

Subliminal Convergence of Kanji and Kana Words: Further Evidence for Functional Parcellation of the Posterior Temporal Cortex in Visual Word Perception

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Abstract

Recent evidence has suggested that the human occipito-temporal region comprises several subregions, each sensitive to a distinct processing level of visual words. To further explore the functional architecture of visual word recognition, we employed a subliminal priming method with functional magnetic resonance imaging (fMRI) during semantic judgments of words presented in two different Japanese scripts, Kanji and Kana. Each target word was preceded by a subliminal presentation of either the same or a different word, and in the same or a different script. Behaviorally, word repetition produced significant priming regardless of whether the words were presented in the same or different script. At

the neural level, this cross-script priming was associated with repetition suppression in the left inferior temporal cortex anterior and dorsal to the visual word form area hypothesized for alphabetical writing systems, suggesting that cross-script convergence occurred at a semantic level. fMRI also evidenced a shared visual occipito-temporal activation for words in the two scripts, with slightly more mesial and right-predominant activation for Kanji and with greater occipital activation for Kana. These results thus allow us to separate script-specific and script-independent regions in the posterior temporal lobe, while demonstrating that both can be activated subliminally. ■

INTRODUCTION

Several lines of evidence have consistently suggested that the left inferior temporal cortex constitutes a cerebral substrate for the perception of visual words (Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999; Puce, Allison, Asgari, Gore, & McCarthy, 1996; Nobre, Allison, & McCarthy, 1994). Although this and adjacent cortical regions were initially thought to represent a multimodal brain area active in a variety of language operations, such as phonological retrieval (Price, 1998), imagery, and writing (Nakamura et al., 2001), more recent work has suggested that the neural processes for invariant visual word recognition are associated with the middle part of the left occipito-temporal sulcus, a region which has been termed the visual word form area (VWFA). This particular subregion may be attuned specifically to the visual representations of words, or more precisely, to abstract (shape-independent) representations of visual letter strings (Cohen, Lehericy, et al., 2002; Dehaene, Le Clec, et al., 2002).

Behavioral evidence for the existence of such abstract representations has been provided by the demonstra-

tion of cross-case repetition priming (Forster & Davis, 1984; Evett & Humphreys, 1981). Visual recognition of a target word is known to be facilitated when it is preceded by the same word, irrespective of whether this prime-target pair is written in the same or different case (e.g., radio-radio vs. radio-RADIO), and regardless of whether the prime and the target are visually similar or dissimilar (e.g., kiss-KISS vs. read-READ). This is the case even when the prime word is masked such that participants are unaware of its presence (subliminal priming).

Using functional magnetic resonance imaging (fMRI), Dehaene, Naccache, et al. (2001) have demonstrated that, at the neural level, this subliminal repetition priming effect is visualized as an attenuated response of the left occipito-temporal sulcus area. The VWFA shows reduced activation upon repetition of words irrespective of whether the prime and the target are presented in same- or different-case. This and a subsequent study further suggested that the occipito-temporal cortex is organized, from posterior to anterior, for storing increasingly more abstract representations of visual words, ranging from physical features in the extrastriate cortex to location- and case-invariant letters and words more anteriorly in the fusiform region (Dehaene, Jobert, et al., 2004).

To further explore the functional architecture of this neural system for reading, the present fMRI study

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employed the subliminal priming method for a language which uses two radically different writing systems to write the same word (Figure 1). That is, we focused on the repetition priming effect that may occur between two writing systems of Japanese, Kanji (logographic) and Kana (syllabic), when participants are engaged in a semantic categorization task. Importantly, when a given word is written in the two scripts, there is no one-to-one correspondence at the sublexical level. For instance, the word “cigarette” is printed as “煙草” in Kanji and “たばこ” in Kana, respectively, while both are pronounced as /ta-ba-ko/. Hence, the cross-script repetition priming, if any, should represent a perceptual phenomenon distinct from the case-independent priming observed in alphabetical systems, attributable only to phonological, lexical, or semantic activations beyond the orthographic representations of words. As such, this particular form of priming might be mediated by a set of areas distinct from the VWFA.

The advantages of studying within- and cross-script priming in Japanese readers with fMRI are threefold. First, the combined use of subliminal masked priming and fMRI enables us to examine the initial stages of reading and their neural correlates while avoiding potential strategic and attentional changes elicited by awareness of the prime–target relation (Naccache & Dehaene, 2001a). That is, this method allows us to focus on bottom-up activations of the neural code associated with the word stimuli, while presumably preventing the top-down re-entry of information (Dehaene, Jobert, et al., 2004; Lamme, 2003; Lamme, Zipser, & Spekreijse, 2002). It may therefore provide precise information about which type of local word code is used in a given brain area, without contamination by the distant global broadcasting that may occur when words cross the threshold of consciousness.

Second, this design allows us to further evaluate the depth of processing involved during unconscious word

perception. Although it is widely accepted that cross-case repetition priming is extremely robust under masking conditions and thus provides clear evidence for the existence of subliminal orthographic processing, there is still a controversy as to whether one can observe a similar phenomenon for higher processing stages (phonological, lexical, and semantic) corresponding to whole-word processing (Kouider & Dupoux, 2004; Forster, Mohan, & Hector, 2003). That is, although some researchers have suggested that subliminal word priming is restricted to an analysis of subword fragments or letters instead of reflecting lexical processing (Abrams & Greenwald, 2000), other studies have found repetition priming for words translated into two different languages, even when written with very different scripts (Jiang, 1999; Gollan, Forster, & Frost, 1997). However, because prime awareness was not measured in these latter studies, it is still not entirely clear whether priming goes beyond the orthographic level under genuinely subliminal conditions. Evidence of masked cross-script priming between Kanji and Kana, together with the demonstration that prime stimuli remained below the threshold of awareness, would provide further unequivocal evidence that unconscious perception can reflect processing at an advanced level. Also, the anatomical localization of brain areas associated with cross-script priming may in turn help interpret the cognitive process underlying this behavioral phenomenon.

Third, the design of the present experiment, with orthogonal manipulations of prime script and target script, incidentally allows us to examine the overlap and the differences between the neural substrates of visual word recognition in Kanji and in Kana. This issue has long been a major concern for neurolinguistic studies of Japanese. Focal brain damage often affects the reading of Kanji and Kana to a different degree, which has led to the idea that visual words in the two formats must have partially distinct neural representations. Specifically, the inferior temporal cortex and a more dorsal part of the occipito-temporal region in the left hemisphere have been thought important for reading of Kanji and Kana, respectively (Iwata, 1986). Also, several lines of studies have suggested the contribution of the right hemisphere in the visual recognition of logograms (Yamaguchi, Toyoda, Xu, Kobayashi, & Henik, 2002; Kamada et al., 1998; Nakagawa, 1994; Sugishita, Yoshioka, & Kawamura, 1986; Hatta, 1977; Sasanuma, Itoh, Mori, & Kobayashi, 1977). Nonetheless, the issue seems not fully resolved, as for instance, a more recent multiple case study found no consistent correlation between specific patterns of impairment and lesion sites (Sugishita, Otomo, Kabe, & Yunoki, 1992). In the brain imaging literature, moreover, although a few previous studies have examined brain activity during reading of Japanese (Sakurai, Momose, Iwata, Sudo, et al., 2000; Sakurai, Momose, Iwata, Ishikawa, et al., 1996; Sakurai, Momose, Iwata,

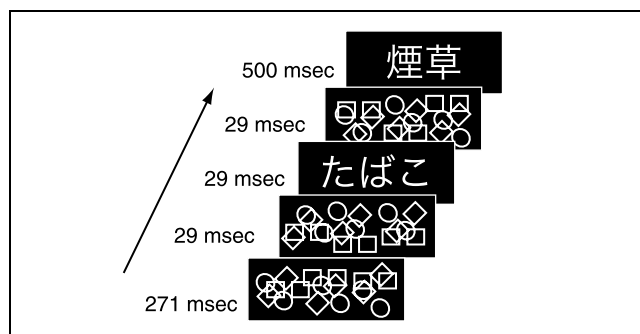


Figure 1. Sequence of events used for the behavioral tasks. Each trial consisted of a visible target word (たばこ) preceded by a masked prime (煙草). The prime–target relation (same or different word), prime script, and target script were manipulated independently. Participants were requested to determine whether the latter represented a natural or artificial object as quickly as possible.

