlap of reading in the two writing systems was not directly tested; however, both groups recruited clusters with similar locations in the fusiform gyrus in the left hemisphere for their native writing systems. Our results clearly demonstrate spatial co-localization of word processing in two distinct writing systems in beginning monolingual readers, this time using a statistical approach. Surprisingly, both groups in the Szwed et al. study also showed activation in left OTC for the non-native writing system, something we observed in the second analysis of our study, but only in our readers of English. Specifically, the French participants' activation to Chinese characters in the Szwed study was much more "object"-like than the Chinese participants' activation to Chinese characters in that they recruited more of the lateral occipital area (Szwed et al., 2014).

In addition to showing script invariance in the VWFA, our whole-brain conjunction analysis yielded some results suggesting other common areas of reading between the two groups. First, there is a portion of the right hemisphere posterior fusiform gyrus that showed activation in both groups for reading, though it is more posterior and inferior than would be expected for a right hemisphere VWFA homologue. Chinese has been found to elicit right hemisphere activation in some cases, and it has been argued that there is greater recruitment of the right hemisphere OTC when reading Chinese due to its visuospatial nature (Bolger et al., 2005; Perfetti et al., 2007; Szwed et al., 2014). It has been suggested that both left and right OTC are needed to perform unique roles in the processing of logographic characters as opposed to alphabetic words, which utilize only the left hemisphere (Bolger et al., 2005; Liu and Perfetti, 2003). Liu and Perfetti (2003) found that right hemisphere activation occurred approximately 50ms after left hemisphere activation, suggesting that the left hemisphere may be the processing center for written words, and the right hemisphere may play a supportive role. The vast majority of the region identified here (which is large in the Chinese Readers) falls outside of the fusiform and inferior temporal gyrus region, which is why it was not observed in the ventral OTC analysis. It is possible that with more experience and/or age (as in the meta-analyses above and individual studies such as Fu et al., 2002, and Liu et al., 2008), the right hemisphere VWFA homologue could become more engaged as the children become older and more experienced. It is also possible that with age and reading experience in Chinese, the spatial demands and complexity of the characters necessitates the use of the right hemisphere. As such, one could say that the left hemisphere activation occurs via neuronal recycling and the right hemisphere may be induced by script characteristics such as spatial layout. The characters used here are simple characters, and as such, we cannot address how complexity of characters may influence the localization of activation. Longitudinal data will be crucial in answering this question.

The conjunction analysis based on whole-brain data also revealed an overlap in left hemisphere lingual gyrus and cuneus, which could reflect the use of Stimuli vs. Fixation as the contrast or early visual information for the individual scripts below the whole-word (or character) level. Lastly, two frontal regions that were identified in the whole-brain conjunction analysis were middle and medial frontal gyri. Converting to Talairach coordinates, the medial frontal gyrus cluster (x=−6, y=6, z=49) is close to that identified as overlapping between alphabetic script and Chinese in the meta-analysis from Bolger et al. (2005; x=0, y=2 z=54). Though both are located in BA 6, the middle frontal gyrus region is medial and superior to the region from Bolger et al. (2005). Interestingly, the English Readers showed inferior frontal activation but not temporoparietal activation for the English

Words task. The Chinese Readers showed the opposite activation pattern for Chinese Characters. Future studies using a phonologically based task would be better suited to identify common activation for Chinese and English Readers in the parietal and frontal regions.

Turning to our second question regarding how the native reading clusters respond to different categories of visual stimuli, it has been suggested that the use of the VWFA is due to extensive training. Our investigation was focused on novice readers, yet it has to be recognized that our observations would likely be different if we were to study these children again once they are more proficient readers. Baker and colleagues examined adult experienced readers, specifically monoliterate readers of English and biliterate readers of Hebrew and English (Baker et al., 2007). Both groups showed VWFA activation for words and consonant strings, but only the group with Hebrew experience showed greater activation for Hebrew compared with other visual categories, including Chinese characters. The importance of experience is also highlighted by a twin study that found stronger contributions of unique environment for words and pseudowords as opposed to consonant strings and false font in the VWFA (Park et al., 2012). In contrast, a series of training studies from Xue and colleagues argues greater activation for an untrained artificial logographic orthography prior to training, and following training expertise is indicated by decreases in right hemisphere fusiform and left posterior occipitotemporal activation, suggesting less activation with more experience (Xue and Poldrack, 2007; Xue et al., 2006a, 2006b). The discrepancy between this and other findings highlights the need for longitudinal imaging studies of reading acquisition in both writing systems.

