

COGNITIVE NEUROSCIENCE

Functional MRI evidence for the importance of visual short-term memory in logographic reading

Maki S. Koyama,^{1,2} John F. Stein,¹ Catherine J. Stoodley^{1,3} and Peter C. Hansen^{1,4}¹Department of Physiology, Anatomy and Genetics, University of Oxford, Oxford, UK²Phyllis Green and Randolph Cowen Institute for Pediatric Neuroscience, New York University Child Study Center, New York, NY 10016, USA³Department of Neurology, Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA⁴School of Psychology, University of Birmingham, Birmingham, UK

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Abstract

Logographic symbols are visually complex, and thus children's abilities for visual short-term memory (VSTM) predict their reading competence in logographic systems. In the present study, we investigated the importance of VSTM in logographic reading in adults, both behaviorally and by means of fMRI. Outside the scanner, VSTM predicted logographic Kanji reading in native Japanese adults ($n = 45$), a finding consistent with previous observations in Japanese children. In the scanner, participants ($n = 15$) were asked to perform a visual one-back task. For this fMRI experiment, we took advantage of the unique linguistic characteristic of the Japanese writing system, whereby syllabic Kana and logographic Kanji can share the same sound and meaning, but differ only in the complexity of their visual features. Kanji elicited greater activation than Kana in the cerebellum and two regions associated with VSTM, the lateral occipital complex and the superior intraparietal sulcus, bilaterally. The same regions elicited the highest activation during the control condition (an unfamiliar, unpronounceable script to the participants), presumably due to the increased VSTM demands for processing the control script. In addition, individual differences in VSTM performance (outside the scanner) significantly predicted blood oxygen level-dependent signal changes in the identified VSTM regions, during the Kanji and control conditions, but not during the Kana condition. VSTM appears to play an important role in reading logographic words, even in skilled adults, as evidenced at the behavioral and neural level, most likely due to the increased VSTM/visual attention demands necessary for processing complex visual features inherent in logographic symbols.

Introduction

Converging evidence from behavioural studies suggests that the cognitive skills required for word reading differ according to the writing system (Huang & Hanley, 1995; Tan *et al.*, 2005b). Writing systems are broadly divided into logographic (e.g. Chinese, Japanese Kanji) and phonographic systems, the latter of which are subdivided into alphabetic (e.g. English) and syllabic (e.g. Japanese Kana) scripts. For logographic systems where visual features of the symbols are complex, children's ability to read words is strongly associated with their visual short-term memory (VSTM; Siok & Fletcher, 2001; Koyama *et al.*, 2008; Ding *et al.*, 2010). In contrast, VSTM plays a less important role in learning non-logographic words, such as in English (Gathercole *et al.*, 2006) and Japanese Kana (Koyama *et al.*, 2008). Given that proficient reading is primarily achieved by phonological recoding, the ability to translate a visual word form into its sound, in all writing systems (Perfetti *et al.*, 2005; de Jong

et al., 2009), it may be supposed that phonological skills, relative to visual skills, generally become more important for reading even in logographic scripts, with increasing age and reading experience. Yet, to our knowledge, no behavioural study has investigated to what extent VSTM capacity remains important for reading logographic words in skilled adult readers.

Direct comparison of functional magnetic resonance imaging (fMRI) activation patterns between logographic Kanji and syllabic Kana in Japanese highlights the importance of visual processing for logographic scripts: relative to Kana, Kanji elicits a higher level of activation in regions associated with visual processing, such as in the occipito-temporal cortex (Thuy *et al.*, 2004; Nakamura *et al.*, 2005, 2007; Ino *et al.*, 2009). Given that Kana and Kanji can represent an identical sound and meaning but differ visually (Fig. 1), greater activation for Kanji than Kana (the 'Kanji effect') is typically attributed to the greater visual complexity inherent in logographic symbols compared with syllabic symbols. However, it remains unclear the extent to which individuals' VSTM abilities are associated with the previously observed Kanji effect as demonstrated in fMRI.

The present study had two principal aims. First, using behavioral testing, we examined the extent to which adult readers' VSTM abilities

Correspondence: Dr M. S. Koyama, ²Phyllis Green and Randolph Cowen Institute for Pediatric Neuroscience, as above.
E-mail: makisophiakoyama@gmail.com

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FIG. 1. A Japanese word printed in both Kana and Kanji. The Japanese word pronounced /to-ke-i/ means 'clock' and can be represented in both syllabic Kana form (upper line) and logographic Kanji form (bottom line). The first and second Kanji symbols have the intrinsic meanings of 'time' and 'to measure', respectively. In general, Kanji symbols are visually more complex than Kana symbols. When the same word is printed in both script forms, the visual word length is typically shorter for Kanji than for Kana.

correlated with Kanji reading. To measure their VSTM abilities, we used the Visual Patterns Test (Della Sala *et al.*, 1999), which has been found to predict reading and writing of logographic words in children (Koyama *et al.*, 2008). Second, using fMRI, we investigated whether processing of logographic Kanji words placed greater demands on VSTM than syllabic Kana words during a visual one-back matching task. Having identified regions that elicited greater activation for Kanji than Kana (the Kanji effect), we then examined the extent to which individuals' behavioral VSTM scores (outside the scanner) correlated with fMRI blood oxygen level-dependent (BOLD) signal changes in these identified brain regions. Writing systems differentially influence reading and reading disorders at the behavioral (Tan *et al.*, 2005b; Goswami & Ziegler, 2006) and neural (Tan *et al.*, 2001, 2005a; Siok *et al.*, 2004, 2009) levels. Hence, it is important to examine activation patterns particular to logographic Kanji reading and their relationships with reading-related abilities (such as VSTM) specifically in adults, who as experienced and skilled readers would be expected to exhibit mature brain functioning.

Methods

Participants

Forty-five native speakers/readers of Japanese (17 males and 28 females, mean age 27.23 years, SD = 5.39 years) volunteered to participate in cognitive assessment, where their intellectual and literacy-related skills were measured. Participants were students at either the University of Oxford or Oxford Brookes University. None of them was an early bilingual, defined as an individual who was exposed to English during early childhood. No participants had any history of neurological or developmental disorders, including dyslexia, specific language impairment or attention deficit hyperactivity disorder, confirmed by both clinical interviews and questionnaires. Fifteen participants from this group (4 males and 11 females, mean age 29.27 years, SD = 6.40 years) participated in the fMRI experiment. All 15 participants were strongly right-handed as measured by the Annett Handedness Questionnaire (Annett, 1970). Informed consent was obtained from each participant in advance of behavioral testing and MRI scanning. The study was approved by the Central Oxford Research Ethics Committee.