Watanabe, et al., 1993), none of them provided a direct statistical comparison of the effect of script type.

EXPERIMENT 1

Results

Behavioral Results

Mean accuracy ($\pm SD$) for the semantic categorization task was 94.83% ($\pm 3.75\%$). The forced-choice test for prime visibility revealed that participants were unable to see the prime words [accuracy = 52.29% correct, $t(15) = 0.60$, $p = .56$], and that the accuracy level did not differ significantly between the two script types [mean = 52.86% and 51.05% for Kanji and Kana, respectively, $t(15) = 0.49$, $p = .63$].

The behavioral priming effect for each script type is summarized in Table 1. Overall, the repetition of same words produced a highly significant effect of priming across the four types of script alternations [$F(1,15) = 44.83$, $p < .001$]. By contrast, neither the script type of primes nor that of targets affected the participants' performance significantly [$F(1,15) = 3.37$, $p = .09$; $F(1,15) = 1.45$, $p = .25$, respectively]. There was a nonsignificant trend of interaction between prime script and target script [$F(1,15) = 4.08$, $p = .06$]. None of the other interactions were significant [$F(1,15) = 3.06$, $p = .10$ for repetition and prime script; $F(1,15) = 0.64$, $p = .44$ for repetition and target script, respectively]. The triple interaction was not significant either [$F(1,15) = 2.96$, $p = .11$].

In further analysis, the priming effect was examined with respect to the script type of primes and targets. The pairwise comparisons indeed revealed that the repetition of words accelerated responses systematically across four types of script-changes between primes and targets [$F(1,15) = 24.54$, $p < .001$ for prime Kanji and target Kanji, $F(1,15) = 37.33$, $p < .001$ for prime Kanji and target Kana, $F(1,15) = 7.78$, $p < .01$ for prime

Kana and target Kana, and $F(1,15) = 14.54$, $p < .002$ for prime Kana and target Kana, respectively].

Imaging Results

Script-specific effects. Regardless of their script type, visual words produced left-predominant activation of the peri-sylvian areas, fronto-parietal junction, and occipito-temporal area relative to the word-absent baseline. These activation sites were distributed quite similarly for both types of script (Figure 2).

Activations that differ according to script type are illustrated in Figure 3 and summarized in Tables 2 and 3. Within the set of brain regions activated by Kanji targets, only a small bilateral region in the fusiform gyrus responded more greatly when target words were presented in Kanji than in Kana, particularly in the right hemisphere. Conversely, target words in Kana relative to those in Kanji exhibited activation of the bilateral occipital pole and left inferior parietal area including the supramarginal gyrus and inferior parietal lobule. In contrast, no region in this neural circuit responded more greatly to subliminal primes in Kanji relative to those in Kana, while conversely the left inferior parietal lobule exhibited greater response to the latter relative to the former.

In the set of brain areas activated by Kana targets, visible targets and subliminal primes in Kanji each produced no significant activation relative to their equivalents in Kana. Targets in Kana relative to those in Kanji activated the bilateral occipital pole, the left lateral occipital cortex, and the left inferior parietal area, whereas similarly subliminal primes in Kana activated the left inferior parietal lobule and thalamus relative to those in Kanji.

Repetition priming effects. Brain regions showing significant repetition suppression are summarized in Table 4. Repetition of words in Kanji produced two distinct clusters in the left posterior temporal area, one in the anterior superior/middle temporal gyri and the other in the medial fusiform gyrus (Figure 4A). Note that this latter cluster overlaps the region showing greater activation to Kanji relative to Kana. By contrast, only the anterior portion of the middle temporal gyrus ($y = -39$) exhibited a significant repetition suppression when words were repeated in the prime Kanji–target Kana condition (Figure 4B and Table 4). In fact, prime words in Kanji produced an attenuated response at this location regardless of whether targets were written in Kana or in Kanji ($x = -44$, $y = -35$, $z = 2$; $Z = 3.36$, see Figure 4C). This site showed a greater effect of priming when primes were presented in Kanji than in Kana ($Z = 3.83$). In contrast to those positive effects of Kanji primes, the priming effect induced by primes in

Table 1. Behavioral Priming Effects in Experiment 1

Prime Script	Target Script	Reaction Time (msec)		Effect Size (msec)
		Repeated	Unrepeated	
Kanji	Kanji	596	624	28***
Kanji	Kana	606	630	23***
Kana	Kanji	603	614	12*
Kana	Kana	598	620	22**

* $p < .05$.

** $p < .01$.

*** $p < .001$.

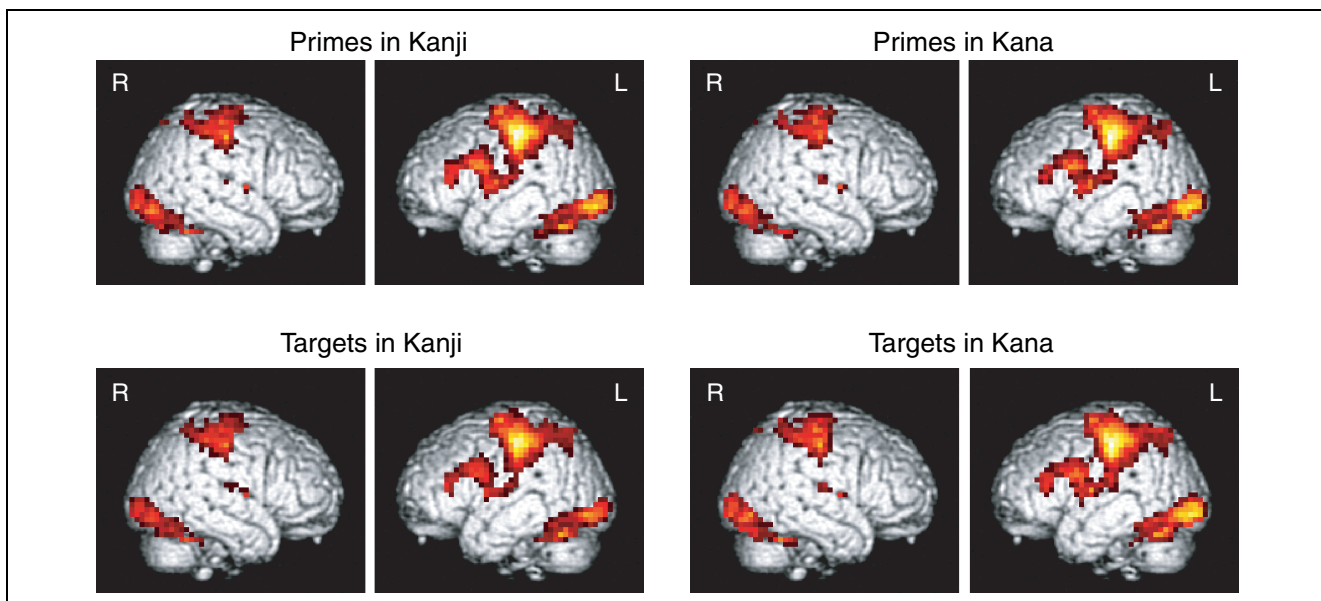


Figure 2. Brain regions activated by primes and targets relative to the word-absent baseline. Irrespective of their script type, primes and targets similarly produced left-predominant activation of the peri-sylvian areas, fronto-parietal junction, and occipito-temporal area.

