

# Cross-Cultural Effect on the Brain Revisited: Universal Structures Plus Writing System Variation

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**Abstract:** Recognizing printed words requires the mapping of graphic forms, which vary with writing systems, to linguistic forms, which vary with languages. Using a newly developed meta-analytic approach, aggregated Gaussian-estimated sources (AGES; Chein et al. [2002]: *Psychol Behav* 77:635–639), we examined the neuroimaging results for word reading within and across writing systems and languages. To find commonalities, we compiled 25 studies in English and other Western European languages that use an alphabetic writing system, 9 studies of native Chinese reading, 5 studies of Japanese Kana (syllabic) reading, and 4 studies of Kanji (morpho-syllabic) reading. Using the AGES approach, we created meta-images within each writing system, isolated reliable foci of activation, and compared findings across writing systems and languages. The results suggest that these writing systems utilize a common network of regions in word processing. Writing systems engage largely the same systems in terms of gross cortical regions, but localization within those regions suggests differences across writing systems. In particular, the region known as the visual word form area (VWFA) shows strikingly consistent localization across tasks and across writing systems. This region in the left mid-fusiform gyrus is critical to word recognition across writing systems and languages. *Hum Brain Mapp* 25:92–104, 2005. © 2005 Wiley-Liss, Inc.

**Key words:** orthographic processing; neuroimaging; word reading; meta-analysis; Chinese; Japanese

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## INTRODUCTION

Writing systems vary in how their visual forms represent units of spoken language; however, there are principles concerning the written representation of language that are universal [Perfetti, 2003]. A central universal is the language constraint: all writing systems represent spoken language, not merely meaning. No known writing system thus encodes meaning directly without correspondence to a spoken word. The idea that written language reflects universal prin-

ciples despite being implemented in markedly divergent ways leads us to ask whether there are universal cortical system for reading across the variety of languages and writing systems. Further, we want to know whether any such universal system includes variations that accommodate differences in languages and writing systems.

To examine these broad issues, we report below the results of a within- and across-writing system meta-analysis using a new quantitative procedure, aggregated Gaussian-estimated sources [AGES; Chein et al., 2002], to determine a set of cortical regions (a reading network) that might be shared by different languages and writing systems and to distinguish the universal components of the system from those that specifically accommodate the properties of a writing system. These goals are shared with a companion article by Tan et al. [2005], who emphasize the differences between Chinese and alphabetic writing. Our conclusions complement these differences to create a picture of the universal reading network.

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## Writing System Differences

Different writing systems code language in very different ways. Currently, as a reader of this article, you are engaged in decoding a writing system whose basic graphic unit encodes spoken units at the level of the phoneme. That is, every grapheme (which in English roughly corresponds to a letter or digraph of letters, such as *th*) represents a single subsyllabic unit of speech. For example, the word *cat* has three graphemes (c, a, and t) that correspond to three units of speech within a syllable (/k/+a/+t/). Alphabetic writing does vary in how consistently it maps a grapheme to a phoneme with “shallow” orthographies, such as Italian and Finnish, having more consistent mappings than does the “deep” orthography of English and its notorious irregularities. However, even the deepest alphabetic orthography maps graphemes to phonemes. By contrast, the Chinese writing system in Chinese does not map graphemes to phonemes, but instead maps a logographic character to a meaningful unit (a morpheme or word) that is also a spoken syllable. (Within a character, units known as radicals provide some partial information about pronunciation or meaning.) Although in principle, one could read Chinese directly for meaning without using pronunciation, the behavioral research on reading suggests that Chinese reading, like alphabetic reading, uses phonology [Perfetti et al., 2005]. The reason is that the character is connected to a syllable pronunciation as well as to a meaning, leading to an activation of a syllable when a character is read. The neurological structures underlying reading for Chinese thus must include phonological processing, as it does in alphabetic reading.

Japanese is written in two different writing systems, neither alphabetic. In the katakana (or Kana), a single grapheme corresponds to a spoken syllable; the kana are combined to produce multisyllabic words. The katakanji (or Kanji) system, borrowed from Chinese, uses characters that correspond directly to words, pronounced either in Japanese or as they would be in Chinese. Our comparison includes both Japanese and Chinese, giving a comparison of alphabetic, syllabic (Kana), and logographic (Chinese and Kanji) writing.

## Neuroimaging Studies of Reading

The study of reading is well represented in the neuroimaging literature with over 150 scientific articles covering visual word recognition in skilled and impaired adults and children. Several meta-analyses of reading have been conducted recently [Fiez and Petersen, 1998; Jobard et al., 2004; Mechelli et al., 2003; Price, 2000; Turkeltaub et al., 2002]. These studies highlight a cortical network associated with the processing of written (and spoken) language. For our purposes, we highlight a non-exhaustive set of highly replicated regions associated with

**TABLE I. Summary of anatomical regions found in various component processes of word reading**

Component process	Anatomical region	Brodman area
Orthographic	Bilateral occipital/posterior fusiform	18,37/19
	Left mid-fusiform/posterior ITG	37
Phonological	Superior temporal sulcus/inferior parietal lobe	22/40/39
	Inferior frontal sulcus/insula/premotor cortex	45/6/9
Semantic	Anterior fusiform/ITG/MTG	37/21
	Anterior inferior frontal gyrus (lateral surface)	44

ITG, inferior temporal gyrus; MTG, middle temporal gyrus.

orthographic, phonological, and semantic processing (Table I).<sup>1</sup>

The idea of cortical routes for reading was anticipated in the neuropathology work of Dejerine [1891, 1892]. Later work articulated the idea that two distinct routes, a direct route with addressed phonology and an indirect route with assembled phonology, were engaged in word reading [Coltheart et al., 1991; Warrington and Shallice, 1980; for reviews of dual-route theories of cortex see Price, 2000; Jobard, et al., 2003]. In an evaluation of cortical dual-route theories of reading using a meta-analysis of functional imaging studies of word reading, Jobard et al. [2003] argue in favor of a dual-route model in which the visual word-form system is common to both the indirect and direct routes for producing pronunciation.