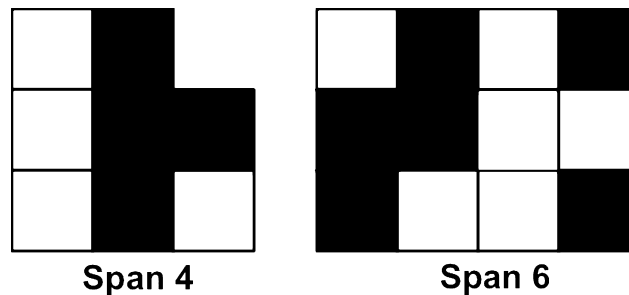


FIG. 2. Examples of the Visual Patterns Test (Della Sala *et al.*, 1999). Participants are asked to memorize the pattern of black squares during the 3-s presentation period, and then to reproduce it on the answer sheet. There are three different visual patterns for each visual span, which range from 2 to 15. In this figure, examples for span 4 and span 6 are illustrated.

Cognitive abilities outside the scanner

Prior to the fMRI experiment, we administered a range of cognitive measures, including non-verbal IQ, VSTM, Kana word reading and Kanji word reading. Non-verbal IQ was measured by Raven's Advanced Progressive Matrices (Raven *et al.*, 1998) with a time limit of 40 min. To measure the ability to read Kana, which has an extremely regular orthography, we used both real words and non-words (Koyama *et al.*, 2008). The ability to read two-character Kanji words was measured by the '100 Rakan', a reading ability test for Kanji words (Kondo & Amano, 1998). To estimate VSTM abilities, we used the Visual Patterns Test (Della Sala *et al.*, 1999; Fig. 2), which has been found to correlate strongly with children's Kanji reading and writing skills (Koyama *et al.*, 2008). In the Visual Patterns Test, the participants were presented with a matrix, in which half of the squares were black and half white, for 3 s. They were then asked to reproduce the pattern of black squares on the answer sheet, by ticking them off with a pen. There were three different visual patterns for each visual span, which ranged from 2 to 15 in length. We subsequently calculated the correlation between these scores and the activation of cortical regions associated with the Kanji effect. All data measured outside the scanner were analysed using SPSS 15.

fMRI procedures

The participants performed a visual one-back matching task that explicitly required VSTM. They were instructed to press a button with the index finger of their right hand when successively presented words were visually identical. We rationalized the use of a one-back task, rather than two-back, based on a previous fMRI study of Tagamets *et al.* (2000). This study used a similar task paradigm and successfully illustrated differential levels of activation for different word types within widespread common networks. Within each block of 24 words, there were three to five correct responses. Figure 3 illustrates the task paradigm and stimuli for the three script conditions: (i) syllabic Kana, (ii) logographic Kanji and (iii) the control script (Tibetan, composed of characters not present in Kana or Kanji). Our participants had no experience in learning to read Tibetan, and thus the letter-strings printed in the control script were not familiar and provided no linguistic information (i.e. word sound, word meaning). In contrast, during both the Kana and the Kanji conditions, adult native readers of Japanese were likely to activate phonological and/or semantic information related to the visually presented word, implicitly or explicitly, as a strategy to facilitate performance (Suchan *et al.*, 2006). Such linguistic information was absent for the control script, and thus

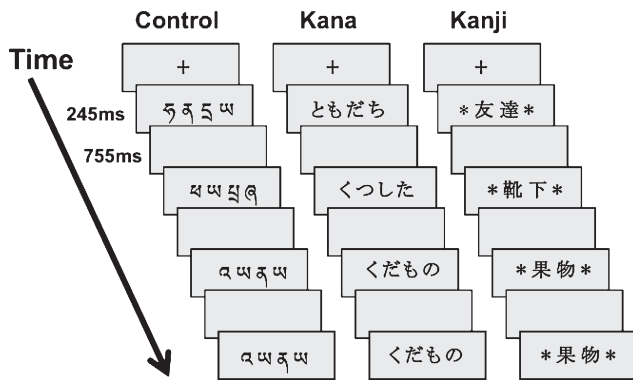


FIG. 3. Task design and stimuli. The paradigm used in the present study was a block design with alternating 24-s task blocks and 15-s rest blocks. In each task block, a fixation cross appeared at the center of the visual display, and then 24 words were presented at a rate of 1/s, with a 245-ms stimulus duration and 755-ms blank period between words. Participants were asked to press a button when stimuli presented in succession were visually identical. Prior to scanning, they performed a computerized practice run. From the top, the words mean 'friend', 'socks', 'fruits' and 'fruits' in both Kana and Kanji conditions.

activation patterns for this script condition served as a relatively pure measure of VSTM reliance.

The paradigm used in the present study was a block design with alternating 24-s task blocks and 15-s rest blocks. In each task block, a small fixation cross appeared at the center of the visual display, and then 24 words were presented at a rate of 1/s, with a 245-ms stimulus duration and 755-ms blank period between words. The words were in either Kana, Kanji or the control script. Each script condition was repeated four times with the order of the blocks randomized across the paradigm. During rest blocks, only the fixation cross appeared on the screen. The participants were encouraged to respond during the blank period as quickly and accurately as possible. Prior to scanning, they performed a computerized practice run to ensure task familiarity. The word stimuli used in the practice run were different from those used in the task inside the scanner to prevent word-specific practice effects.

fMRI task stimuli

All Japanese words were nouns with high familiarity ratings (mean \pm SD = 6.42 \pm 0.36; Amano & Kondo, 1999) and were four morae (syllables) long phonologically. Tibetan script, after removal of any characters that might resemble existing Kana or Kanji characters, was utilized as the control script. Tibetan symbols presented were entirely unfamiliar to our participants and their visual features were not similar to either Kana or Kanji.