Kana did not survive the current statistical criteria, irrespective of the script type of targets. However, a nonsignificant trend of repetition suppression was detected in a close vicinity of the above left temporal region for the prime Kana–target Kanji condition ($x = -44$, $y = -51$, $z = -4$; $Z = 2.42$).

To clarify the role of this region in cross-script priming, we further examined the priming effect by computing a linear combination of prime Kanji–target Kana and prime Kana–target Kanji conditions (inclusively masked by both contrasts at $p < .05$). This additional analysis revealed that this anterior part of the left middle temporal gyrus exhibited a significant effect of repetition suppression when words were repeated in different script, irrespective of the direction of script alternations ($x = -48$, $y = -43$, $z = 2$; $Z = 3.65$, see Figure 4D).

On the other hand, when the priming effect was compared between within- and cross-script conditions (i.e., prime Kanji–target Kanji and prime Kana–target Kana vs. prime Kanji–target Kana and prime Kana–target Kanji), the same part of the left middle temporal gyrus showed a greater trend of priming when words were presented in different script than in same script ($Z = 2.82$). However, no brain region exhibited a significant priming effect when words were repeated in same scripts.

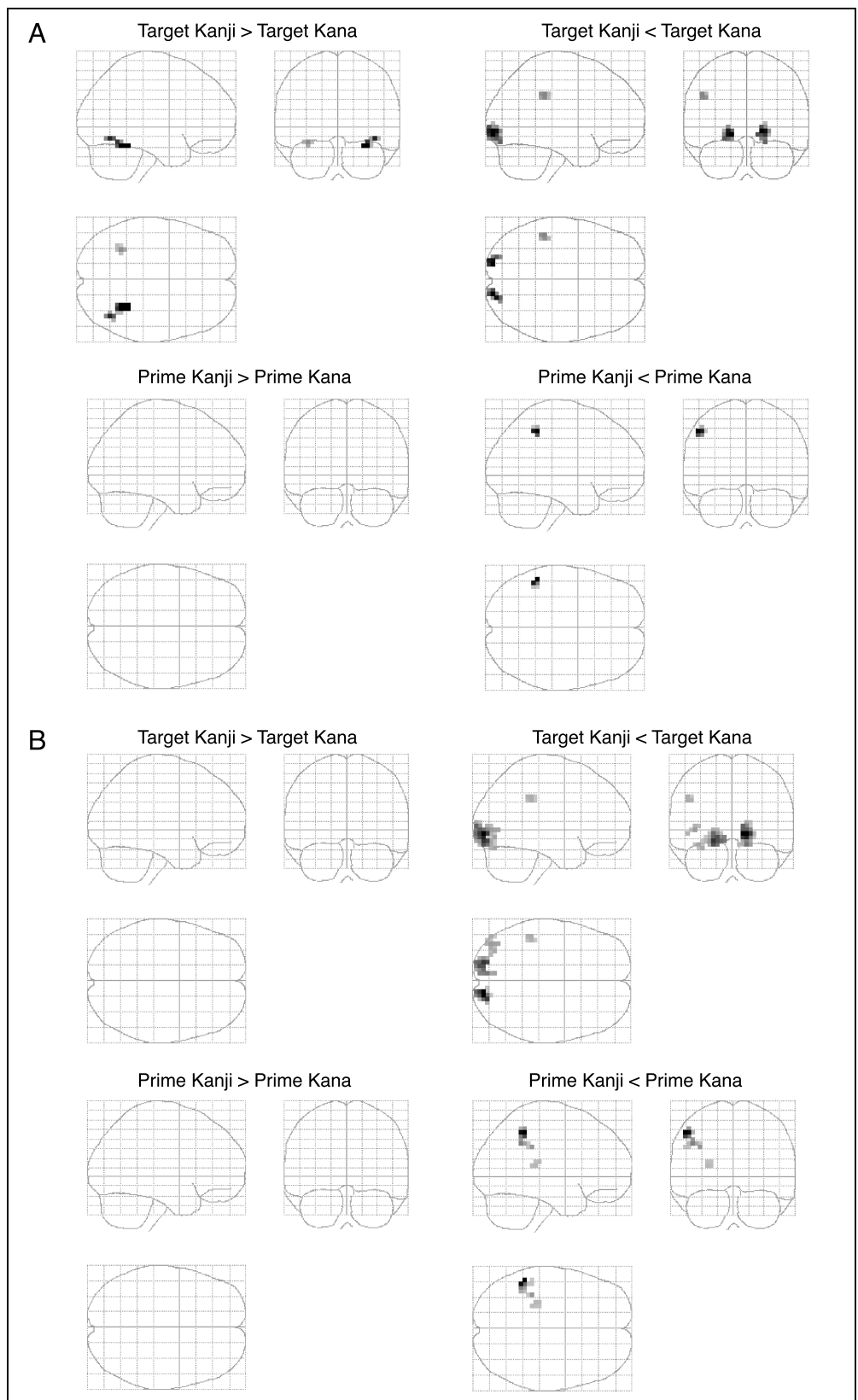
Additionally, we examined the priming effect by computing the across-participant mean of percent signal change within a 5-mm-radius spherical volume of interest (VOI) centered at the VWFA as identified with alphabetic letter-strings (Cohen, Dehaene, et al., 2000). The VOI analysis revealed that this region was active during perception of both Kanji and Kana relative to the

baseline, while showing greater activation for words in Kana than those in Kanji [$t(15) = 2.57$, $p = .02$]. The priming effect, however, was not significant at this location for any of the four types of script alternations. To summarize the imaging results, the anatomical locations and priming effects for three posterior temporal regions of interest are illustrated in Figure 5.

EXPERIMENT 2

A second behavioral experiment was designed to establish whether the subliminal cross-script effect observed in Experiment 1 reflects a repetition priming effect, or whether it results from response priming related to prime–target congruity (Damian, 2001). The issue arises because all the unrepeated trials in Experiment 1 comprised only primes and targets that belonged to opposite categories (e.g., prime: natural; target: artifact). This feature of the design introduced a confound between prime–target repetition (repeated or different words) and response congruity (congruent or incongruent responses to the prime and target). Thus, the observed repetition priming effect might in fact be imputable to a motor conflict. Processing of the prime would lead to covert preparation of an appropriate motor response, and such response bias would need to be overcome by the overt motor response on targets. Note that this response competition might occur for two reasons: either the motor response induced by the primes resulted from subliminal semantic processing (Abrams, Klinger, & Greenwald, 2002; Naccache & Dehaene, 2001b), or more

Figure 3. Statistical parametric maps showing differential activation to the script type. Within the set of brain regions active during reading of Kanji (A), visible targets produced activation of the bilateral fusiform region more greatly for Kanji, whereas those written in Kana activated the bilateral occipital pole and the left inferior parietal region more greatly. Subliminal primes in Kanji produced no significant activation relative to those in Kana, whereas the latter activated the left inferior parietal lobule relative to the former. All these effects of script type, except the one in the fusiform region for Kanji targets, were similarly observed within the neural network active during reading of Kana (B).



simply it resulted from stimulus–response associations which could develop because the subliminal primes were also practiced as targets during the experiment (Damian, 2001). To control for this confound, and

examine the behavioral effect of word repetition independently of response factors, we performed a second behavioral experiment in which primes and targets always belonged to the same category in both repeated

Table 2. Effects of Script Type in Brain Regions Active during Reading of Kanji

Brain Region	No. of Voxels	Z Value	Coordinate		
			x	y	z
<i>Prime Kanji > Prime Kana</i>					
(No suprathreshold clusters)					
<i>Prime Kanji < Prime Kana</i>					
Left inferior parietal lobule	9	4.16	-51	-44	48
<i>Target Kanji > Target Kana</i>					
Right fusiform gyrus	16	3.54	32	-48	-20
Left fusiform gyrus	7	3.22	-29	-41	-13
<i>Target Kanji < Target Kana</i>					
Left occipital pole	18	3.94	-16	-89	-2
Right occipital pole	19	3.90	16	-89	1
Left supramarginal gyrus	8	3.03	-48	-33	35

and nonrepeated trials, thereby eliminating any difference in response congruity.