An important aspect of cross-cultural studies such as this one is that there are differences in teaching methods, and in the case of Chinese, learning to read usually involves Pinyin (phonetic transcription of Chinese characters using Latin script). The question arises whether the children in our study, through their experience with Pinyin achieved some Latin script familiarity. For them, schooling began with a dedicated period of Pinyin instruction of about six weeks, preceding the introduction of characters. Pinyin learning bootstraps Chinese character reading. A period of mixed presentation of characters and letters (used for the first appearance of a character) occurred throughout first grade. It is important to note that the learning of Pinyin occurred in the context of a dedicated connection between Pinyin and Chinese characters; it is not connected to English, which has much more complex grapheme-phoneme connections. In fact, the children in our study were not speakers of English (deliberately chosen to be monolingual), and therefore their learning of Pinyin was strictly and uniquely tied to Chinese character learning and was never put into the context of English. In some other schools where Chinese children learn to speak English, Pinyin learning is delayed until the second semester, or even later, because the learning of Pinyin and English at the same time interfere with each other, as some letters are pronounced differently in Pinyin and English. Specifically, while most Pinyin combinations probably also occur in English (with exceptions such as *q*), the reverse is not true: English has many combinations, consonant clusters in particular, that do not occur in Chinese. It is also worth mentioning that Pinyin is 100% transparent; in contrast, English is not.

So while our Chinese children will have had a level of familiarity with the Latin script that is higher than the familiarity of American children with Chinese characters, we do not think this would affect the results or interpretation of our second question examining the left OTC regions dedicated to the native writing system vis-a-vis processing of objects and the non-native writing system. Our examination of the activity in OTC revealed that Chinese Characters elicited a stronger response than did English Words in the Chinese Readers, indicative of experience-dependent tuning to their own writing system compared with the foreign alphabetic stimuli. This goes hand in hand with the recognition test that was taken by the children following the scan. It revealed that in the Chinese Reader's recognition of the English Words was 55.3% correct (while it was 73.4% for their native Chinese characters). Importantly, this represents the same degree of accuracy as the analogous response for the English Readers in response to the list of Chinese Characters, for which this group achieved 53.6% accuracy. As such there is no indication that there was more familiarity exhibited by the Chinese Readers towards English words relative to the familiarity (or lack of) exhibited by the American English Readers towards Chinese characters. The explanation for why Pinyin learning does not increase familiarity to Latin script is probably twofold in that (1) prior exposure to letters of the Latin script did not occur in the context of English, and generalization to English carries with it some complexity, as discussed above; and (2) our study involved whole words, and recognizing whole words depends on significant exposure to these words. This last point is especially relevant to our imaging data, where it needs to be considered that while the Chinese children will have had exposure to *letters* from the Latin alphabet, they would not have had exposure to the *words* presented during the scan. The premise of the VWFA is that it responds to words or pseudowords, or as some have argued, only to real words that are maintained in the VWFA much like a dictionary (Glezer et al., 2009).

There are of course several differences between English and Chinese that are relevant to the teaching of reading in these two different writing systems, and to the interpretation of our results as a whole: first, the difference in visual appearance (script), and second, the difference in the mapping system (whether the system uses phonemes like in English or morpheme syllables like in Chinese). Aside from the difference in appearance between characters and words, successful acquisition of each language relies differently on reading-related skills. While reading ability in both languages is predicted by phonological skills, Chinese reading ability is also strongly predicted by orthographic skill as measured by character writing (Tan et al., 2005b). Also, in a group of Chinese-English bilingual children, Chinese orthographic choice scores predicted Chinese character reading (Wang et al., 2005), again providing evidence for the importance of orthographic skill in learning to read Chinese. The difference in phonological and orthographic awareness between these writing systems is also highlighted in a study of English- and Chinese-reading monolingual children and adults focused on oral language processing (Brennan et al., 2013), where they found a reorganization of the phonological awareness system (superior temporal gyrus, inferior parietal lobule, and inferior frontal gyrus) only in the English readers during a rhyming task. If writing Chinese characters is part of learning to read Chinese (as noted above), this kind of training could help tune the VWFS more than the phonological skills trained in learning to read English do. For example, English cursive handwriting (which may better approximate the visual complexity of characters seen in Chinese writing; for discussion see Nakamura et al., 2012; Perfetti and Tan, 2013) is often taught after learning to read and may represent a difference in “training” between the two cultures.