Kana words and Kanji words were matched for sound, meaning, visual familiarity level and visual length. Given that visual familiarity influences activation patterns in reading networks (Ischebeck *et al.*, 2004), it was crucial to select Kana words and Kanji words whose visual familiarity levels were matched as closely as possible. Thus, we asked another group of Japanese native readers ($N = 20$, mean age 29.7 years) to rank the visual familiarity of 100 words printed in both Kana and Kanji forms, and selected the words that were ranked between 6 and 7 out of 10 for both script forms. As to visual length, the procedure was challenging because visual length is typically longer for Kana than Kanji when representing the same word (e.g. the word 'friend' is represented as ともだち in Kana and as 友達 in Kanji). Because of this, to equate the retinal image size of the stimuli between the two script forms, we placed an asterisk '*' at the beginning and the end of each Kanji word. An asterisk '*' was chosen

because it had the least disruptive effect on visual word recognition among five potential symbols (*, #, %, +, Δ) in non-readers of Japanese ($n = 15$, mean age 24.7 years). The accuracy and reaction times were statistically comparable for the Kanji words with and without asterisks, thus indicating that the insertion of asterisks on the outside of the Kanji words had no measurable effect on performance. In addition, we asked the same non-readers of Japanese to rank the visual complexity (1 = least complex, 3 = most complex) of Kana words, Kanji words and the letter-strings printed in the control Tibetan script. As expected, Kanji reliably ranked the highest among the three script conditions.

MRI data acquisition

Functional and structural images were acquired with a Varian Siemens 3T scanner at the Centre for the Functional Magnetic Resonance Imaging of the Brain in Oxford (FMRIB). A Magnex head-dedicated gradient coil was used in conjunction with a birdcage head radio frequency coil tuned to 127.4 MHz. For functional imaging, a T2*-weighted gradient echo sequence (EPI) was used [TR = 3000 ms, TE = 30 ms, flip angle = 90°, field of view (FOV) = 192 mm², voxel size = 3 \times 3 \times 3 mm, number of volumes = 368]. The initial four volumes were eliminated from further processing. For anatomical imaging, a high-resolution T1-weighted structural scan was acquired (3D Turbo FLASH sequence, TR = 13 ms, TE = 5 ms, TI = 200 ms, flip angle = 8°, FOV = 265 mm², in-plane resolution = 1 mm²). An automated shimming algorithm was used to reduce magnetic field inhomogeneities (Wilson *et al.*, 2002; Note – in the present study, there was incomplete coverage for the inferior areas of the cerebellum because our scan coverage was optimized for the cerebral cortex).

MRI data analysis

All data were first pre-processed using tools from the FMRIB Software Library (FSL, <http://www.fmrib.ox.ac.uk/fsl>), applying the following procedures: a high-pass filter cut-off of 40 s, motion correction using MCFLIRT, regular-up slice timing correction and spatial smoothing using a Gaussian spatial filter of 5-mm full-width half-maximum. The registration of low-resolution functional images for each participant into standard brain space was carried out using FMRIB NonLinear Image Registration Tool (FNIRT). Following pre-processing, statistical analyses of individual participants' data were computed using a general linear model (GLM) with local autocorrelation correction or prewhitening (FILM; Woolrich *et al.*, 2001). To identify brain activation patterns associated with the Kanji effect, the Kanji > Kana contrast was set up to create mean difference images. In addition, we also examined the reverse Kana > Kanji contrast to see if there was a Kana effect, although this was not the primary aim of the current study. Group analysis was performed with a random effects analysis using FMRIB's Local Analysis of Mixed Effects (FLAME). The group Z statistic images were created by cluster-thresholding with corrections for multiple comparisons at the cluster level using Gaussian random field theory ($Z > 2.3$; cluster significance: $P < 0.05$, corrected).

To better understand activation patterns in regions associated with the Kanji effect and their relationships with individuals' VSTM abilities, we estimated the BOLD signal changes in regions of interest (ROIs) for each of the script conditions. Each ROI was created based on functional clusters associated with the observed Kanji effect and by reference to the anatomical structure's probability map (Harvard-Oxford Cortical Structure Atlas; Kennedy *et al.*, 1998). ROI masks were applied to the functional images of each individual. A percentage

TABLE 1. Descriptive statistics of the mean performance (\pm SD) of the cognitive tasks for all participants and for those who additionally underwent the fMRI experiment

	All participants ($n = 45$)	fMRI ($n = 15$)
Kana word reading (%)	100.00 \pm 0.00	100.00 \pm 0.00
Kana non-word reading (%)	100.00 \pm 0.00	100.00 \pm 0.00
Kanji word reading (%)	66.96 \pm 12.71	65.40 \pm 15.01
Raven's matrices (max. = 36)	26.91 \pm 6.72	27.27 \pm 5.06
Visual Patterns Test (max. = 42)	22.07 \pm 3.85	21.20 \pm 3.91

BOLD signal change was then extracted for every voxel in the ROI per individual and collapsed into a single measure by calculating the 90th percentile value across the ROI. We selected the 90th percentile value of BOLD signal changes, rather than the mean or maximum value, because it is considered as the measure of typical 'active' ROI (Buck *et al.*, 2008): mean values have been considered to correlate less with the amplitude of evoked potentials than maximum values (Arthurs & Boniface, 2003), whereas maximum values tend to have large variability. All subjects' 90th percentile BOLD signal change values were then used for further correlation analyses.

Results

Cognitive abilities outside the scanner

Table 1 describes the group mean and standard deviation of each cognitive measure based on all participants ($n = 45$) and those who additionally underwent the fMRI experiment ($n = 15$). All participants' scores on Raven's matrices (Raven *et al.*, 1998) and Kanji word reading (Kondo & Amano, 1998) fell within ± 1 SD of published norms, ensuring that none of the participants had intellectual disability or reading impairment. Confirming the exclusion of impaired readers was important in the present study, particularly because it has been well demonstrated that brain activation patterns in response to word stimuli differ between impaired readers and unimpaired readers in all writing systems (Shaywitz *et al.*, 1998; Paulesu *et al.*, 2001; Siok *et al.*, 2004, 2008; Hoefl *et al.*, 2007). Of note, our participants (i.e. adult readers) made no errors in Kana word reading, largely due to the extremely regular symbol-sound correspondence for Kana orthography. Thus, we were unable to perform any statistical analysis regarding Kana results. However, this ceiling effect in adults was entirely expected given that even young children (e.g. 2nd graders) show a ceiling effect for Kana reading (Koyama *et al.*, 2008).