Results

The level of accuracy was almost the same as in the previous experiment (mean \pm SD = 94.67% \pm 3.00%). Response time for each condition is summarized in Table 5. The main effect of repetition, although diminished in size across the four conditions of prime and

Table 3. Effects of Script Type in Brain Regions Active during Reading of Kana

Brain Region	No. of Voxels	Z Value	Coordinate		
			x	y	z
<i>Prime Kanji > Prime Kana</i>					
(No suprathreshold clusters)					
<i>Prime Kanji < Prime Kana</i>					
Left inferior parietal lobule	21	4.16	-51	-40	46
Left thalamus	6	2.78	-28	-30	13
<i>Target Kanji > Target Kana</i>					
(No suprathreshold clusters)					
<i>Target Kanji < Target Kana</i>					
Right occipital pole	43	4.90	16	-85	1
Left occipital pole	57	4.12	-20	-86	-6
Left lateral occipital area	9	3.29	-40	-78	4
Left supramarginal gyrus	8	3.03	-48	-33	35

Table 4. Brain Regions Showing Reduced Response to the Repetition of Words

Brain Region	No. of Voxels	Z Score	Coordinate		
			x	y	z
<i>Prime Kanji–Target Kanji</i>					
Left superior/middle temporal gyri	26	4.00	-55	-38	20
Left medial occipital lobe	15	3.82	-20	-58	10
Right medial frontal area	17	3.68	16	-9	52
Right middle temporal gyrus	20	3.68	48	-20	-6
Left fusiform gyrus	32	3.68	-32	-63	-14
Right superior temporal gyrus	24	3.60	63	-34	16
Left medial frontal area	8	3.38	-16	-1	59
Left anterior cingulate gyrus	36	3.14	-24	14	40
Right lateral occipital area	23	3.06	12	-73	7
Left middle temporal gyrus	8	2.91	-51	-61	14
<i>Prime Kanji–Target Kana</i>					
Left middle temporal gyrus	11	3.17	-48	-39	2
<i>Prime Kana–Target Kana</i>					
(No suprathreshold clusters)					
<i>Prime Kana–Target Kanji</i>					
(No suprathreshold clusters)					

target script, remained significant even when the contribution of the response priming was discounted [$F(1,21) = 39.57, p < .001$]. Participants responded significantly faster when the targets were written in Kanji [$F(1,21) = 54.37, p < .001$], whereas the script type of primes did not affect the response time [$F(1,21) = 2.10, p = .16$]. The effect of repetition did not interact with the script type of primes [$F(1,21) = 1.25, p = .28$] nor with that of targets [$F(1,21) = 0.50, p = .49$]. None of the other interactions reached statistical significance.

Furthermore, pairwise comparisons revealed that the priming effect was significant in the four conditions of prime and target scripts [$F(1,21) = 23.92, p < .001$ for prime Kanji and target Kanji, $F(1,21) = 6.33, p = .02$ for prime Kanji and target Kana, $F(1,21) = 5.11, p = .04$ for prime Kana and target Kanji, and $F(1,21) = 5.51, p = .03$ for prime Kanji and target Kana].

Joint Behavioral Analysis of Experiments 1 and 2

The effects of repetition and response congruity were contrasted by pooling the two sets of behavioral data obtained from Experiments 1 and 2. The combined analysis therefore consisted of a $2 \times 2 \times 2 \times 2$ factorial design where the effects of repetition (repeated and

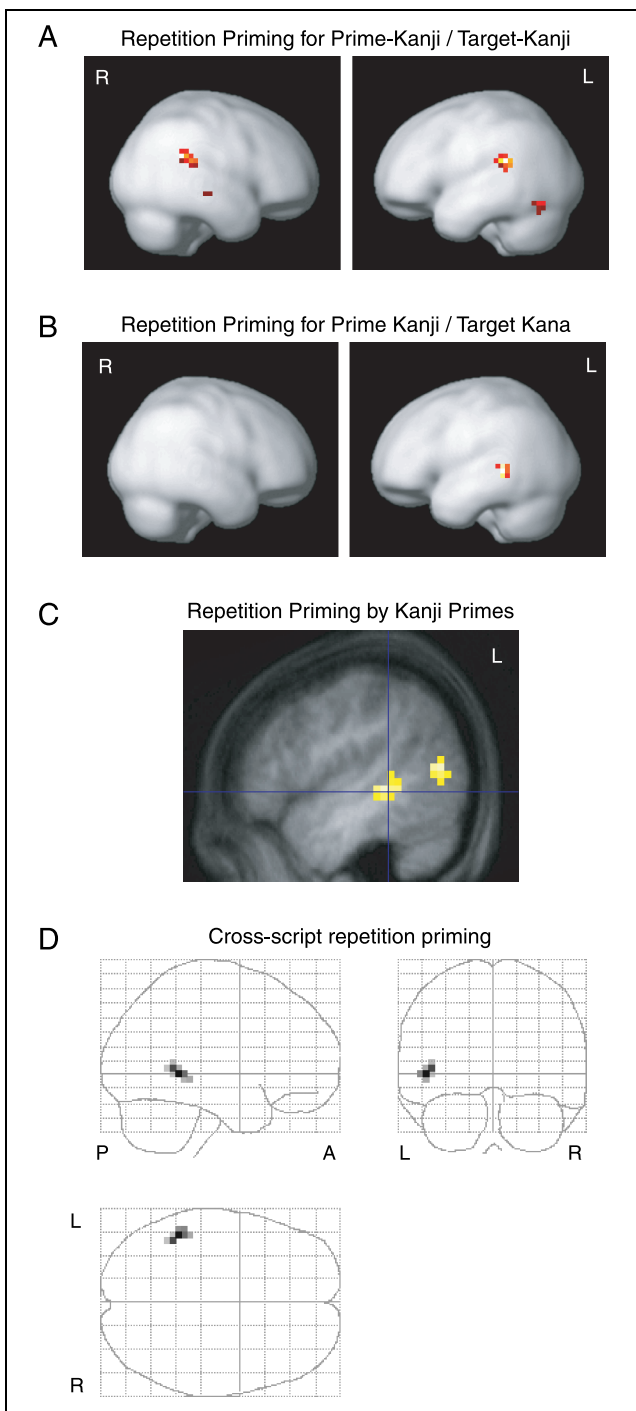


Figure 4. Brain regions showing the repetition priming effect. The left lateral occipito-temporal cortex exhibited reduced activation when both primes and targets were written in Kanji (A), whereas a mid-lateral part of the left middle temporal gyrus showed reduced response when primes and targets were written in Kanji and Kana, respectively (B). This same region exhibited reduced activation for primes in Kanji regardless of whether targets were written in Kana or in Kanji (C), while no brain area showed the activation reduction when primes were presented in Kana script. Only the mid-lateral portion of the left temporal gyrus exhibited a significant repetition priming effect when words were repeated in different scripts, irrespective of the direction of script change (D).