Models of reading acquisition are also in line with this idea. Frith (1986, 1985) described the acquisition of reading as beginning with a logographic strategy (recognizing known words much like one would recognize known objects), followed by the emergence of alphabetic and orthographic strategies. While the alphabetic-reading children will also begin using the former strategy, the nature of Chinese as a logographic script may facilitate earlier recognition of characters. Another model of reading acquisition from Ehri (1999) begins with a pre-alphabetic phase prior to children having strong phonological awareness skills, so they use visual features as cues. They then build alphabetic skills before reaching a level where familiarity with orthographic strings (such as whole words) becomes automatic. The importance of orthographic skill in learning Chinese and the logographic nature of the script as opposed to English could explain why the VWFA appears more mature in the Chinese children than in the English-reading children.

In conclusion, this study addressed key questions regarding the neuronal recycling hypothesis by studying reading using the same task in separate groups of monolingual English- and Chinese-reading children. Our main analysis showed that after only the first year of formal reading instruction, these two groups show statistically significant overlap of reading activation in the VWFA, confirming inference based on overlap from meta-analyses and providing direct evidence for script invariance. Individual analyses in each group showed that both demonstrate activation for reading in a region of cortex that also shows strong activation for objects, in line with the idea of recruitment from the neuronal recycling hypothesis (Dehaene and Cohen, 2007). We also found that English Readers showed greater activation for Objects compared with Words, and Chinese Readers showed equivalent activation for Objects and Characters. These profiles of activation for the visual stimuli in the two groups might be related to the difference in the nature of the written language in these two writing systems and in how these writing systems are taught. Longitudinal studies will be necessary to determine how ventral visual processing of orthographic stimuli develops during reading acquisition beyond the first year of formal reading instruction. How these different writing systems recruit ventral visual cortex differently may also inform our understanding of acquired as well as developmental reading disorders in both cultures.

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Abbreviations

VWFA	visual word form area
VWFS	visual word form system

fMRI	functional magnetic resonance imaging
OTC	occipitotemporal cortex
WASI	Wechsler Abbreviated Scale of Intelligence

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Highlights

- English and Chinese readers activate left OTC while reading their native script
- Overlap of activation for English Words and Chinese Characters occurs in left VWFA
- Chinese readers show similar activation for characters and objects in left OTC
- English readers show less activity to words than objects in left OTC

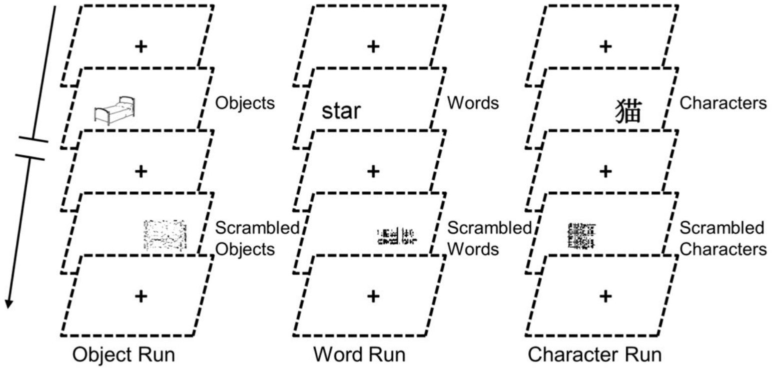

Figure 1. fMRI Paradigm and Stimuli

Schematic of example Object, Word, and Character stimuli from each type of run. Size and proportions of the stimuli are not representative of the actual presentation during the study, but are enlarged for visualization purposes. Alternating blocks of whole stimuli and scrambled stimuli (two blocks of each per run) were presented with blocks of fixation in between. Each subject had two runs of each stimulus type (six total), with one run beginning with whole stimuli and the other run beginning with scrambled stimuli.