We performed correlation analyses based on scores of the 45 participants. Individuals' Kanji word reading scores measured by the 100 Rakan (outside the scanner) correlated strongly with their VSTM abilities measured by the Visual Patterns Test ($r = 0.66$, $P < 0.01$; Fig. 4). We further performed a multiple regression analysis; even after the effect of non-verbal IQ (Raven) was removed, VSTM remained a significant predictor of Kanji word reading in adult readers (R^2 change = 0.021, $F = 12.98$, $P < 0.05$).

Behavioural performance in the scanner

Figure 5A shows the results of the mean performance accuracy for each script condition. Mean accuracy was 96, 93 and 86% for the Kana, Kanji and control conditions, respectively. There was no significant difference in accuracy between Kana and Kanji words ($t = 1.19$, $P = 0.25$). However, the mean accuracy for the Tibetan control script, with which none of the participants was familiar (hence it was

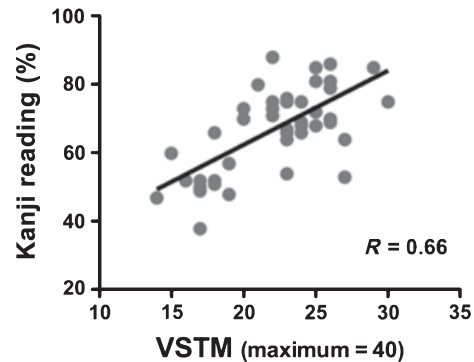


FIG. 4. A scatter plot depicting the relationship between visual short-term memory (VSTM) scores and Kanji reading accuracy outside the scanner ($N = 45$). VSTM ability was measured by the Visual Patterns Test, and the Kanji reading ability was tested by the 100 Rakan. The significant positive correlation ($r = 0.66$, $P < 0.01$) indicates the importance of VSTM in logographic Kanji reading in adult readers.

processed purely visually), was the lowest among all the script conditions (relative to Kana, $t = 3.66$, $P < 0.01$; relative to Kanji, $t = 2.36$, $P < 0.05$). Similarly, mean reaction times did not significantly differ between Kana (0.51 s) and Kanji (0.52 s), but were significantly longer for the control script (0.68 s) than the other script conditions (relative to Kana, $t = 2.53$, $P < 0.05$; relative to Kanji, $t = 2.19$, $P < 0.05$).

Subsequently, we investigated the relationships between the VSTM scores (i.e. performance outside the scanner) and accuracy for each script (i.e. performance inside the scanner; Fig. 5B). Individuals' VSTM abilities correlated strongly with their accuracy for the control script ($r = 0.78$, $P < 0.01$), but no significant correlations were found with either Kana words ($r = 0.07$, $P = 0.81$) or Kanji words ($r = 0.18$, $P < 0.53$). The strong positive correlation observed between individuals' VSTM scores and accuracy in the control script condition confirms the strong dependence upon purely VSTM for processing unpronounceable and meaningless control words. This is contrasted with pronounceable and meaningful Kana and Kanji words, which can also be retained in phonological or semantic memory. It therefore seems likely that cortical activation patterns in response only to the control script are most likely to reflect the specificity of the VSTM demands in this condition.

Whole brain analyses

General linear model analysis showed that Kana words and Kanji words activated regions in the known reading networks for alphabetic systems (Fiez & Petersen, 1998; Pugh *et al.*, 2000), and that patterns of activations were topographically overlapping in these two scripts (Fig. 6A and B). Although the control condition appears to recruit similar regions (Fig. 6C), this condition failed to show significant activation in the left temporo-parietal junction (black ovals in Fig. 6), a region associated with phonological decoding (Simos *et al.*, 2000; Graves *et al.*, 2008). Clearly, both Kana words and Kanji words, decodable words to the participants, significantly activated this region. These results confirm our assumption that the control script would be processed only visually, while phonological information would be activated when reading Kanji words and Kana words. Peak MNI coordinates of significant activation clusters for each script condition are shown in Table 2.

More importantly, we identified regions that elicited greater activation for Kanji than Kana in the bilateral superior intraparietal

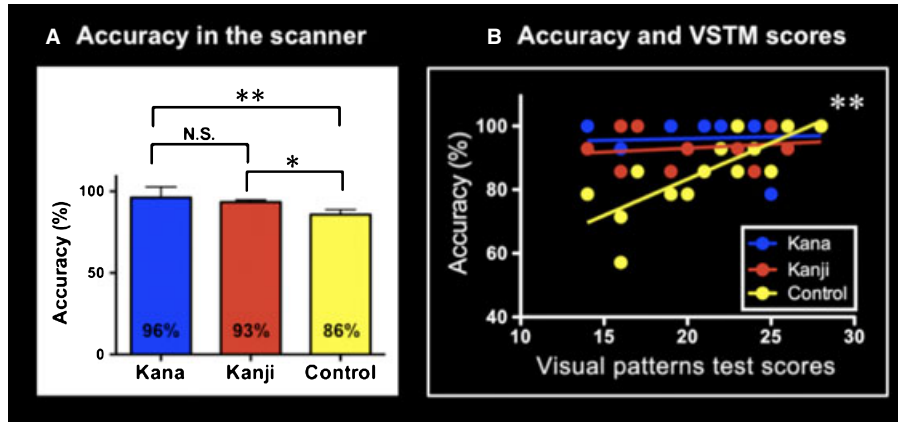


FIG. 5. (A) Mean accuracy in the scanner and (B) its relationship with visual short-term memory (VSTM) scores outside the scanner ($n = 15$). The Kana, Kanji and control script conditions are represented in blue, red and yellow, respectively. (A) Each bar represents \pm SEM, $*P < 0.05$. The mean accuracy in the scanner did not differ between Kana words (96%) and Kanji words (93%), but it was significantly lower for the control script (86%) than Kana and Kanji. (B) Individuals' VSTM abilities, measured by the Visual Patterns Test (Della Sala *et al.*, 1999) outside the scanner, strongly correlated with their accuracy for the control script, but not for either Kana or Kanji; $**P < 0.01$.