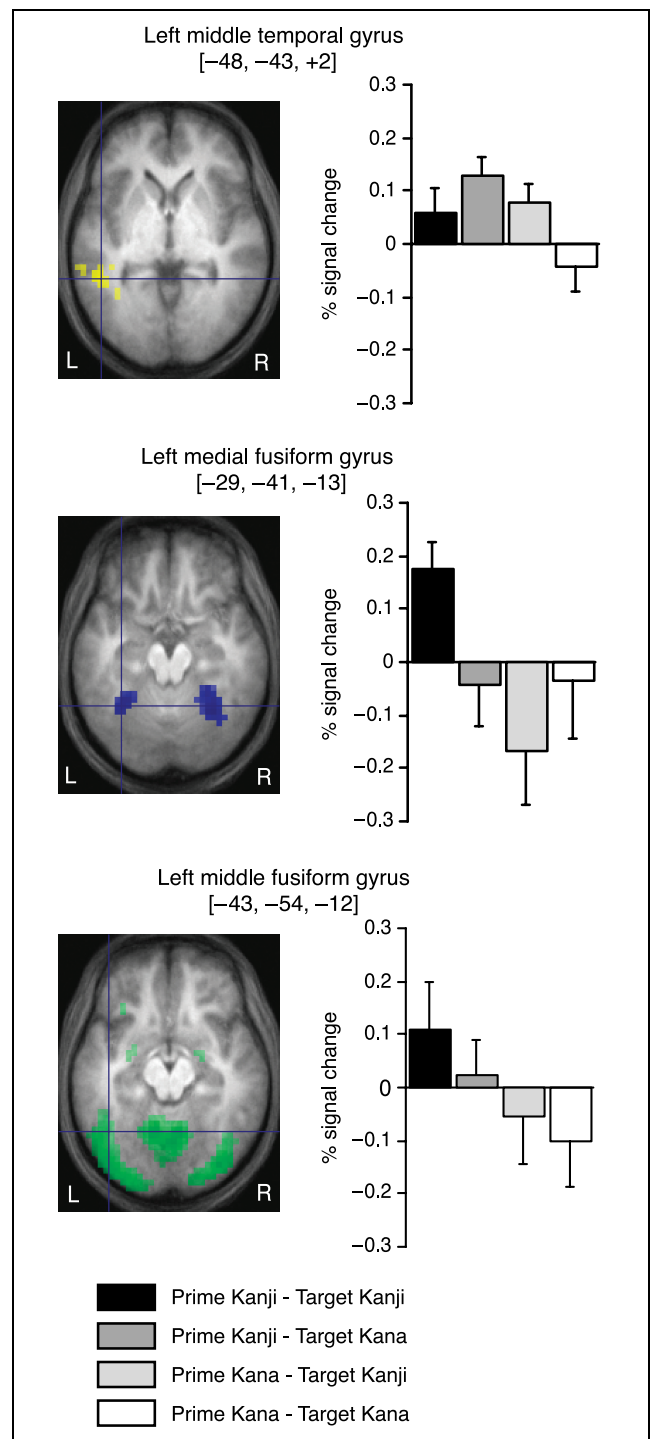


Figure 5. Magnitude of activation reduction ($\pm SEM$) in posterior temporal regions of interest. Top: The left middle temporal gyrus exhibited a cross-script priming effect, irrespective of the direction of script change (yellow). This region also exhibited a significant priming effect when primes were presented in Kanji. Middle: The left medial fusiform gyrus showed greater activation to Kanji than to Kana (blue). The priming effect was significant at this location only when words were repeated in the former script. Bottom: The left middle fusiform gyrus or VWFA identified for European alphabetic scripts was active during reading of Kanji and Kana relative to the baseline (green). This region did not produce significant activation reduction for either type of script, although there is a nonsignificant trend of priming for the prime Kanji–target Kanji condition.

Table 5. Behavioral Priming Effects in Experiment 2

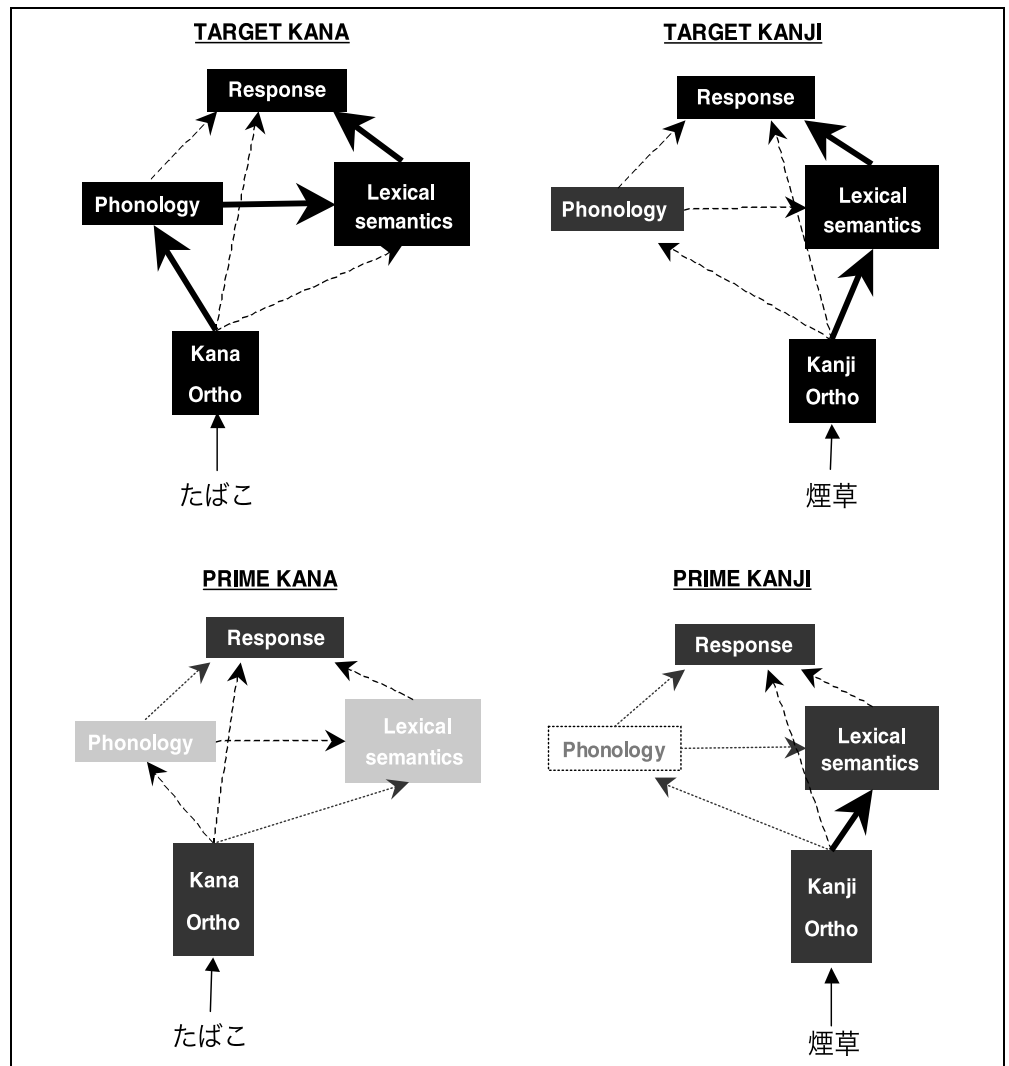
Prime Script	Target Script	Reaction Time (msec)		Effect Size (msec)
		Repeated	Unrepeated	
Kanji	Kanji	569	582	13***
Kanji	Kana	586	592	6*
Kana	Kanji	578	584	6*
Kana	Kana	586	593	7*

* $p < .05$.*** $p < .001$.