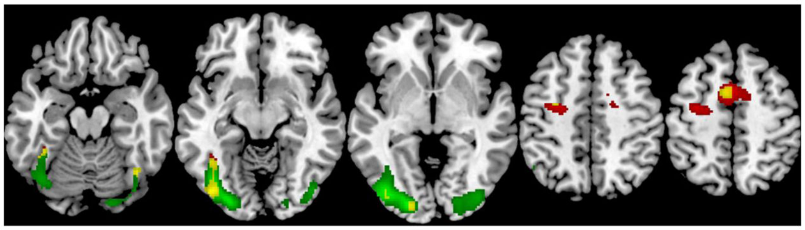

Figure 2. Script Invariance: Maps for Whole-Brain Analysis in Chinese and English Readers with Conjunction

Conjunction analysis result (whole brain) for Chinese Character processing in Chinese-reading children (Chinese Characters vs. Fixation: green) and English Word processing in English-reading children (English Words vs. Fixation: red). The conjunction of these is in yellow. Analysis was conducted at the whole-brain level, and axial slices represent the z coordinate of the peak location of the conjunction clusters (See Table 3).

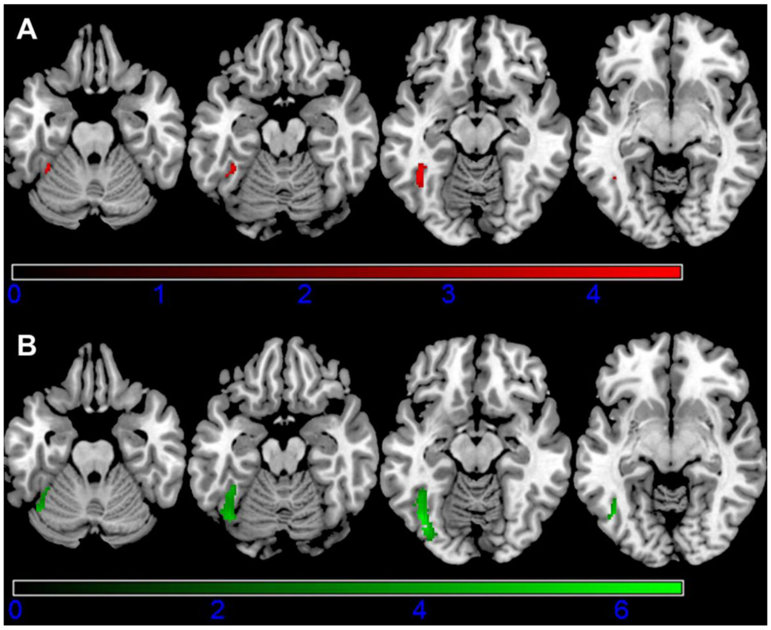

Figure 3. Native Script Reading Clusters (OTC Analysis)

Response to the native writing system in English-reading (A, red) and Chinese-reading children (B, green) in the analysis restricted to OTC. Each panel shows axial slices from left to right: z = −23, z= −18, z= −13, z= −8. Color bars represent the t statistic. Height threshold p<0.001 for A and B. FWE cluster correction p<0.05 for A and B. English Word and Chinese Character stimuli were contrasted with Fixation.

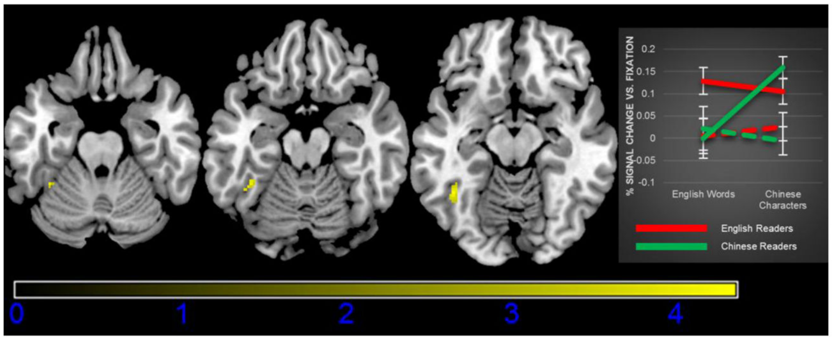

Figure 4. Script Invariance: Map for OTC Analysis with Conjunction

The conjunction null cluster generated in SPM for the analysis restricted to OTC showing overlap (yellow) of the native script reading clusters identified in Figure 3 A and B. The conjunction null test is an F test; the voxel threshold was set at 10 to identify only substantial clusters.

Right Panel: For visualization purposes only, the PSC was extracted from the conjunction cluster for English Words and Chinese Characters as well as their scrambled counterparts (vs. Fixation). English Readers are in red, Chinese Readers are in green. Whole stimuli are solid lines, and scrambled stimuli are dotted lines. Error bars represent standard error.