Paulesu et al. [2000], who identified a “cultural effect” in reading, were among the first to analyze directly how the cortical network of regions associated with reading are engaged differentially when processing shallow compared to deep alphabetic orthographies. Based on their findings of pseudoword reading, Paulesu et al. [2000] suggested that the dual-route cortical system enables shallow orthographies such as Italian to more actively engage a dorsal pathway (via superior posterior temporal regions) as a reflection of the computation of assembled phonology from individual graphemes, whereas deeper orthographies such as English engage a ventral pathway (via left inferior temporal cortex) along which phonological and semantic processing takes

<sup>1</sup>Two regions associated with orthographic processing: bilateral posterior occipitotemporal cortex and left mid-fusiform gyrus [see Cohen et al., 2000, 2002; McCandliss et al., 2003]; two regions associated with phonological processing: left superior posterior temporal/temporoparietal junction roughly corresponding to angular gyrus [Rumsey et al., 1997] and inferior frontal gyrus extending into premotor cortex [Fiez and Petersen, 1998], two regions corresponding to semantic processing: anterior fusiform/inferior temporal/middle temporal gyrus extending to the temporal pole [see Price, 2000] and the anterior inferior frontal sulcus (ventral and anterior to Broca’s area; see Poldrack et al. [1999]).

place after visual word identification (addressed phonology).

The cultural effect identified in the Paulesu et al. [2000] study is limited to alphabetic orthographies that use an identical script (Roman alphabet) and encode related European languages. Compared to the differences between Chinese and English, such differences are at the level of detailed implementation of shared language and writing system. When we examine Chinese and Japanese as comparisons with English, we are at the system level where even greater cultural effects might be expected. To find universals in cortical activation at this level would indeed be interesting.

### Studies of Non-Alphabetic Languages

Studies of Japanese Kana and Kanji processing enable a within-subject, within-language comparison of two writing systems with differential mapping properties. Several neuroimaging studies of Japanese reading reveal differential processing routes for Kana and Kanji processing [Hamasaki et al., 1995; Sakurai et al., 1994]. Similar to conclusions on English reading, Japanese researchers have postulated a ventral route that maps graphemic forms to lexical/semantic information for the processing of Kanji (logographic) and a dorsal route for the processing of Kana (syllabographic) [Nakamura et al., 2002]. The neuroimaging study of Chinese reading has revealed generally similar patterns of activation to that shown for Chinese and English [Chee et al., 1999] and between Chinese character and pinyin (an alphabetic system for Chinese commonly used in early childhood) reading [Fu et al., 2002]. Some differences from alphabetic writing have also been shown, particularly in the visual processing system. For example, Tan et al. [2000] found right-lateralized occipital activation in processing simple and complex Chinese characters. The unique activity in right hemisphere (RH) locations found by Tan et al. [2000] was reported also by Liu and Perfetti [2002] with source localization of event-related potential (ERP) data and in recent unpublished Pittsburgh studies of English learners of Chinese. Recently, studies of Chinese reading have focused on the left dorsolateral frontal region [Siok et al., 2003, 2004] as another unique source of variation from alphabetic languages [Tan et al., 2005]. This region strongly predicts reading ability in Chinese [Siok et al., 2004] and is suggested to underlie the addressed phonology system in Chinese reading [Tan et al., 2005]. As we noted above, English, Japanese (Kana), and Chinese have developed different levels of mapping to the phonological and meaning components of language. From the standpoint that writing systems share a universal principle, that all writing systems encode spoken word forms, one expects a common network of cortical regions that map visual forms to spoken word forms to emerge from convergent evidence. From the standpoint of the different levels of mapping used by writing systems, one expects some accommodation of this universal network to specific differences. At the core of this universal network, based upon the findings of Jobard et al. [2003], lies a visual word-form system responsible for recognizing the graphic forms of words and

relaying that information on to those regions central to phonological and lexical/semantic processing. Regions unique to each language will reflect the language-specific nature of phonological and semantic decoding [Tan et al., 2005].

A region of the left mid-fusiform gyrus has been identified as the target visual word form processor and labeled the visual word form area [VWFA; Cohen et al., 2000, 2002; McCandliss et al., 2003]. Based on a series of findings, this region is characterized as performing abstract, prelexical computations [McCandliss et al., 2003] and thus has been referred to as a gateway region to lexicosemantic and phonological processing [Perfetti and Bolger, 2004]. A third goal of this meta-analysis is therefore to assess the cross-linguistic, cross-writing system nature of the putative VWFA, and how well it localizes across these systems.

## MATERIALS AND METHODS

### Literature Selection

Our search of the literature began with the goal to collect all studies of single-word reading in each of the target languages and writing systems: English and Western alphabetic languages (e.g., French, German, Italian, etc.), Japanese Kana and Kanji, and Chinese characters. These could include studies with children and adults with normal or impaired reading ability; however, only findings of normal subject reading were included in the meta-analysis we report below. Over 150 studies and the findings reported within were compiled and entered into a database. This may not be an exhaustive list of studies that use visual word stimuli for differing functional tasks such as memory or attention (e.g., the Stroop task), were not included because if the reported contrasts of these studies did not target word recognition processing.

We relied primarily on the PubMed, Medline, and Science Citation Index databases to find and retrieve these studies. However, in a few cases studies were found by perusing the citations of collected studies. The search consisted of functional imaging studies, both positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), that predominantly used whole-brain scanning; however, several studies with restricted coverage were included. For example, Poldrack et al. [1999] used coronal slices of frontal and prefrontal cortex in an fMRI investigation of word reading, but this study was included in our analysis. We created a database from which target contrasts (see below for details) across studies could be aggregated for each language/writing system (Table II).