unrepeated), prime script (Kanji and Kana), and target script (Kanji and Kana) were within-participant factors, whereas that of experiment (1 or 2) was a between-group factor. The analysis of variance revealed that the main effects of repetition and target script were both

significant across the two experiments [$F(1,36) = 79.90, p < .001$ and $F(1,36) = 23.92, p < .001$, respectively], whereas that of prime script was not [$F(1,36) = 0.17, p = .68$]. The main effect of experiment was not significant [$F(1,36) = 0.88, p = .35$]. By contrast, there was a significant interaction between repetition and experiment [$F(1,36) = 18.14, p < .001$], suggesting a greater priming effect in Experiment 1, that is, a substantial contribution from response priming. The effects of prime script and target script interacted with each other [$F(1,36) = 6.88, p = .01$]. There was a significant interaction between repetition and prime script [$F(1,36) = 4.34, p = .04$], suggesting that the effect of priming was larger when prime words were presented in Kanji. A significant interaction was also found between prime script and experiment [$F(1,36) = 5.93, p = .02$] and between target script and experiment [$F(1,36) = 4.35, p = .04$], suggesting a greater effect of experiment (i.e., response congruity for words presented in Kanji script). The triple interaction

Figure 6. A tentative model of the pathways traversed by conscious and subliminal Kanji and Kana words in our task. Thick continuous, dashed, and dotted lines represent connections of strong, weak, or very weak strength. Top: Conscious reading of Kana words engages principally a phonologically mediated route, and conscious reading of Kanji words a lexical route. In both cases, the response is emitted mostly from the lexico-semantic level because the task requires semantic classification. However, because the same words are repeatedly used, direct motor associations can also develop from the other levels of representations. Bottom: The lexico-semantic route and the response associations remain available during subliminal processing (Dehaene, Naccache, Le Clec, et al., 1998), but the phonological route is largely unavailable (Kouider et al., submitted). The overlap between the representations activated by primes and targets can then explain the size and location of the observed behavioral and fMRI priming effects as a function of prime and target script (see text for details).



was significant only between repetition, prime script, target script [$F(1,36) = 4.96, p = .03$]. All the other interactions were nonsignificant.

GENERAL DISCUSSION

Commonalities and Differences in Reading of Kanji and Kana

The present imaging data indicate that words printed in Kanji and in Kana activate largely overlapping brain regions, including the fronto-temporal junction, inferior parietal and occipito-temporal cortices, and that these activations are more extensive in the left hemisphere for both scripts. We also found that the left middle fusiform gyrus, a hypothesized neural substrate of orthographic representation (Cohen, Dehaene, et al., 2000), is active during reading for both types of script.

Amid this common neural circuit for reading, we found small differences between scripts, the most notable of which was a greater activation of the bilateral medial fusiform area (BA 37) for words in Kanji relative to those in Kana. To date, this script-specific activation for Kanji has never been demonstrated using a direct statistical comparison, although a similar observation was reported by a previous PET study (Sakurai, Momose, Iwata, Sudo, et al., 2000). The activation focus in the left fusiform gyrus (peak at $y = -41$), although smaller in spatial extent than in the right homologous area, occupied the medial surface of the ventral temporal cortex. It is unlikely that the script-specific effect at this location can be attributed simply to differences in physical features between words in Kanji and those in Kana, because the anterior division of the occipito-temporal cortex ($-50 < y < -40$) has been shown to be insensitive to the retinal size and position of the visual stimuli presented (Vuilleumier, Henson, Driver, & Dolan, 2002; Grill-Spector et al., 1999). Rather, we envisage two possible interpretations of this finding.

First, the partial specialization for Kanji reading may be seen in the larger context of specialization for different categories of visual stimuli such as faces, houses, words, or objects within the inferotemporal visual stream. Hasson et al. (2002) have shown that this specialization relates in part to a retinotopic bias. Object specialization would reflect the requirements placed on foveal processing by each category of visual stimuli, with objects requiring high precision (words, faces) falling within lateral regions biased towards foveal processing, and stimuli requiring more global retinal processing (places) falling within mesial regions biased towards the lateral field. In this context, it might be suggested that the Kanji script requires slightly more global processing than alphabetic or Kana script, hence, that its identification tends to be supported by neurons biased towards the more lateral sectors of the retina, located in a more mesial portion of the fusiform gyrus.

A second possible interpretation is that reading of words in Kanji induces greater activation of regions associated with higher-order, abstract knowledge of words, especially semantics. Indeed, a meta-analysis of previous neuroimaging data by Cohen, Dehaene, et al. (2002) suggested that the anterior portion of the left fusiform region ($y = -43$ on average) is sensitive to increased task demand for semantic processing of visual or auditory words. The close linkage of Kanji and semantics in the left basal temporal cortex is supported by neuropsychological studies of alexia in Japanese readers. Those studies confirm that damage to the left inferior temporal area can affect the reading of Kanji while leaving that of Kana almost intact, and further demonstrate this particular form of alexia often appears in conjunction with anomia (Sakurai, Sakai, Sakuta, & Iwata, 1994; Yokota, Ishiai, Furukawa, & Tsukagoshi, 1990; Soma, Sugishita, Kitamura, Maruyama, & Imanaga, 1989; Kawahata, Nagata, & Shishido, 1988). This may reflect the fact that naming of objects and reading of Kanji both place a particular emphasis on semantic access prior to phonological retrieval.

Regardless of whether the visual or semantic interpretation is correct, the more extensive activation of the right fusiform area by Kanji than by Kana may represent a neuroanatomical substrate of the long-standing hypothesis of a right hemisphere advantage in processing of Kanji. Their logographic nature was long thought to allow readers to extract meaning directly from their written forms without the mediation of phonological recoding. The rightward asymmetry for the recognition of Kanji has been suggested by several lines of studies, including behavioral (Nakagawa, 1994; Hatta, 1977; Sasanuma et al., 1977), neuropsychological (Sugishita & Yoshioka, 1987; Sugishita, Yoshioka, et al., 1986), electrophysiological (Yamaguchi et al., 2002; Hayashi, Kayamoto, Tanaka, & Yamada, 1998), and magnetoencephalographic (Kamada et al., 1998) data. Although these studies have located the right-predominant activity in different brain regions, such as fronto-central (Yamaguchi et al., 2002), parietal (Hayashi, et al., 1998), and occipito-temporal cortices (Kamada, et al., 1998), the present fMRI results suggest that the hemispheric specialization differs between the two scripts early in the ventral visual pathway.

In the converse direction, there were a few regions where Kana yielded greater activation than Kanji. First, reading of Kana relative to Kanji produced activation in bilateral retinotopic areas around the occipital pole ($y \sim -90$ mm) and in the left anterior lateral occipital area ($y = -74$ mm). Both differences are likely to arise from the slight asymmetry in retinal size between the two scripts. Second, visual words in Kana, not only targets but also primes, activated the left inferior parietal lobe more than those in Kanji. A body of neuropsychological and neuroimaging data have associated this region, especially the left supramarginal gyrus, with the transla-

tion from orthography to phonology (e.g., Price, 1998; Price, Moore, Humphreys, & Wise, 1997). The left parietal activation may also relate to the deployment of visuospatial attentional processes that are needed to serially assemble phonology from the spatially extended series of characters that together represent a word. Under both of these interpretations, the greater response to Kana at this location would reflect the greater use of phonological decoding that has been postulated for Kana over Kanji (Nomura, 1981). If this interpretation is correct, interestingly, our findings suggest that the neural processes for converting orthography to phonology may proceed to a certain extent even in the absence of awareness (see below for further discussion).