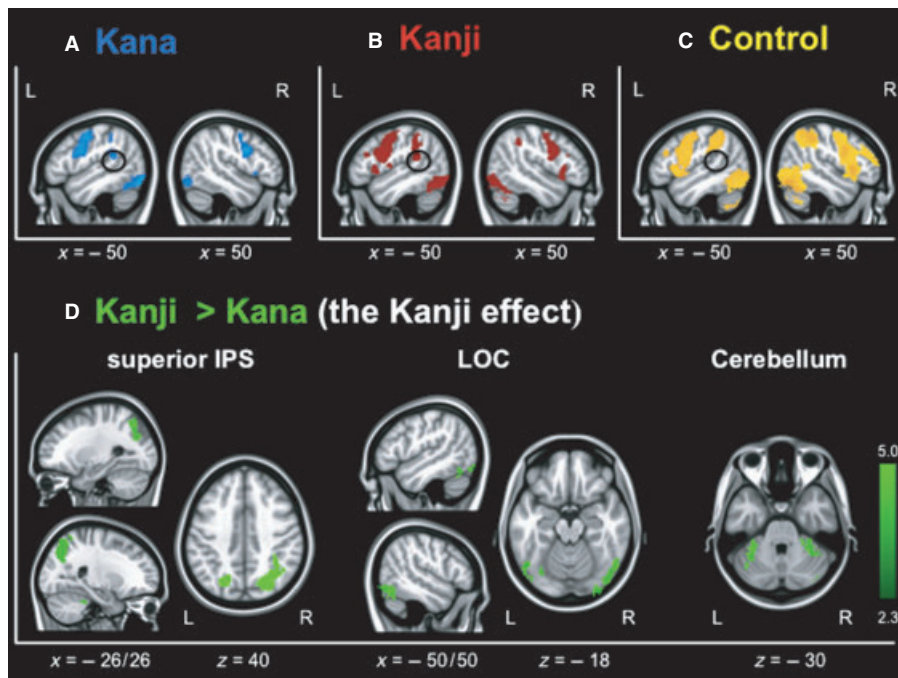


FIG. 6. Brain regions associated with Kana (A), Kanji (B), Control (C) and the Kanji effect (D) ($n = 15$). All the script conditions activated largely overlapping cortical regions, but Kanji words elicited greater activation than Kana words in the lateral occipital complex (LOC), the superior intraparietal sulcus (superior IPS) and the cerebellum in both hemispheres (D). No brain region showed significantly greater activation for Kana than Kanji in the present study. Unlike the Kana and Kanji conditions, the control condition failed to significantly activate the left temporo-parietal junction (black ovals in A, B and C): $z > 2.3$, $P < 0.05$, corrected.

sulcus (superior IPS; peak MNI coordinates, $x = -26/36$, $y = -68/-58$, $z = 48/44$, Z score = 3.98/4.53), the inferior part of the bilateral lateral occipital complex (LOC; peak MNI coordinates, $x = -46/52$, $y = -62/-64$, $z = -18/-18$, Z score = 3.32/4.83), and the superior part of the bilateral cerebellum (lobule VI; peak MNI coordinates, $x = -32/34$, $y = -36/-46$, $z = -30/-30$, Z score = 3.43/3.99). Of note, the activation of the left LOC extended into a part of the left fusiform gyrus, a region known as the 'Visual Word Form Area' identified for alphabetic words (Dehaene *et al.*, 2002). However, this activation failed to extend into the medial part of the left fusiform gyrus, which

exhibited greater activation for Kanji than Kana in previous studies (Thuy *et al.*, 2004; Nakamura *et al.*, 2005). The group statistic maps associated with the Kanji effect are shown in Fig. 6D. With the same thresholding ($Z > 2.3$, cluster significance: $P < 0.05$, corrected) as used for the Kanji effect, no clusters survived thresholding for the reverse 'Kana > Kanji' contrast (the Kana effect). However, removing the requirement for cluster thresholding and using only voxel thresholding ($Z > 2.3$) showed that a small Kana effect was observed in the bilateral occipital pole ($x = -14/8$, $y = -104/-90$, $z = -6/6$, Z score = 3.42/3.02), consistent with previous observations (e.g. Nakamura *et al.*, 2005).

TABLE 2. Peak MNI coordinates of significant activation clusters for each script condition

Brain regions	Kana				Kanji				Control			
	x	y	z	Z score	x	y	z	Z score	x	y	z	Z score
IFG/PCG (L)	-42	4	26	5.43	-44	6	24	4.66	-48	4	16	4.35
IFG/PCG (R)	48	4	30	3.93	48	4	26	3.91	46	4	26	4.59
Insula/FPC (L)	-34	22	8	4.75	-34	16	12	5.30	-36	26	-2	5.36
Insula/FPC (R)	28	24	-4	5.81	38	24	0	5.28	40	16	-2	6.00
SMA/ParaCG	0	10	52	4.16	0	-2	58	4.37	-4	14	46	4.94
IPS (L)	-22	-66	50	3.37	-34	-60	38	5.10	-22	-68	48	5.10
IPS (R)	32	-56	44	3.44	38	-64	38	5.38	28	-66	46	6.55
TPJ (L)	-50	-40	22	4.20	-50	-44	20	3.52				
SMG	-40	-52	40	3.13	-40	-48	32	3.46	40	-50	44	6.12
FFG (L)	-42	-60	-22	3.63	-44	-64	-18	4.10	-48	-64	-18	4.55
FFG (R)	44	-64	-20	4.01	44	-66	-22	5.56	48	-68	-18	5.11
LOC (L)	-44	-84	-10	5.73	-40	-84	-12	5.79	-42	-82	-8	6.69
LOC (R)	44	-74	-16	4.68	40	-86	-18	4.90	38	-92	-14	4.88
Cerebellum (L)					-8	-82	-40	4.97	-30	-62	-42	5.43
Cerebellum (R)					10	-76	-40	4.48	32	-36	-30	7.65

$Z > 3.1$, $P < 0.05$, corrected. L, left; R, right; IFG, inferior frontal gyrus; PCG, precentral gyrus; FPC, frontal operculum cortex; SMA, supplementary motor area; ParaCG, paracingulate gyrus; IPS, intraparietal sulcus; TPJ, temporo-parietal junction; SMG, supramarginal gyrus; FFG, fusiform gyrus; LOC, lateral occipital complex.

Region of interest analyses

To investigate the Kanji effect further, we conducted ROI analyses on four regions associated with the Kanji effect: (i) the left LOC, (ii) the right LOC, (iii) the left superior IPS and (iv) the right superior IPS. Figures 7 and 8 illustrate the comparisons of the BOLD signal changes in the LOC and superior IPS, respectively. Although the bilateral cerebellum exhibited the Kanji effect, we could not perform ROI analysis on these regions because our scan coverage was optimized for the cerebral cortices. The ROI results confirmed the GLM results that Kanji words elicited greater activation in the left LOC ($t = 4.635$, $P < 0.01$), the right LOC ($t = 3.415$, $P < 0.01$), the left superior IPS ($t = 2.597$, $P < 0.05$) and the right superior IPS ($t = 2.984$, $P < 0.05$) relative to Kana words.