### Analysis

The approach to the meta-analysis conducted here was the AGES approach adapted from Chein et al. [2002]. This approach enabled us to find consistently reported regions of activation across a number of studies that utilize similar contrasts (e.g., comparing word reading to a resting base-

**TABLE II. Compilation of studies, tasks, number of subjects, and experimental contrasts included in metaanalysis of each language/writing system**

Study	Task	n	Contrast
Chinese			
Chen et al., 2002	Reading	9	Chinese characters vs. fixation
		9	Chinese characters vs. PinYin
Fu et al., 2000	Reading fast: 60 wpm Reading slow: 20 wpm	8	Chinese characters vs. fixation
		8	Chinese characters vs. fixation
Luke et al., 2002	Judgment task (syntactic or semantic)	7	Chinese syntax vs. font-size judgment
		7	Chinese semantic vs. font-size judgment
Peng et al., 2003	Attentional mask task (short exposure: 51 ms)	8	High-freq characters vs. noncharacters
		8	Low-freq characters vs. noncharacters
	Attentional mask task (long exposure: 151 ms)	8	High-freq characters vs. noncharacters
		8	Low-freq characters vs. noncharacters
Tan et al., 2001	Judgment task (meaning or homophone)	6	Meaning judgment vs. fixation
		6	Homophone judgment vs. fixation
Tan et al., 2003	Judgment task	12	Rhyme decision vs. font-size judgment
Siok et al., 2003	Judgment task	11	Homophone judgment vs. font-size judgment
Kuo et al., 2003	Reading (ER design)	11	Initial consonant vs. font-size judgment
		20	All characters vs. fixation
Kuo et al., 2001	Reading	7	Characters vs. fixation
		7	Characters vs. visual and motor control task
Japanese Kanji			
Nakamura et al., 2002	Writing Recall	9	Words vs. rest
		9	Words vs. rest
Nakamura et al., 2000	Recall	10	Words vs. rest
Sakurai et al., 2000	Silent reading	15	Words vs. rest
Uchida et al., 1999	Silent reading	6	Kanji vs. baseline
		6	Kanji vs. scrambled Kanji
Japanese Kana			
Nakamura et al., 2002	Writing Recall	9	Words vs. rest
		9	Words vs. rest
Nakamura et al., 2000	Transcription Reading	10	Kana-Kanji vs. single character
		10	Silent word reading vs. single character
	Semantic judgment	10	Semantic decision vs. single character
		12	Kana vs. Korean words
Lee et al., 2003	Silent reading	15	Words vs. rest
Sakurai et al., 2000	Silent reading	15	Words vs. rest
Katanoda et al., 2001	Writing and naming objects	17	Writing Kana vs. finger tapping
English/Western			
Binder et al., 2003	Lexical decision	24	Words vs. rest
Bookheimer et al., 1995	Naming	16	Passive viewing vs. rest
		16	Naming vs. rest
Cabeza et al., 2003	Word recognition (ER) and target detection task (VA)	25	Regions acted by ER and SA tasks
Cohen et al., 2002	Word and nonword reading (blocked)	7	Alphabetic vs. checkerboards
		9	Alphabetic vs. checkerboards
Cohen et al., 2003	Reading	9	Alphabetic vs. checkerboards
Cohen et al., 2000	Hemifield word reading	7	LVF and RVF vs. rest
Dehaene et al., 2001	Masked and unmasked word reading	37	Visible words vs. rest
		37	Masked words vs. rest
Fiebach et al., 2002	Lexical decision	11	Words vs. pseudowords
Fiez et al., 1999	Word reading (aloud)	11	Positive activation across all word conditions
		11	Positive activation-hypothesis generation
		11	Words vs. fixation
Hagoort et al., 1999	Word reading	15	Words vs. fixation
Haist et al., 2001	Lexical decision (pseudoword foils) Lexical decision (pseudohomophone foils)	15	Words vs. fixation
		15	Words vs. fixation
Herbster et al., 1997	Reading aloud words and nonwords	10	Regular and irregular words vs. repeated speech
Howard et al., 1992	Word reading and word repetition	12	Word reading vs. "see and say"
Jernigan et al., 1998	Word identification Word recognition	8	Word identification vs. fixation
		8	Word recognition vs. fixation
Paulesu et al., 2000	Word reading	72	Main effect word reading
Petersen et al., 1989	Lexical processing	8	Fixation task vs. passive-nouns task (visual)
Petersen et al., 1990	Word reading	8	Real words vs. fixation
Poldrack et al., 1999	Semantic and phonological decision tasks	8	Semantic vs. case judgment
		8	Phonological vs. case judgment
Polk and Farah, 2002	Visual processing	9	Alternating-case and pseudowords vs. consonant str.
Price et al., 1994	Reading task Lexical decision	12	Reading aloud vs. feature decision
		12	Lexical decision vs. feature decision
		12	Silent viewing: words vs. false font
Price et al., 1996	Reading task (silent and aloud)	6	Silent vs. rest
		6	Aloud vs. rest
Rumsey et al., 1997	Lexical decision	14	Phonological vs. visual fixation
		14	Orthographic vs. visual fixation
Shaywitz et al., 2001	Processing printed and/or spoken words	25	Select attention to words vs. simple task
Tagamets et al., 2000	Matching task Matching task	11	Words vs. rest
		11	False fonts-words
Xu et al., 2001	Rhyming	12	Word rhyming vs. rest
		12	Alternating case vs. rest

line). This approach provides a quantitative means for finding highly convergent regions within a large body of neuroimaging studies.

The first step in this approach was to compile reported peak voxels of activation reported in a standardized set of coordinates, in this case Talairach and Tournoux [1988], for a given experimental contrast. We assumed that these reported peaks had been preprocessed and met the statistical requirements for significance. Unlike other meta-analytic procedures [see for example Mechelli et al., 2003], we did not account for the reported effect sizes for each peak voxel. We treated each of these peak coordinates as unique sources for 3D Gaussian distributions, which thus allowed us to compute each source as a Gaussian sphere, enabling localization of its spatial distribution with some degree of control. Whereas some researchers have used more liberal smoothing parameters in their analyses, we selected relatively conservative smoothing parameters to enable more unique sources within a small spatial range. In compiling the set of source distributions across studies, we created an activation map (meta-image) that measured the probability of convergent activation that was quantifiable and visually identifiable. We then simulated activation maps with randomly distributed sources (also transformed in Gaussian distributions) equal to the number of aggregated sources from our search. We compiled these simulated images to determine the convergence threshold values for an  $\alpha$  of  $P < 0.05$  and  $0.01$ . Application of this threshold to our resulting meta-image showed only those regions that were activated consistently (with 95% confidence) across tasks and the spatial extent (in terms of the probability distribution) of those regions (see below for details of simulated images).