Cross-Script Priming in the Left Lateral Temporal Cortex

Behavioral results from Experiment 1 suggested that the repetition of subliminal words facilitates participants' response not only when they are written in same script but also when written in different script. This priming effect, although reduced, remained significant when the contribution from response priming was discounted in Experiment 2. Many previous experiments have demonstrated subliminal orthographic priming across lowercase and uppercase presentations of the same words in alphabetic scripts (Bowers et al., 1998; Humphreys et al., 1990; Forster & Davis, 1984; Evett & Humphreys, 1981). The present results, however, suggest that subliminal processing goes beyond the orthographic level, as no graphic code is shared between words written in Kanji and in Kana. The cross-script priming effect implies the activation of abstract, script-independent representations over and above the orthographic knowledge of words, namely, at the phonological, lexical, or semantic levels. These results replicate those previously obtained with cross-language repetition priming for translation equivalents (Jiang, 1999; Gollan, et al., 1997), and show that they can be obtained under conditions of total nonconsciousness of the masked primes. Furthermore, fMRI reveals the cerebral correlates of this abstract priming effect. We found that cross-script repetition priming correlates with an attenuated response in a mid-lateral part of the left middle temporal cortex ($x = -48, y = -43, z = 2$).

Previous neuropsychological and brain imaging studies indicate that the VWFA, the hypothetical site of an invariant orthographic code, is located at $x = -43, y = -54, z = -12$ in the left fusiform gyrus, with a standard deviation of ~ 5 mm in each coordinate axis (Cohen, Dehaene, et al., 2000). The present cross-script priming site, however, is more anterior and superior, approximately 18 mm further along in the posterior temporal cortex. Taken together, these results suggest an anterior-to-posterior progression in word processing (Dehaene, Jobert, et al., 2004). This may correspond to a

progressive abstraction process, as also proposed for object recognition, whereby raw visual features of stimuli are transformed progressively from perceptual to conceptual (Lerner, Hendler, Ben-Bashat, Harel, & Malach, 2001; van Turennout, Ellmore, & Martin, 2000; Henson, Shallice, & Dolan, 2000). In fact, this part of the left middle temporal gyrus has been associated with the semantic network by both functional brain imaging (Chao, Haxby, & Martin, 1999; Buchel, Price, & Friston, 1998; Vandenberghe, Price, Wise, Josephs, & Frackowiak, 1996) and neuropsychological studies (Chertkow, Bub, Deaudon, & Whitehead, 1997). More recent work further suggested that the same region is invariably active during semantic judgment of objects irrespective of their categories (Tyler et al., 2003). Using fMRI, Thompson-Schill, D'Esposito, and Kan. (1999) also observed activation reduction of the left inferolateral temporal cortex associated with the repeated retrieval of semantic knowledge. Moreover, a recent fMRI study by Devlin, Jamison, Matthews, and Gonnerman. (2004) has reported that this region shows reduced activation to semantically related word-pairs relative to unrelated pairs. Collectively, these data suggest that the left posterior temporal cortex is fractionated into several distinct subcomponents, and that an abstract, plausibly supramodal semantic representation in the left temporal lobe can be contacted by subliminal primes.

In addition, some caution may be needed in interpreting the present imaging results as the experimental design included the effect of motor congruity as a potential confound, which can be inflated by "response association" learned through repeated exposure to the same items. In fact, a recent study by Dobbins, Schnyer, Verfaellie, and Schacter (2004) have suggested that such response learning lead to the activation reduction of the posterior temporal cortex. It is our position, however, that the observed repetition suppression in the left lateral temporal cortex should have only a negligible contribution from the response congruity per se, because (1) response priming and competition have been associated with fronto-parietal regions (Hazeltine, Poldrack, & Gabrieli, 2000; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Carter et al., 1998; Dehaene, Naccache, Le Clec, et al., 1998); (2) the lateralized priming effect was detected in the present study irrespective of the actual side of manual response; and (3) two recent fMRI studies have shown that repetition priming for visual words in the occipito-temporal cortex under the condition where no response congruity was present between repeated and nonrepeated trials (Dehaene, Jobert, et al., 2004; Devlin, et al., 2004).

Asymmetries in Priming

Both behavioral and fMRI analyses suggested that script type affected priming differently across conditions, notably: (1) subliminal primes produced greater behavioral

priming when written in Kanji than in Kana; (2) the magnitude of behavioral priming decreased in cross-script conditions, especially when the prime was in Kana and the target in Kanji; (3) participants responded more quickly to target words in Kanji irrespective of the script type of primes; (4) the effect of response congruity was larger when words were presented in Kanji, both for primes and targets; and (5) fMRI priming in the left temporal cortex was mostly due to Kanji primes.

The faster response to targets in Kanji may be related to a potential difference in visual familiarity between the two formats. That is, despite the initial assumption derived from the previous behavioral data (Amano & Kondo, 2000), it is possible that the current stimuli were substantially lower or at least more varied in familiarity when presented in Kana, as suggested by their slightly lower plausibility ratings. Note that although this potential familiarity bias can explain the faster processing of Kanji targets, it can hardly account for the larger priming induced by Kanji primes. Masked repetition priming is usually insensitive to word frequency (Forster & Davis, 1984; Evett & Humphreys, 1981). Even if it was sensitive to frequency/familiarity, as it is the case for unmasked repetition priming, the reverse asymmetry should be predicted because repetition priming is larger for low- than for high-frequency words (Bowers, 2000; Forster & Davis, 1984).

More plausibly, the asymmetries between Kana and Kanji can be interpreted as reflecting differences in depth of phonological and semantic activation induced by the two scripts. Kanji words may predominantly activate a visual-lexical route, whereas lexical processing of Kana words may require the mediation of phonological codes to a greater degree, especially when they are lower in visual familiarity (Besner & Hildebrandt, 1987; Hirose, 1984; Feldman & Turvey, 1980). The smaller priming induced by Kana words might then be imputable to the lesser automaticity of the phonological route. That is, although activation of phonological representation is thought to be mandatory during visual word recognition (Brybaert, 2001; Lukatela, Carello, Savic, Urosevic, & Turvey, 1998; Van Orden, Johnston, & Hale, 1988), recent behavioral studies using a primed lexical decision task and controlling for prime awareness suggest that visual words produce a phonological effect only when participants consciously perceive the prime stimuli (Kouider, Peereman, & Dupoux, submitted). Those findings suggest that phonological decoding may not occur automatically for subliminal words, at least when the task emphasizes lexico-semantic processing rather than grapheme-phoneme conversion processes. Indeed, cross-task comparisons have shown that masked phonological priming is absent in word recognition tasks such as lexical decision, but that it occurs when participants are engaged in explicit phonological production such as in the naming task (Shen & Forster, 1999).

Assuming that lexical access requires phonological mediation to a greater extent for Kana than Kanji words, and that subliminal presentation considerably reduces the availability of phonological codes, the observed asymmetries in priming may be explained as follows (Figure 6). First, when primes and targets are written in Kanji, they both activate lexico-semantic codes through an orthography-to-lexicon route. This results in a strong priming effect reflecting shared prime-target activation at orthographic, lexical, and semantic levels. Second, when the prime is in Kanji and the target in Kana, both stimuli activate the lexico-semantic system. Subliminal primes in Kanji activate it through the orthography-to-lexicon route, as in the previous condition. By contrast, visible targets in Kana activate it mainly by way of the phonological route. Because shared lexico-semantic codes are ultimately activated, a large cross-script effect is observed. Third, when the prime is in Kana and the target in Kanji, there is also some shared lexico-semantic activation resulting in a cross-script effect. However, this effect is weaker because of the weakness of the lexical route for Kana, and because this route cannot be compensated by the alternative phonological route when observers are unaware of the Kana stimuli. Fourth, by the same token, the presentation of primes and targets in Kana results in orthographic activation as well as a small amount of lexico-semantic activation, thus resulting in a shallower but still significant form of repetition priming.