Notably, the control (Tibetan) words elicited the highest BOLD signal change in all the ROIs amongst the three script conditions: the left LOC (relative to Kana, $t = 9.498$, $P < 0.001$; relative to Kanji, $t = 4.863$, $P < 0.01$), the right LOC (relative to Kana, $t = 9.029$, $P < 0.001$; relative to Kanji, $t = 5.615$, $P < 0.001$), the left superior IPS (relative to Kana, $t = 9.003$, $P < 0.001$; relative to Kanji, $t = 6.407$, $P < 0.001$) and the right superior IPS (relative to Kana, $t = 8.349$, $P < 0.001$; relative to Kanji, $t = 5.365$, $P < 0.001$). Overall, these ROI analyses demonstrate that the regions associated with the Kanji effect elicited the highest activation during the control condition, which was the least familiar to the participants and processed only visually.

Correlation analyses

We examined the relationships between the BOLD signal changes in the ROIs showing the Kanji effect and the participants' behavioural VSTM scores (Figs 7 and 8, and Table 3). The VSTM scores, measured by the Visual Patterns Test, significantly positively correlated with BOLD signal changes during both Kanji and control conditions, in the right LOC ($r = 0.52$, $P < 0.05$ for Kanji; $r = 0.58$, $P < 0.05$ for Control) and the right superior IPS ($r = 0.58$, $P < 0.05$ for Kanji; $r = 0.58$, $P < 0.05$ for Control). That is, the higher the VSTM abilities, the higher the BOLD signal changes. However, no significant correlation was found between the VSTM scores and BOLD signal changes in the left LOC or the left superior IPS in any script condition. Notably, the VSTM scores showed no correlation

with the BOLD signal changes in any ROIs during the Kana condition. These results highlight a close coupling between VSTM and activations in the right hemisphere regions associated with the Kanji effect.

Discussion

The behavioral results measured outside the scanner, as shown by the significant correlation between VSTM and Kanji reading skill, strongly suggest an important role of VSTM in logographic Kanji reading in adults. This is consistent with our previous findings in children (Koyama *et al.*, 2008), suggesting that VSTM remains important in processing logographic words across life span. The fMRI results also demonstrate the importance of VSTM for logographic Kanji, by showing the Kanji effect (greater activation for logographic Kanji than syllabic Kana) in two regions that are often reported to be activated by VSTM tasks, the LOC and the superior IPS (Todd & Marois, 2004; Xu & Chun, 2006; Xu, 2007). BOLD signal changes in these two regions, in the right hemisphere, additionally exhibited significant positive correlations with individuals' VSTM scores when words were presented in the Kanji form, but not in the Kana form. Together, these findings suggest that the observed Kanji effect in VSTM regions, specifically in the right hemisphere, is associated with increased VSTM demands for Kanji than Kana (although note that our correlation analyses do not permit assessment of directionality). Given that the differences between Kana and Kanji were minimized to the difference in the level of visual complexity in our fMRI experiment, it seems likely that the observed Kanji effect arises primarily from the greater visual complexity inherent in logographic symbols.

Further ROI analyses, however, revealed that all four ROIs (left/right LOC and superior IPS), which were associated with the Kanji effect, elicited the strongest activation during the control condition. In this condition, visually presented letter-strings were unfamiliar to the participants and provided no linguistic information, and thus were processed purely visually. That is, no phonological (or semantic) information was available to facilitate task performance. This was clearly reflected in the lower accuracy scores and the longer reaction times for the control stimuli relative to Kana and Kanji words, stimuli that were phonologically decodable and semantically mean-

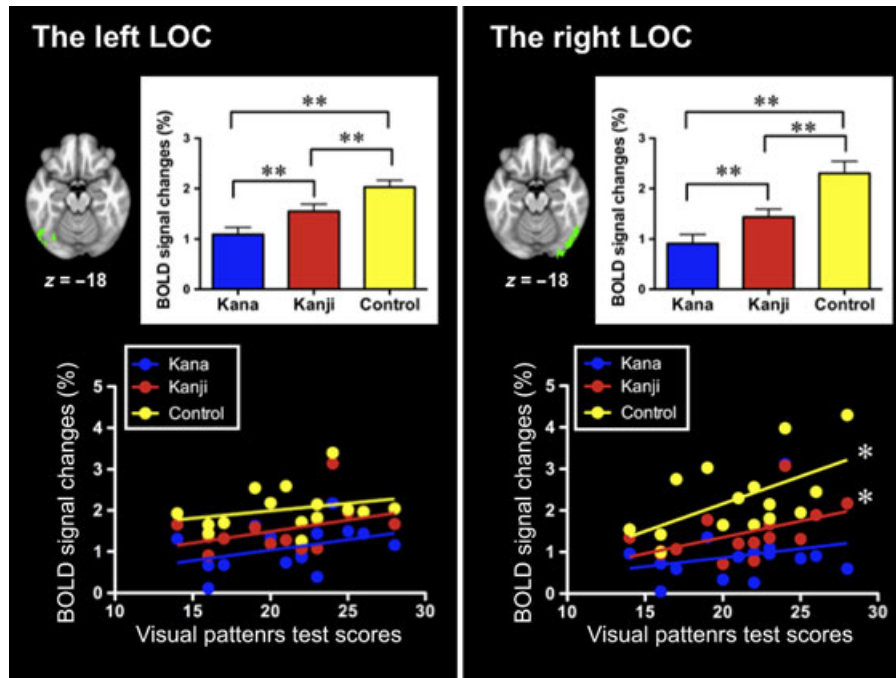


FIG. 7. BOLD signal changes in the lateral occipital complex (LOC; $n = 15$). Bar graphs describe the group mean BOLD signal changes in the left and right LOC for each script. These regions of interest are displayed in MNI standard space (green). Each bar represents mean \pm SEM; $**P < 0.01$, $*P < 0.05$. Scatter plots of the relationships between individuals' BOLD signal changes for each script condition and their visual short-term memory (VSTM) abilities. The group mean BOLD signal change was the highest for the control script, followed by Kanji words. Individuals' VSTM scores showed significant positive correlations with their BOLD signal changes in the right superior IPS when viewing the control script and Kanji words, but not during Kana words. No correlation was found between VSTM scores and BOLD signal changes in the left LOC during any script condition.