In the Chein et al. [2002] meta-analysis, 30 neuroimaging studies of verbal working memory in PET and fMRI were compiled from which they isolated group averaged stereotaxic coordinates in a variety of tasks. Utilizing the AGES approach, they computed a Gaussian distribution with a 15-mm spread (full-width half-maximum [FWHM] = 15 mm) for each source point reported. The size of the Gaussian spread was determined from both assessments of typical spatial smoothing parameters in the literature and based on random simulations of near neighbors [Chein et al., 2002]. To determine their intensity threshold, Chein et al. [2002] randomly simulated image maps to derive a false-probability ( $\alpha$ ) level of  $P < 0.05$ . These maps were computed by modeling the equivalent number of sources entered into their working memory meta-image across all stereotaxic space with a Gaussian spread of 15 mm. A similar but not identical method of deriving probability levels has been conducted by Turkeltaub et al. [2002] in a meta-analysis of word reading.

In our meta-analyses, we gathered data from a series of neuroimaging studies in PET and fMRI investigating word reading in Western languages ( $n = 25$ ), Japanese Kana ( $n = 5$ ), Japanese Kanji ( $n = 4$ ), and Chinese ( $n = 9$ ). Sources of activation were selected from studies of single word recognition from active tasks (e.g., overt naming, rhyming, lexical

decision, etc.) to more passive tasks (e.g., 1-back recognition, covert naming, passive viewing, etc.). Contrasts that best reflected a comparison between word processing and resting baseline were selected (e.g., fixation, checkerboards, noise, etc.); however, a number of contrasts were included in which word processing was compared to nonlinguistic visual-motor control tasks (e.g., case judgments, visual feature detection, false fonts, repeated speech, etc.). Table II provides a complete listing of studies and contrasts for each language/writing system. Following the AGES method [Chein et al., 2002], we compiled a list of peak voxels for each of the contrasts between word and rest and aggregated them into a single map. Separate image maps were created for the four written language conditions (English/Western European, Chinese, Japanese Kana, and Kanji). We assigned each of our identified sources equal intensity values and set our 3D Gaussian parameter to a width of 10 mm FWHM. This was a more conservative estimate than that used in Chein et al. [2002] to facilitate the identification of several distinct sources within small regions of cortex, such as the ventral occipitotemporal cortex and the frontal regions. The activation maps were overlaid onto a T1-weighted high-resolution 3D full-brain image. Threshold values then were computed for each meta-image by creating randomly simulated activation maps using an identical number of source points as each of the language condition images. In the case of English/Western writing systems, we created 1,000 simulated images each with 498 randomly selected sources in stereotaxic space (using a Talairach mask) to which we applied the same Gaussian smoothing parameter as our meta-image (10 mm FWHM). The values of each simulated voxel were aggregated to create a distribution of values for voxels in stereotaxic space. Average values for each voxel in the cortical mask were obtained by dividing the summed values by the number of simulated images (1,000). From this distribution, we selected critical threshold values at the top 5% and 1%. These values represented the probability of activating a particular voxel by chance at 0.05 and 0.01. This was similar to the procedure described by Turkeltaub et al. [2002] for the activation likelihood estimate (ALE) method. Thresholds were determined for each language meta-image by the same simulation method with the number of sources equal to the number of sources in the meta-image.

## RESULTS

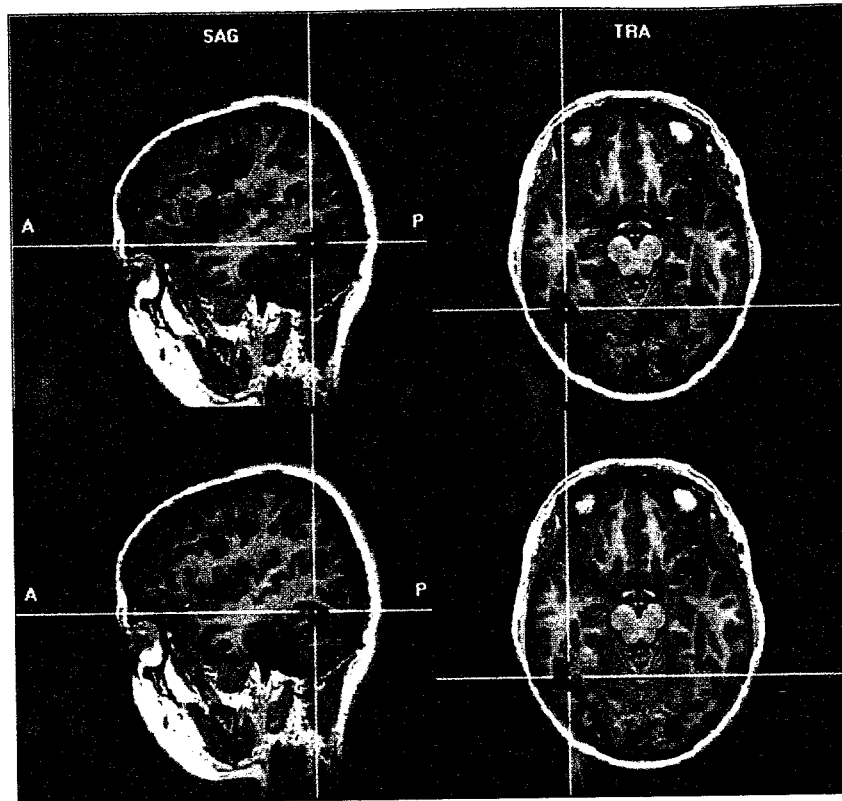
Our analysis replicated Chein et al. [2002] in demonstrating the value of this procedure for identifying highly convergent regions of activation across a wide set of studies. The AGES meta-analytic approach was found to be highly consistent with other meta-analytic techniques and empirical findings in the literature such as those reported in Table I. The regions commonly identified in studies of word reading in English were replicated in our meta-image of English/Western languages (Table III). Remarkably, we were able to find dissociable regions with foci or centroids (centers of mass activation) approximately 1 cm apart for word reading studies within the ventral temporal stream (notably