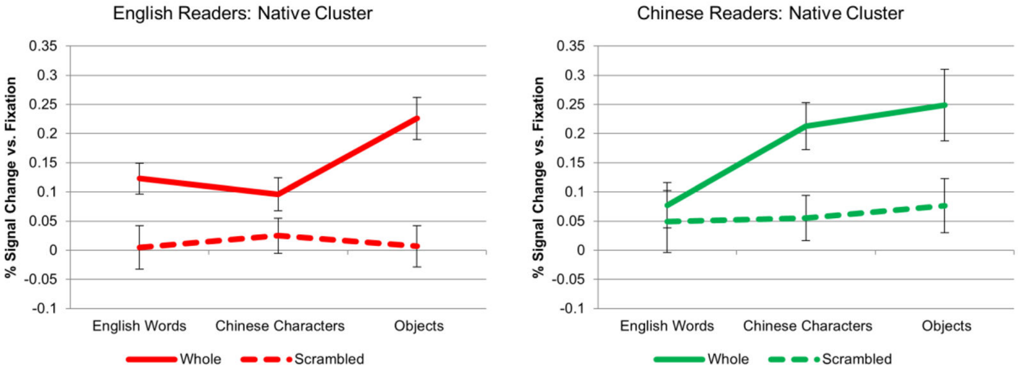

Figure 5. Percent Signal Change in Native Script Reading Clusters for all Stimuli Relative to Fixation

For visualization purposes, PSC is shown for the three stimuli (English Words, Chinese Characters, and Objects- solid lines) and their scrambled counterparts (dotted lines) relative to Fixation. The signal change was extracted for each group of children from their respective native script reading clusters. English Readers are in red, Chinese Readers are in green. Error bars represent standard error.

Table 1

Subject Demographics

	English Readers (n=17)	Chinese Readers (n=17)	P value
Male/Female	7:10	6:11	0.734
Age in Years (s.d.)	7.3 (0.3)	7.1 (0.4)	0.063
Single Word Reading (s.d)	119 (6.5)		n/a
Character Reading (max = 200; s.d.)		108 (23.4)	
Matrix Reasoning (s.d.)	115 (11.9)	116 (7.4)	0.796

Measures of Single Word Reading and Matrix Reasoning are standard scores, meaning the average score is 100 with a standard deviation of 15. Single Word Reading was assessed in the English-reading children using the Woodcock Reading Mastery Test–Revised Word Identification subtest. Character Reading is based on aloud reading of the Beijing Graded Reading Test which includes 200 characters taught during 1st through 3rd grade in Beijing. For Matrix Reasoning, the English-reading children's scores are from the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999), and the Chinese-reading children's scores are from Raven's Standard Progressive Matrices (Zhang and Wang, 1985).

Table 2

In-Scanner Behavior

	English Readers	Chinese Readers
Accuracy: % Correct (s.d.)		
Words	98.4 (1.8)	97.3 (3.8)
Scrambled Words	98.4 (2.0)	97.2 (5.6)
Characters	96.0 (4.4)	96.9 (3.6)
Scrambled Characters	97.0 (2.4)	96.8 (3.7)
Objects	96.3 (3.0)	93.4 (5.2)
Scrambled Objects	97.6 (2.6)	94.6 (5.8)
All Stimuli	97.3 (2.5)	96.0 (4.5)
Reaction Time: ms (s.d.)		
Words	613.49 (125.19)	851.53 (141.06)
Scrambled Words	620.22 (110.15)	829.67 (112.45)
Characters	659.92 (120.64)	855.91 (128.86)
Scrambled Characters	625.63 (115.10)	841.74 (101.55)
Objects	658.09 (116.43)	924.79 (119.91)
Scrambled Objects	645.03 (128.02)	937.22 (101.09)
All Stimuli	638.03 (121.40)	873.38 (140.08)

Table 3

Script Invariance: Results for Whole-Brain Analysis in Chinese and English Readers With Conjunction