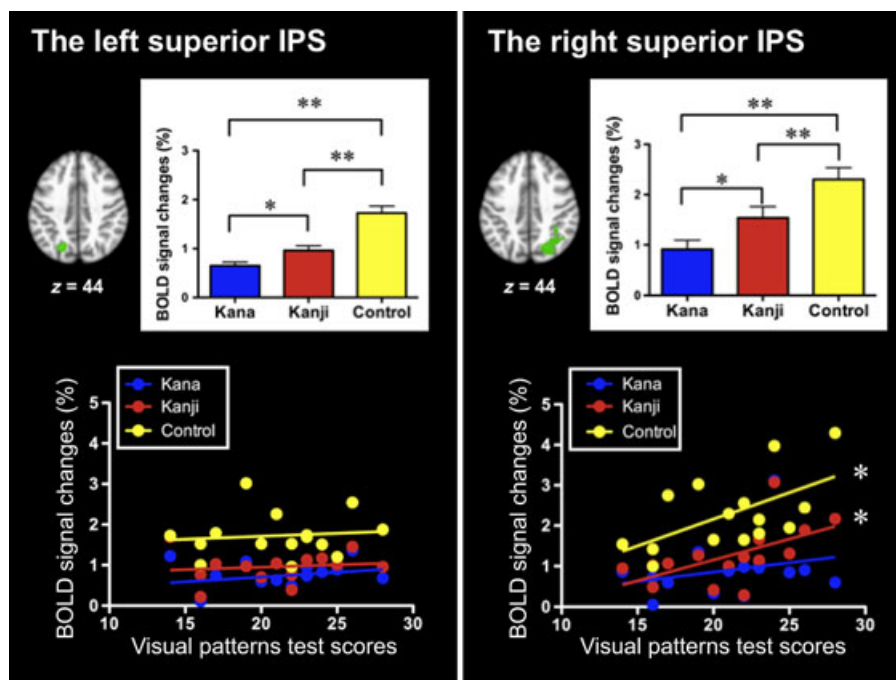


FIG. 8. BOLD signal changes in the superior intraparietal sulcus (superior IPS). Bar graphs describe the group mean BOLD signal changes in the left and right superior IPS for each script. These regions of interest are displayed in MNI standard space (green). Each bar represents mean \pm SEM; $**P < 0.01$, $*P < 0.05$. Scatter plots present relationships between individuals' BOLD signal changes for each script condition and their visual short-term memory (VSTM) abilities. The group mean BOLD signal change was highest for the control script, followed by Kanji words. Individuals' VSTM scores significantly correlated with their BOLD signal changes in the right superior IPS during the control script and Kanji words, but not during Kana words. No correlation was found between their VSTM scores and BOLD signal changes in the left superior IPS during any script condition; $*P < 0.05$.

TABLE 3. Correlations between individuals' scores of the Visual Patterns Test and their BOLD signal changes in the left/right LOC and left/right IPS ($n = 15$)

	Kana		Kanji		Control	
	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>
Left LOC	0.39	N.S.	0.41	N.S.	0.28	N.S.
Right LOC	0.25	N.S.	0.52	0.04*	0.58	0.02*
Left IPS	0.26	N.S.	0.13	N.S.	0.11	N.S.
Right IPS	0.26	N.S.	0.58	0.02*	0.58	0.02*

N.S., not significant. IPS, intraparietal sulcus; LOC, lateral occipital complex. * $P < 0.05$. The group averages of BOLD signal changes (%) for ROIs are follows: Left LOC = 1.09 for Kana, 1.55 for Kanji, and 2.03 for Control; Right LOC = 0.91 for Kana, 1.44 for Kanji, and 2.30 for Control; Left IPS = 0.65 for Kana, 0.96 for Kanji, and 1.73 for Control; Right IPS = 0.90 for Kana, 1.27 for Kanji, and 2.30 for Control.

ingful. Indeed, significant activation of the left temporo-parietal junction, a region associated with phonological decoding (Smith & Jonides, 1997; Simos *et al.*, 2000; Graves *et al.*, 2008), was observed only for Kana and Kanji words, but not for the control condition (the black oval in Fig. 6C, Table 2). Of note, this phonological region showed no differences in activation between Kana and Kanji, presumably due to the nature of the task, as it was heavily dependent on visual word recognition. Given the greater BOLD activation across regions for the control condition, which we attribute to the increased VSTM processing required for the encoding of unfamiliar orthography, we infer that the observed Kanji effect in the LOC and superior IPS similarly reflects greater VSTM demands for processing Kanji than for Kana.

It is likely that the Kanji effect in the LOC and superior IPS is more likely to be mediated by bottom-up rather than top-down attention (Jiang *et al.*, 2000). In the present study, the visual familiarity of Kanji words was matched with the Kana words, and thus the greater level of visual complexity inherent in logographic symbols may be responsible for increased bottom-up attention for Kanji. In contrast, the observed highest activation of the same regions for the control script may be predominantly associated with increased top-down attention due to the demands of processing unfamiliar and undecodable stimuli. Such top-down modulation on parietal and temporo-occipital activations has been previously reported by Tagamets *et al.* (2000), where the activation was greater for an unfamiliar/undecodable script condition (i.e. letter-strings in a false font) was reported than for familiar/decodable script conditions (i.e. real words and pseudowords). It seems possible that there is an interaction between these two types of attentional effect; however, this is beyond the scope of the present study.