**TABLE III. Reported foci resulting from meta-analysis within language/writing systems and common across systems**

Language/script	Anatomical region	Lateral	BA	x	y	z
English/Western	Ventral visual					
	Inf. occipital gyrus g.	Left	17,18	-25	-85	-13
		Right	17,18	22	-86	-13
	Post. fusiform g.	Left	19	-37	-65	-11
	Fusiform g.	Left	37	-48	-56	-16
	Fusiform g.	Left	37,21	-36	-47	-16
	Posterior auditory					
	Sup. post. temporal g.	Left	22	-58	-49	8
	Sup. temporal g.	Left	13	-58	-43	16
	Sup. temporal g.	Left	41	-52	-30	10
	Frontal/Premotor					
	Inf. frontal g.	Left	9	-53	-5	25
	Precentral g.	Left	4	-48	-10	42
	Precentral g.	Left	6	-50	10	9
	Insula	Left	13	-36	17	6
Japanese Kana	Ventral visual					
	Inf. occipital/Post. fusiform g.	Left	18,19	-32	-77	-8
		Right	18,19	31	-78	-8
	Fusiform g.	Left	37	-46	-55	-8
	Posterior auditory					
	Sup. temporal/Inf. parietal 1.	Left	40	-35	-41	45
	Sup. temporal g.	Left	22	-49	-31	5
	Frontal/Premotor					
	Inf. frontal g.	Left	6/9	-49	-4	26
	Inf. frontal g.	Left	9	-37	26	7
Japanese Kanji	Ventral visual					
	Inf. occipital/post. fusiform g.	Left	18,19	-39	-79	-2
	Fusiform g.	Left	37	-45	-58	-9
	Posterior auditory					
	Sup. temporal g.	Left	22	-53	-23	4
	Frontal/premotor					
	Inf. frontal g.	Left	6/9	-45	2	30
	Inf. frontal g.	Left	9	-40	23	9
Chinese	Ventral visual					
	Inf. occipital	Left	18	-23	-92	-10
		Right	18	29	-89	-9
	Post. fusiform g.	Left	19	-37	-75	-14
		Right		33	-67	-14
	Fusiform g.	Left	37	-49	-53	-10
	Posterior auditory					
	Sup. temporal	Left	40	-63	-21	2
	Frontal/premotor					
	Inf. frontal g.	Left	9	-42	21	7
	Inf. frontal g.	Right	9	36	16	5
	Insula	Left	45	-45	32	7
	Inf. frontal g.	Left	9	-48	9	30
	Inf. frontal g.	Left	9	-48	9	30
	All	Ventral visual				
Inf. occipital/post. fusiform g.		Left	18,19	-37	-67	-8
Fusiform g.		Left	37	-45	-57	-12
Posterior auditory						
Sup. temporal g.		Left	22	-53	-27	5
Frontal/premotor						
Precentral g.		Left	6	-45	2	30
Precentral g.		Left	9	-42	19	10
Inf. frontal g.		Left	9	-42	19	10
Ant. cingulate g.		Medial		0	2	54

BA, Brodmann area; x, y, z, Talairach coordinates.

in the anterior-posterior y-dimension at -85, -65, and -56). This implies that by providing probabilistic values of convergence, the AGES technique is sensitive enough to distinguish several foci within a limited spatial range such as the posterior fusiform in the anterior occipital region and the mid-fusiform in the ventral temporal lobe. Once we



**Figure 1.**

AGES meta-image of word reading in English/Western European languages. The results are shown in the sagittal view ( $x = -43$ ), coronal view ( $y = -54$ ), and axial plane ( $z = -12$ ). The views correspond to the crosshairs that mark the coordinates predicted by Cohen et al. [2002] as the word-form area ( $x, y, z = -43, -54, -12$ ). The meta-image is derived from 35 studies in which indi-

identified convergent foci for word recognition across investigations within distinct written language systems, we then compared these sources across languages because meta-images were computed individually for each language/writing system. These maps were then overlaid with one another to determine common and language-specific foci.

#### **Meta-Image of English/ Western European Languages**

After aggregating the 498 unique sources from 38 experimental contrasts reported in 25 studies of Western alphabetic word processing (e.g., naming, passive viewing, matching, etc.) compared to a baseline task, the resulting meta-image revealed a stream of activation in the left ventral occipital-temporal pathway, and foci in left superior posterior temporal, inferior frontal, and insula/premotor cortex (Table III). Figure 1 shows the result of the meta-analysis that was conducted with a false probability rate of 0.05 (top row) and at 0.01 (bottom). The images reveal dissociable regions within the left ventral pathway with peaks at 85, 65, and 55 mm posterior to the anterior commissure. The most