This framework allows us to interpret the imaging result that the repetition suppression in the left temporal region, putatively associated with lexico-semantic processing, was significant only when primes were presented in Kanji. Furthermore, assuming that all levels of representations transmit some activation to the response decision stage (Jaskowski, Skalska, & Verleger, 2003; Jaskowski, van der Lubbe, Schlotterbeck, & Verleger, 2002; Schmidt, 2002; Eimer & Schlaghecken, 1998), the model can explain why strong response priming is observed in all conditions of primes, even though Kana primes are assumed to achieve a shallower level of word processing than Kanji primes.

Conclusions

Subliminal repetition priming, when combined with fMRI, provides a powerful method to dissect the levels of representation involved in word processing and their cerebral substrates (Dehaene, Jobert, 2004; Naccache & Dehaene, 2001a). Here, we replicated with Japanese subjects the repetition priming effects previously observed in readers of an alphabetic script (French). This allowed us to demonstrate an additional, abstract level of subliminal priming occurring at the convergence of processing streams for Kanji and Kana scripts, and associated with the left temporal lobe. The present imaging data suggest that distinct cortical subsystems within

the ventral stream contribute to visual word processing according to the decoding procedures required by the orthographic systems used. This serial, posterior-to-anterior axis of the ventral visual system appears to be structured similarly across readers of different orthographies, and is only partially modulated by the specific requirements of each script. The most notable effect is that different scripts put a differential emphasis on phonological versus lexico-semantic routes, as previously suggested by comparisons of brain activations in readers of Italian or English (Paulesu et al., 2000). Taken together, these results begin to dissect the universal organization of posterior reading pathways and their adaptation to specific cultural requirements.

METHODS

Experiment 1

Participants

Sixteen right-handed, native Japanese speakers (age range 25–38 years) volunteered to participate in the present fMRI experiment. None had a previous history of neurological or psychiatric disease. All of them gave written informed consent prior to the imaging experiment. The protocol of this study was approved by the regional ethical committee.

Materials and Procedures

The visual stimuli consisted of 40 Japanese nouns of higher familiarity (mean \pm *SD* = 6.04 \pm 0.32, according to the NTT database; Amano & Kondo, 2000). None of the words had homophones. Half of them represented natural objects (e.g., cat, peach) and the other half artifacts (e.g., telephone, cigarette). These words were composed of one to two characters when written in Kanji (mean orthographic plausibility \pm *SD* = 4.83 \pm 0.17) and two to three characters when written in Kana (mean orthographic plausibility \pm *SD* = 3.76 \pm 0.31) [Here the orthographic plausibility is a 5-point scale provided by the same database indicating the likelihood that a specific script is used for writing a given word. For example, words normally written in Kanji are usually high in plausibility for Kanji but much lower in that for Kana, and vice versa. Importantly, behavioral data by Amano and Kondo (2000) have shown that the response time required for lexical decision does not differ between words written in Kanji (mean plausibility \pm *SD* = 4.84 \pm 0.17) and their transcriptions in Kana (mean plausibility \pm *SD* = 3.28 \pm 0.28), suggesting that normal adults are equally familiarized with the two forms of words when their plausibility level is sufficiently high for each script.]

Each trial consisted of a precisely timed sequence of a masked prime and a visible target (Figure 1). The masks were created by semirandom arrangement of circle and

square shapes with the same line thickness as character fonts, covering up the central area of the screen. Participants were not informed about the presence of prime words. They were requested to decide as quickly and as accurately as possible whether target words denoted natural objects or artifacts. In “unrepeated” trials (i.e., when the prime and target word differed), they always belonged to different categories (one natural and the other artificial) and shared no character in common at the same location. The word length was always the same between the prime and the target in “same script” conditions (on average 3.2° for Kana and 2° for Kanji, respectively), whereas that of Kana forms was longer by one character (\sim 0.8°) in “different script” conditions. The experiment was therefore arranged in a $2 \times 2 \times 2$ factorial design where the main effects of interest were prime–target repetition (same or different word), prime script (Kanji or Kana), and target script (Kanji or Kana). In addition, a ninth type of trials, comprising the same sequence of masks without prime and target words, was used as a baseline to measure the event-related activation with fMRI. Participants performed four experimental sessions, each comprising five initial training trials followed by 200 trials (20 trials for each event type except for the “word-absent” baseline with 40 trials, all in random order).

Immediately after the imaging sessions, participants performed a forced-choice test inside the scanner (64 trials) designed to evaluate the visibility of primes. They were told about the presence of hidden primes at this stage. Each trial comprised the same sequence of masks and words as in the activation task, followed by a pair of choices (a same word as the prime and a distractor) presented left and right of the fixation. Participants were asked to determine which of the two items corresponded to the prime word within the preceding event sequence.

fMRI Procedures

The experiment was conducted using a 3-T whole-body system (Bruker, Germany) using a standard head coil optimized for a gradient-echo–echo-planar imaging sequence (26 contiguous axial slices, thickness 4.5 mm with 0.5 mm gap, TR = 2400 msec, TE = 40 msec, flip angle = 90°, field-of-view = 192 \times 256 mm², 64 \times 64 pixels). High-resolution anatomical images were obtained prior to the main experiment. Four scanning sessions, each lasting 8 min 12 sec and giving 205 volumes, were performed.

Data Analysis

After image reconstruction, the functional images were processed using the SPM99 software (Wellcome Department of Cognitive Neurology, London, UK). Five initial

images were discarded to eliminate nonequilibrium effects of magnetization. Images were corrected for head motion, resampled every 4 mm using sinc interpolation, normalized to the standard brain space (Friston, Ashburner, et al., 1995), and spatially smoothed with an isotropic Gaussian filter (7 mm full width at half maximum). These images were then high-pass filtered at 120 sec and smoothed with a 4-sec Gaussian kernel. Group-based statistical inference was made using a random effect model (Friston, Holmes, & Worsley, 1999). For each participant, a weighted-mean image for each contrast was computed by fitting each voxel time-series with the known time-series of the nine event types convolved with a canonical hemodynamic response function with time and dispersion derivatives. The effect of repetition priming, or repetition suppression, was calculated as activation reduction in repeated trials relative to nonrepeated trials (Henson & Rugg, 2003). Brain activation specific to the script type was examined separately for primes and targets. To discount voxels inactive during reading, we first determined brain regions activated by target words relative to the “word-absent” baseline for Kanji and Kana, respectively (thresholded at voxelwise, $p < .005$). The resulting statistical parametric maps served as a masking image for comparing “target Kanji” with “target Kana” and “prime Kanji” with “prime Kana,” respectively. The two script-specific masks were used separately because it is unknown whether, and to what extent, Kanji and Kana activate overlapping brain regions. Unless stated otherwise, all the effects of interest were tested voxelwise at $p < .005$. Only regions with contiguous clusters of more than five voxels, corresponding to an activated volume of 320 mm³, were interpreted.

Experiment 2

Participants

Twenty-two right-handed Japanese speakers (age range 20–34 years) were recruited. None of them participated in Experiment 1.

Materials and Procedure

Using the same set of words as Experiment 1, 40 prime–target pairs were created for nonrepeated trials so that both of them belonged to the same category, either natural or artificial. Hence, primes were semantically congruent with targets irrespective of whether words were repeated or not. The same stimulus materials and event sequence as Experiment 1 were used. The experimental design was a $2 \times 2 \times 2$ factorial arrangement in which repetition, prime script, and target script were within-participant factors. Participants were seated approximately 50 cm from a computer monitor in a dimmed room and performed a total set of 640 trials

without the word-absent baseline trials, giving 80 trials for each condition.

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The data reported in this experiment have been deposited in the fMRI Data Center (www.fmridc.org). The accession number is 2-2004-1178P.

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