MNI Peak Coordinate X	Y	Z	Cluster Size (voxels)	T-statistic	Z-score	Anatomical Location
English Readers: English Words vs. Fixation						
−40	−78	−10	239	4.88	4.19	L Inferior Occipital Gyrus BA 19
−42	*−48*	*−16*		*4.62*	*4.01*	*L Fusiform Gyrus BA37*
−40	*−66*	*−10*		*3.43*	*3.14*	*L Inferior Occipital Gyrus BA 37*
−26	−10	52	291	4.99	4.26	L Middle Frontal Gyrus BA 6
−32	*−8*	*52*		*4.83*	*4.15*	*L Precentral Gyrus BA 6*
−34	*−8*	*48*		*4.62*	*4.01*	*L Middle Frontal Gyrus BA 6*
−46	6	6	284	4.06	3.62	L Insula/IFG BA 13
−44	*−6*	*12*		*3.91*	*3.51*	*L Insula BA 13*
−36	*12*	*14*		*3.85*	*3.45*	*L Insula/IFG BA 13*
−4	6	56	595	6.21	4.99	L Superior Frontal Gyrus BA 6
18	*−6*	*50*		*3.93*	*3.53*	*R Cingulate Gyrus BA 24*
Chinese Readers: Chinese Characters vs. Fixation						
−20	−92	2	2323	8.05	5.91	L Cuneus BA17
−28	*−86*	*−8*		*7.89*	*5.84*	*L Inferior Occipital Gyrus BA 18*
−40	*−78*	*−4*		*7.36*	*5.59*	*L Middle Occipital Gyrus BA 19*
−56	−50	34	259	5.11	4.34	L Supramarginal Gyrus BA 40
−48	*−58*	*42*		*4.03*	*3.60*	*L Inferior Parietal Lobule BA 40*
22	−98	8	1139	7.04	5.43	R Cuneus BA 18
42	*−78*	*−8*		*5.34*	*4.48*	*R Inferior Occipital Gyrus BA 19*
36	*−80*	*−24*		*5.31*	*4.46*	*R Posterior Cerebellum*
Conjunction						
−18	−92	−4	80	4.25	3.76	L Lingual Gyrus BA 17
−20	*−94*	*4*		*3.78*	*3.41*	*L Cuneus BA 18*
−40	−78	−10	200	4.88	4.19	L Inferior Occipital Gyrus BA 19
−42	*−52*	*−14*		*4.38*	*3.85*	*L Fusiform Gyrus BA 37*
−38	*−46*	*−20*		*4.27*	*3.77*	*L Fusiform Gyrus BA 37*

MNI Peak Coordinate			Cluster Size (voxels)	T-statistic	Z-score	Anatomical Location
X	Y	Z				
−30	−6	48	19	3.91	3.51	L Middle Frontal Gyrus BA 6
−6	4	54	71	4.17	3.70	L Medial Frontal Gyrus BA 6
40	−64	−18	25	4.43	3.89	R Fusiform Gyrus BA 37

Table 4

Script Invariance: Results for OTC Analysis with Conjunction

MNI Peak Coordinate			Cluster Size (voxels)	T-statistic	Z-score	Anatomical Location
X	Y	Z				
English Readers: English Words vs. Fixation						
−42	−48	−16	102	4.62	4.01	L Fusiform Gyrus BA 37
−42	*−52*	*−14*		*4.38*	*3.85*	*L Fusiform Gyrus BA 37*
−38	*−46*	*−20*		*4.27*	*3.77*	*L Fusiform Gyrus BA 37*
−40	*−62*	*−12*		*3.55*	*3.23*	*L Fusiform Gyrus BA 37*
Chinese Readers: Chinese Characters vs. Fixation						
−40	−66	−12	314	6.62	5.22	L Fusiform Gyrus BA 19
−38	*−70*	*−12*		*6.25*	*5.02*	*L Fusiform Gyrus BA 19*
−38	*−76*	*−14*		*5.35*	*4.49*	*L Fusiform Gyrus/Middle Occipital Gyrus BA 19*
−40	*−62*	*−22*		*4.62*	*4.02*	*L Fusiform Gyrus/Posterior Cerebellum BA 37*
−40	*−50*	*−16*		*4.61*	*4.01*	*L Fusiform Gyrus BA 37*
Conjunction						
−42	−52	−14	69	4.38	3.85	L Fusiform Gyrus BA 37
−38	*−46*	*−20*		*4.27*	*3.77*	*L Fusiform Gyrus BA 37*
−40	*−46*	*−16*		*4.16*	*3.69*	*L Fusiform Gyrus BA 37*
−40	*−62*	*−12*		*3.55*	*3.23*	*L Fusiform Gyrus BA 37*