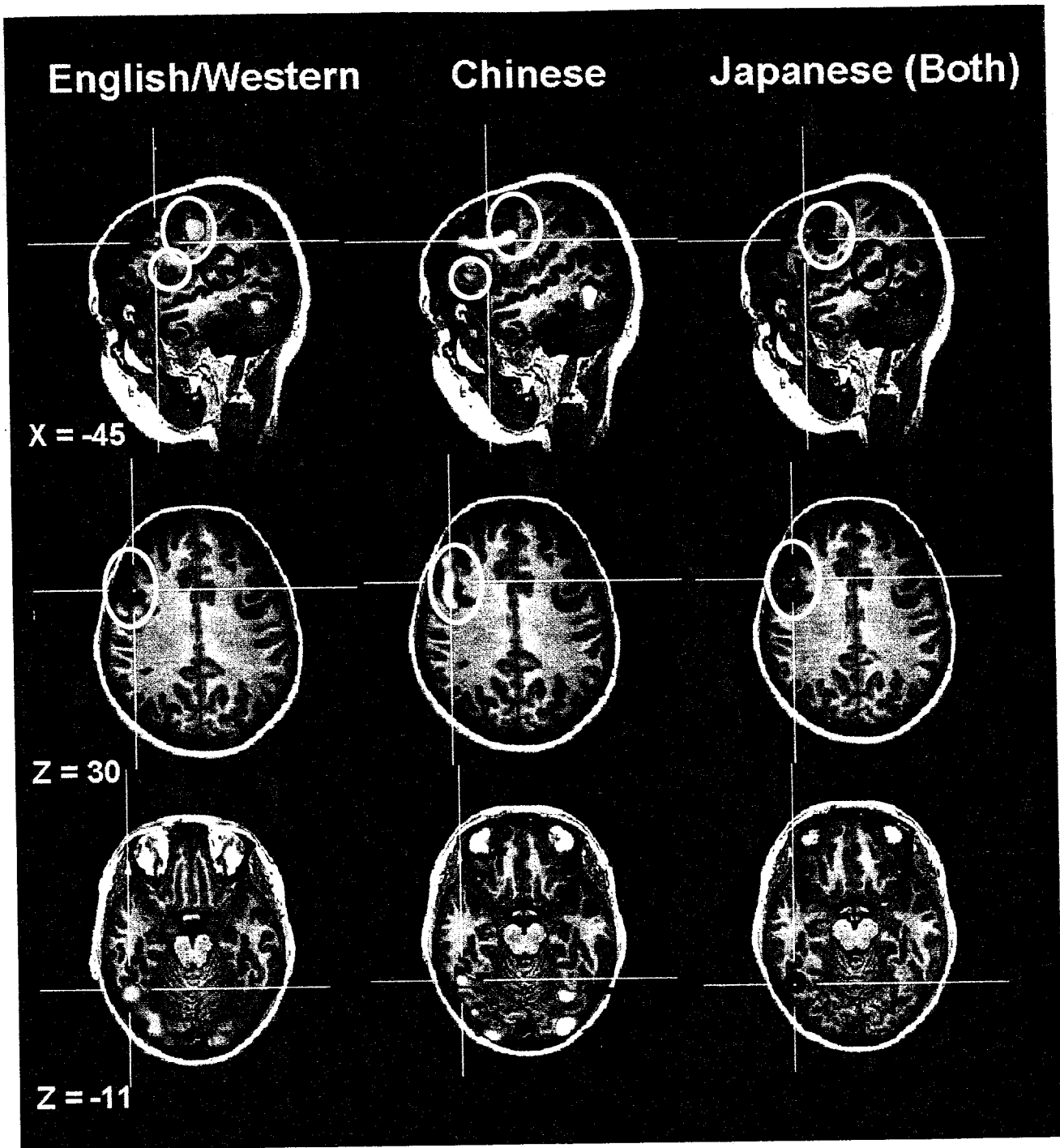
vidual word reading is compared to a stable resting baseline condition. The top row images are results of the meta-analysis with a threshold level equal to an  $\alpha$  level of 0.05; the bottom row images reflect an increase in the  $\alpha$  level to 0.01. Red lines indicate right hemisphere regions of inferior occipital and fusiform gyrus.

anterior focus is consistent with the location for VWFA predicted by Cohen et al. [2002] ( $x, y, z = -42, -57, -15$ ), which is represented in Figure 1 by the crosshairs. As Figure 1 shows, these predicted coordinates fell just slightly superior to the center of activation across the set of studies that we analyzed but were well within the range of probability.

#### **Meta-Image of Eastern Writing Systems**

Meta-images were generated for individual languages/writing systems based upon and identifying the primary foci in each analysis. These images were then overlaid with one another and common foci across languages were identified. Primary foci within each language as well as foci common to all languages are reported in Table III.

The meta-analysis of 5 Kana processing studies aggregated 73 sources from 8 contrasts, and the meta-analysis of 4 Kanji reading studies aggregated 49 sources from 6 experimental contrasts. The resulting meta-images (Fig. 2) reveal two common regions in the bilateral posterior and left mid-fusiform gyrus that are common to both Kana and Kanji reading (Table III). The more anterior region of the fusiform



**Figure 2.**

Meta-images of English/Western alphabetic (first column, green), Chinese character (middle column, yellow), and Japanese (third column) Kana (blue) and Kanji (red) systems. Row 1 displays the results in the sagittal view ( $x = -45$ ) revealing four critical regions: (1) the occipitotemporal boundary region (not circled); (2) superior posterior temporal and inferior parietal region (red circles); (3), ventral inferior frontal region (yellow circles); and (4) the dorsal inferior frontal area (blue circles) discussed in Tan et al. [this volume]. Row 2 displays this dorsal lateral frontal region in

the axial plane ( $z = 30$ ) suggesting an anterior–posterior dispersion of foci across languages. The crosshairs localize the region identified by Siok et al. [2004] and Tan et al. [this volume]. Row 3 displays results in the axial plane ( $z = -11$ ) of the occipitotemporal region with the crosshairs again indicating the putative VWFA [Cohen et al., 2000, 2002]. Red lines indicate right hemisphere regions of inferior occipital and fusiform/lingual gyrus in Chinese.



gyrus shown in Figure 2 (Row 3C) in the crosshairs ( $x, y, z = -46, -55, -11$ ) is consistent with the VWFA predicted by Cohen et al. [2000] ( $x, y, z = -43, -54, -12$ ) and with our finding in Western alphabetic systems ( $x, y, z = -45, -56, -16$ ). Although the meta-analysis did reveal that Kana-specific activations in the left superior posterior temporal gyrus were more extensive, consistent with the idea of a more dorsal processing route, there was focal activity in this region (Brodmann area [BA] 22) for Kanji (Fig. 2, Row 3A). In addition, there was no advantage of Kanji compared to Kana in processing in the left frontal regions. Studies of Kana and Kanji have shown reliable activation of the dorsal aspect of the inferior frontal gyrus (BA9/6) just posterior to the lateral frontal region reported by Tan et al. [2005] for Chinese phonological processing.

The analysis of 9 recent studies of Chinese character reading consisted of 317 sources from 18 contrasts. The resulting meta-image revealed a set of regions that were consistently activated across the set of studies (Table III). Compared to reading in Western European, Japanese Kana and Kanji, Chinese character reading seems to incorporate many of the same general regions. According to these data, Chinese character processing consistently engages bilateral aspects of the ventral occipitotemporal region, specifically inferior occipital and posterior fusiform gyri. Chinese character studies have shown convergence at the predicted VWFA ( $x, y, z = -49, -53, -10$ ). Chinese character reading also elicits a convergent region in the left superior posterior temporal gyrus (Table III). This region is not visible in Figure 2, but lies just lateral to the anterior extent of the common foci for Japanese Kana and Kanji region and does not include the posterior aspect shown in studies of Western alphabetic systems. In addition, broad foci in the left dorsal lateral frontal cortex were identified for Chinese character reading (Fig. 2, Row 1B, 2B) as observed in Tan et al. [2005]. Convergent foci for Chinese character processing were also found in the ventral aspect of inferior frontal gyrus, a region common to both Japanese and Western alphabetic systems.