Although a wide range of brain regions, including the superior IPS and the LOC, are strongly activated during VSTM tasks (Baker *et al.*, 1996; Courtney *et al.*, 1997; D'Esposito *et al.*, 2000; Haxby *et al.*, 2000), the special role of the superior IPS in VSTM storage has recently attracted great interest (Todd & Marois, 2004; Xu & Chun, 2006; Chee & Chuah, 2007; Xu, 2007; Majerus *et al.*, 2010). The reported MNI coordinates in these previous studies encompass or are adjacent to the location of the superior IPS (peak MNI coordinates, $x = -26/28$, $y = -68/-58$, $z = 48/44$) that exhibited the Kanji effect in the current study. In particular, Xu (2007) demonstrated that the amplitude of activations in the superior IPS ($z = 50$) is influenced not only by the number of visual objects/items but also by the complexity of the visual features held in VSTM. When the same number of objects with different levels of visual complexity (i.e. colour and

shape vs. only shape) was retained in VSTM, the superior IPS activation was higher for the visually more complex objects. Such sensitivity to visual complexity may help explain the observed Kanji effect in the superior IPS. That is, the higher level of visual complexity inherent in logographic symbols leads to the increased VSTM demands, as reflected in the greater level of superior IPS activation for Kanji than Kana. In the fMRI literature, the superior IPS and surrounding sub-regions of the IPS are strongly activated by various different cognitive tasks (Behrmann *et al.*, 2004), such as modulation of attention (Majerus *et al.*, 2006), sustained attention (Serences & Yantis, 2007; Kelley *et al.*, 2008; Thakral & Slotnick, 2009), mental rotation (Jordan *et al.*, 2001; Zatorre *et al.*, 2010), online manipulation of information (Champod & Petrides, 2007) and visuomotor control (Grefkes *et al.*, 2004). However, the current study focused on VSTM associated with logographic Kanji words, and thus the precise specification of the role of the superior IPS is beyond its scope.

The majority of the aforementioned fMRI studies on the posterior parietal cortex have reported bilateral activation of the superior IPS, irrespective of whether the task modality is visual or verbal. However, our results highlight the close coupling between the right superior IPS activation (for the Kanji and control scripts) and VSTM performance outside the scanner. Recent neuropsychological studies have shown that damage to the right superior IPS is associated with deficits in a verbal short-term memory task with high visual-spatial demands (i.e. the location of the verbal stimuli presented was not fixed, and varied with different trials; Ravizza *et al.*, 2005). Hence, the observed brain-behaviour relationship in the right superior IPS may indicate a greater reliance on visual-spatial short-term memory when processing logographic Kanji words. Given that the recognition of logographic symbols requires the understanding of both visual complexity (i.e. local visual features) and spatial relationships (i.e. global visual features) within each logographic symbol, it will be of interest to investigate the relationships between different levels of visuo-spatial complexity in logographic symbols and the activation of the right superior IPS.

Unlike the superior IPS, which is one of the key brain structures underlying VSTM, the LOC is primarily considered to represent perceptual visual features such as shape during object recognition (Grill-Spector *et al.*, 1998, 2001; Kourtzi & Kanwisher, 2000, 2001). This region has also been found to be involved in encoding perceptual information about objects retained in VSTM (Fuster & Jervey, 1981; Courtney *et al.*, 1997). Hence, the observed Kanji effect on the right LOC is likely to be associated with the increased perceptual demands of information storage in VSTM when encoding visually complex logographic Kanji symbols. The observed activation in the left LOC extended into the left fusiform gyrus, a region known as the Visual Word Form Area (VWFA; Dehaene *et al.*, 2002; McCandliss *et al.*, 2003). The VWFA is considered to be sensitive to word forms and orthographic patterns, although such functional specificity remains controversial, with others arguing that it is more related to general perceptual expertise (Poldrack, 2002; Xue & Poldrack, 2007). Of note, the peak coordinates of the fusiform gyrus associated with the Kanji effect in the present study were more lateral to those reported in previous fMRI studies on Japanese reading (Thuy *et al.*, 2004; Nakamura *et al.*, 2005). Some minor variation in the location of the Kanji effect within the occipito-temporal cortex may be attributed to the use of different tasks and registration methods. Nevertheless, fMRI studies comparing activation between Kana and Kanji within the Japanese writing system appear to favor the effect of visual perceptual expertise in the VWFA.

In addition, the Kanji effect was evident in the superior part of the right cerebellum (lobule VI). Although no ROI analysis was conducted for

this region due to incomplete scan coverage, a recent meta-analysis focusing on the cerebellum has reported that cerebellar activation patterns are related not only to motor control but also to cognitive processes such as verbal and visual processing (Stoodley & Schmahmann, 2009a). In light of recent findings that implicate the importance of the cerebellar integrity in language processes including reading (Ackermann, 2008; Pernet *et al.*, 2009; Stoodley & Schmahmann, 2009b; Strick *et al.*, 2009), it will be of interest to investigate the role of the cerebellum in reading and reading disorders in different scripts.

Educational implications of the Kanji effect

Although comprehension is the ultimate goal of reading, letters and words need to be visually recognized in the initial stages of the reading process. Thus, the ability to retain the visual information about symbols and words in VSTM is particularly important in logographic writing systems, where an enormous number of visually complex symbols must be learnt (e.g. 1000 symbols by the end of 6th grade, 3000 symbols for everyday use, such as reading a newspaper, in Japan). Outside the scanner, the adult participants' Kanji word reading scores (the 100 Rakan) significantly correlated with their VSTM abilities (the Visual Patterns Test), suggesting that the importance of VSTM in reading logographic Kanji words extends beyond childhood. Recently, Siok *et al.* (2009) have demonstrated that a visual deficit, which is one of the characteristics of reading difficulties in logographic systems, is reflected in reduced activation of the superior IPS ($z = 48$) in Chinese dyslexics. Although there have been no fMRI studies on dyslexia in Japanese Kanji, our fMRI results, together with previous neuroimaging studies in Japanese Kanji and in Chinese, suggest that the investigation of regions involved in VSTM (and visual attention), particularly the superior IPS, is key to understanding the neural mechanisms of reading and reading disorders in logographic systems.

Conclusions

The present study investigated brain-behaviour relationships in adult readers of logographic Kanji and syllabic Kana within the Japanese writing system, and demonstrated that VSTM abilities remain important for logographic Kanji reading beyond childhood. We also provide cross-script evidence to support the concept that Kanji places greater demands on VSTM relative to Kana. These behavioural and fMRI results, which highlight the close relationship between VSTM and logographic reading, are most likely due to the increased demand on VSTM required to cope with the complex visual features inherent in logographic symbols. Further research is needed to better characterize neural mechanisms/functions in regions associated with the Kanji effect, particularly in individuals who suffer from reading difficulties in logographic systems or those with impairments in VSTM.

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Abbreviations

BOLD, blood oxygen level-dependent; fMRI, functional magnetic resonance imaging; FMRIB, Centre for the Functional Magnetic Resonance Imaging of the Brain in Oxford; IPS, intraparietal sulcus; LOC, lateral occipital complex; ROI, region of interest; VMFA, Visual Word Form Area; VSTM, visual short-term memory.

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