## DISCUSSION

Claims of cross-linguistic similarities have not been without controversy. In contrast to the findings reported in several studies by Tan et al. [2000, 2001], Chee et al. [1999] found that Chinese-English bilinguals engage the same network of regions when reading English words and Chinese characters. The source of this difference is not completely clear but may be due to differences in the populations studied. The Singapore bilinguals studied by Chee et al. [1999] probably had stronger English skills, which may have promoted a more alphabetic way of reading that might have been observable in Chinese as well as in English. This Chinese-English difference in right occipitotemporal regions will be discussed below.

Our results suggest that across the range of languages and writing systems, a predictable network of regions associated with reading (as presented in Table I) is replicated well across language and writing systems. Until now, this clear

identification of a universal reading network has not been well quantified. Meta-analytic techniques such as AGES and ALE [Turkeltaub et al., 2002] enable us to quantify the degree of convergence across findings reported in the literature and thus reduce the variance that occurs across reported findings. For instance, studies of reading in English, Chinese, and Japanese have found regions of the left occipital-temporal region to be activated, and they refer to these activations as the VWFA. The consistency of localization of this region has not been straightforward. For example, early PET studies by Petersen et al. [1989, 1990] localized the VWFA to a more medial region on the left lingual gyrus. By employing a meta-analytic technique for findings across studies of native language users in which participants engage in the processing visual word forms and the neural response is measured against similar control states (i.e., resting baseline, fixation, etc.), we attempt to gain a clear and quantifiable measurement of a common cortical network for visual word processing. Because our analysis incorporates a variety of word-processing tasks, we acknowledge that our findings cannot provide direct evidence regarding particular functions such as phonological and lexical/semantic processing. We also note that the variation in the number of studies and experimental contrasts, particularly the lack of Japanese, limits our ability to make strong inferences with respect to absent foci. As the literature expands, these meta-analytic techniques will be well suited to capture the cross-linguistic effects for more specific functions and contrasts.

## Regions of Convergence

Despite the variability in mapping between orthography and phonology and between orthography and lexical/semantics, our results suggest that writing systems activate a strong network of common regions. Three general regions seem highly convergent across all writing systems that we analyzed<sup>2</sup>: (1) the left superior posterior temporal gyrus (the mid/anterior portion; BA22); (2) the left inferior frontal gyrus (the superior posterior region; BA6); and (3) the left occipitotemporal region (two foci: the posterior fusiform/inferior occipital region [BA19] and the mid-fusiform gyrus [BA37]).

## Regions of Divergence

Considering the degree of convergence found across languages, we identified several language-specific foci in which one or another writing system failed to localize to in our meta-analysis. Many of these regions fall within the same general vicinity of our convergent foci, but mark clear differences in localization or absence of a particular language/writing system. The following regions reflect where lan-

<sup>2</sup>We also found high convergence in the bilateral anterior cingulate region. We assume this region is involved in the executive functioning of the various tasks included in the meta-analysis and, thus, have not included this region in our results and discussion of the reading network.

guages and writing systems primarily differed among their patterns of activation: (1) superior temporal gyrus (posterior aspect); (2) left anterior dorsal frontal region; and (3) right occipitotemporal cortex (inferior occipital and posterior fusiform).

### Superior-Posterior Temporal/Inferior Parietal Cortex

Several studies have focused on the multifaceted role that the superior temporal gyrus region plays in spoken language [Price, 2000], reading [Booth et al., 2003; Temple, 2002; Temple et al., 2003], and verbal working memory [Chein et al., 2003; Paulesu et al., 1996; Ravizza et al., 2004]. Many of these studies suggest a distinction between the more posterior temporoparietal boundary region (including angular and supramarginal gyri) involved in phonological analysis and graphophoneme conversion [Booth et al., 2003; Temple et al., 2003], and a more anterior perisylvian region (Heschl's gyrus and planum temporale) that is involved in more complex aspects of speech comprehension.

Our meta-analysis found convergence across English and Japanese Kana in posterior regions of superior temporal gyrus (BA39/40; Table III), but an absence of Japanese Kanji and Chinese character processing. We did find convergence across all languages in more anterior and lateral regions of superior temporal gyrus (STG; BA22). In a study of auditory decision making, Binder et al. [2004] suggest a posteromedial to anterolateral processing stream in the left temporoparietal region for sound identification. Our findings thus suggest that phonographic writing systems (mapping speech sounds to graphemes) such as English and Kana engage both early and late components of this processing stream as a function of mapping to fine-grained aspects of the speech stream (phoneme and syllable). However, Kanji and Chinese map to whole-word units, a distinction with behavioral consequences for how phonology is activated [Perfetti et al., 2005]. Tan et al. [2005] found greater convergence of activation (via ALE value) in the dorsal extent of the inferior parietal lobe (BA40) for Chinese than for English/alphabetic studies, and similar to that found in our study, the converse was true in the ventral aspect of this region. It is thus not clear from our findings the exact role that the temporoparietal and posterior parietal region plays in reading and language [see for review Ravizza et al., 2004; Temple, 2002]. Based on the assumption of the universal phonological principle, we speculate that the convergence of all writing systems at the anterolateral region of superior temporal gyrus may implicate this region with the phonological identification of word forms, and that alphabetic and syllabographic writing systems may target earlier regions of this auditory processing stream [Binder et al., 2004; Zatorre et al., 1996] according to the level of analysis [see Poldrack et al., 2001].

### Inferior Frontal Gyrus/Dorsal Lateral Frontal Region

Our results show that a superior posterior region of the inferior frontal gyrus bordering on the precentral gyrus

(BA6/9) was a common foci across all writing systems selected for this analysis. In addition, a broad foci for Chinese character reading was identified clearly moving anterior from this location along the lateral surface of frontal cortex. This region as described by Tan et al. [2005] is associated with the processing of addressed phonology in the Chinese script. Gandour et al. [2002] found this region to be highly active in the processing of tonal information and vowel duration in Thai subjects for auditory pseudowords, which suggests at least a more general phonological process that can be applied to word-like stimuli. This same study [Gandour et al., 2002] found that Chinese subjects activated the posterior aspect of this region (consistent with the area convergent to all languages in our meta-analysis) for non-linguistic pitch and temporal judgments compared to that during passive listening. This result is consistent with the suggestion by Binder et al. [2004] that this left posterior inferior frontal (into precentral gyrus) region is involved in phonological decision making.

The conclusion of Tan et al. [2005], that this region is involved in a "look-up" process of addressed phonology may lead to the interpretation of this region as a phonological lexicon or lexical store. In fact, the meta-analysis of verbal working memory tasks carried out by Chein et al. [2002], from which our method is based, found that this more superior posterior aspect of inferior frontal gyrus was associated with difficulty level (e.g., load manipulations), whereas the anterior ventral aspect of inferior frontal gyrus was associated with contrasts of words and pseudowords. This finding was consistent with that of Poldrack et al. [1999] in which the superior posterior aspect of inferior frontal gyrus was involved in phonological processing, whereas the ventral anterior region was engaged in more semantic processing. It is this ventral region that Tan et al. [2005] assign to the phonological processing of Chinese and English along with the superior-posterior region (BA6). Our analyses replicate Tan et al.'s [2005] findings that this region is engaged consistently and reliably in Chinese character processing, more so than in Western alphabetic or Japanese writing systems. This region may support an identification process that is distinctive to reading Chinese characters and involves synchronous processing of semantic and phonological (tone plus segments) connections that mutually constrain the identification of the graphic form [Perfetti et al., 2005]. It is not enough in Chinese to "recode" the graphic form into phonology, because the large number of homophones makes identification indeterminate. A structure that could serve to coordinate the multiple components (graphic form, phonology including tone, and meaning) would have an important function.

### Occipitotemporal Region

Our meta-analysis reveals that although all writing systems engage regions in the left ventral occipitotemporal region, studies of Chinese seem to elicit the greatest convergence in the right inferior occipital and posterior fusiform regions. We hypothesized that the left occipitotemporal re-

gions are critical to visual word-form processing regardless of the nature of mapping across language and writing systems. However, for Chinese it is possible that it is the radical, the basic unit within a character, that constitutes the functional word form for this area, whereas the character's spatial arrangement of the radicals requires right-hemisphere regions as well [Liu and Perfetti, 2003].

Another perspective comes from the ERP study with source localization by Liu and Perfetti [2003], which found both patterns in Chinese bilinguals, depending on the time window involved: bilateral overall, with left and then right visual areas early in processing. They suggested that right occipital areas, which specialize in global and low spatial frequency information, support processing of the spatial layout of the character whereas the left occipital area, which functions for local and high spatial frequency information processing [Hellige, 1995], supports radical identification (within the character). A meta-analysis on temporally insensitive imaging data cannot clarify this possibility, although it can suggest that a bilateral left hemisphere-dominant pattern will emerge in Chinese as well as in alphabetic writing.

In a recent commentary, McCandliss et al. [2003] propose that the VWFA "constitutes a special case of perceptual expertise," and that "extensive visual experience with a class of stimuli drives enhancement of perceptual mechanisms and changes in the supporting functional architecture in the left fusiform gyrus" (p. 296). They argue that much of the ventral visual processing stream is well equipped for invariant recognition processes at the level of foveal acuity and thus the emergence of visual word expertise is subject to the same competition for neural tissue within this region as any other class of objects is (however, see Price and Devlin [2003]).

Our results find that all writing systems analyzed have a high degree of convergence on this left mid-fusiform VWFA region. The meta-images shown in Figure 2 (Row 3) provide a visual testament to the degree of consistency across these systems. Previous studies have shown the spatial variation of the VWFA ( $x, y, z = -43, -56, -16$ ) across individual subjects [Cohen et al., 2002] and across 25 studies of word recognition [Cohen et al., 2000] to be less than 5 mm in the  $x$ - and  $y$ -dimensions. We compared the foci in the left mid-fusiform gyrus across languages and calculated the degree of spatial variance for this region. The results, shown in Table IV, find that the VWFA can be localized at the target location ( $x, y, z = -42, -55, -12$ ) with less than a 2-mm deviation in the  $x$ - and  $y$ -dimensions and 4 mm in the  $z$ -dimension. Our results suggest that despite the variation in visual features and mapping function to phonological and semantic codes, individual writing systems are a class of visual stimuli that share an underlying neural circuitry at a higher-order visual level.

### Conclusions

The investigation by Paulesu et al. [2000] suggested that reading engages particular cortical processing routes, dorsal versus ventral, based upon the efficiency of the orthog-

**TABLE IV. Resulting foci reported in stereotaxic coordinates of the left mid-fusiform (VWF) region across languages and writing systems**

Stimuli	x	y	z
Western words	-46	-56	-15
Chinese characters	-49	-53	-10
Japanese Kana	-46	-55	-8
Japanese Kanji	-47	-58	-9
Average (SD)	-47.2 (1.3)	-55.2 (1.9)	-11.6 (3.6)

SD, standard deviation.

raphy for mapping print to sound. A similar claim is made for two Japanese systems, with Kana and Kanji relying on dorsal and ventral routes, respectively [Nakamura et al., 2002]. Our meta-analysis of Kana and Kanji studies demonstrated common regions for these two systems. However, variations in localization of superior temporal foci for Kanji and Chinese (anterolateral) compared to that for Kana and Western alphabetic reading (postero-medial) may suggest that recruitment of the temporal-parietal system reflects differential engagement of the auditory processing stream as part of the phonological component of reading.

Commonalities across all writing systems are visible particularly in the ventral occipitotemporal regions of the left hemisphere. Japanese Kana and Kanji, Chinese characters, and Western alphabetic languages elicit strong convergence of activity in the left anterior occipital and mid-fusiform regions. This mid-fusiform region identified in each language was consistent with the predicted VWFA [Cohen et al., 2000, 2002]. The magnitude of convergence for this region across such disparate writing systems suggests a gateway region that is highly generalized for orthographic form processing, with right-hemisphere regions providing additional support for specific graphic form properties.

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