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An ERP investigation of visual word recognition in syllabary scripts

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Abstract The bimodal interactive-activation model has been successfully applied to understanding the neurocognitive processes involved in reading words in alphabetic scripts, as reflected in the modulation of ERP components in masked repetition priming. In order to test the generalizability of this approach, in the present study we examined word recognition in a different writing system, the Japanese syllabary scripts hiragana and katakana. Native Japanese participants were presented with repeated or unrelated pairs of Japanese words in which the prime and target words were both in the same script (within-script priming, Exp. 1) or were in the opposite script (cross-script priming, Exp. 2). As in previous studies with alphabetic scripts, in both experiments the N250 (sublexical processing) and N400 (lexical–semantic processing) components were modulated by priming, although the time course was somewhat delayed. The earlier N/P150 effect (visual feature processing) was present only in "Experiment 1: Within-script priming", in which the prime and target words shared visual features. Overall, the results provide support for the hypothesis that visual word recognition involves a generalizable set of neurocognitive processes that operate in similar manners across different writing systems and languages, as well as pointing to the viability of the bimodal interactive-activation framework for modeling such processes.

Keywords ERP · Priming · Lexical decision

In recent years, much progress has taken place in describing the neurocognitive processes involved in visual word recognition, by a systematic effort to link the modulations of ERP components that have been observed in masked repetition priming with component processes in the bimodal interactive-activation model (BIAM; e.g., Holcomb & Grainger, 2006; see Grainger & Holcomb, 2009, for a review). Most of this research has targeted word recognition in languages that use a single script to express written words, and in most cases this script has been the Roman alphabet; yet, the same general approach should in principle be applicable to different writing systems. Indeed, it could well be the case that the same basic neurocognitive processes are involved in reading words in different scripts. Under this scenario, reading words in different scripts would involve certain script-specific adaptations of the same underlying architecture, such as a modulation of the relative weights given to mapping orthography onto semantics versus phonology. In the present study, we show how the same method and theoretical framework that have been applied to understanding reading in alphabetic scripts can usefully be applied to an investigation of reading in syllabary scripts.

Studies combining masked priming with event-related potential (ERP) recordings have revealed a series of components that are sensitive to prime–target relatedness (see Grainger & Holcomb, 2009, for a review). The most relevant with respect to the present study are the N/P150, N250, and N400 components, which our prior research has shown to reveal robust effects of masked repetition priming (e.g., Grainger & Holcomb, 2009; Holcomb & Grainger, 2006, 2007). Given the precise timing of these three components, it has been argued that they reflect three successive

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processing stages involved in mapping visual features onto meaning during visual word recognition. The N/P150 effect reflects the initial mapping of visual features onto letter representations (in languages that use an alphabetic script). The N250 reflects the mapping of letter-level information onto whole-word-form (orthographic and phonological) representations, and the N400 reflects the subsequent mapping of whole-word representations onto meaning.

This tentative mapping of the masked repetition priming effects seen in different ERP components onto the underlying processes involved in visual word recognition is summarized in Fig. 1, which applies the theoretical framework of the BIAM, which was developed to account for interactions between orthographic and phonological processing during the recognition of printed and spoken words (Grainger, Diependaele, Spinelli, Ferrand, & Farioli, 2003; Grainger & Ferrand, 1994; Grainger & Holcomb, 2009). In the orthographic pathway of the BIAM, a printed word (e.g., CAR) activates a set of visual features that then activates a sublexical orthographic code (e.g., representations of the individual letters C, A, and R). These sublexical orthographic representations then activate their corresponding phonological representations (e.g., the sounds [k], [a], [r]) via the sublexical interface between orthography and phonology. Orthography and phonology also communicate directly at the level of whole-word representations. Once whole-word representations are activated, semantic representations finally receive activation.

To date, the original results of Holcomb and Grainger (2006) have been replicated and extended in many studies using Roman-script languages such as English and French. And while a number of studies have examined ERPs to non-Roman-script languages (e.g., Maurer, Zevin, & McCandliss, 2008; Yum, Holcomb, & Grainger, 2011), as mentioned above, very little work has applied the combination of masked priming and ERP recordings to study word recognition in other writing systems (but see Hoshino, Midgley, Holcomb, & Grainger, 2010). Therefore, the aim of this study was to investigate whether this framework could be more broadly applied to other languages with completely different scripts, such as Japanese.

The Japanese writing system

The Japanese writing system has three different sets of characters, and in any given sentence, all three types of characters often appear together. The most frequently used set of characters is kanji. Kanji are ideographs derived or borrowed from Chinese characters, which represent whole words or parts of words. This study focuses on the other two sets of characters: hiragana and katakana, which are both kana systems in which each character represents one syllable. One interesting attribute of these syllabaries is that they have no ambiguity in the mapping of spelling onto sound. In other words, every hiragana and katakana character corresponds to one sound (mora), regardless of its position in a word.

It is important to note that hiragana and katakana are visually dissimilar (see the examples in Table 1), but since they are phonologically equivalent, it is possible to write any Japanese word in either script. However, each of these systems has distinct conditions of use. Hiragana is used to write words for which there is no kanji transcription and to inflect words, whereas katakana is mainly used to transcribe foreign loan words and to write out onomatopoeia. Therefore, depending on the word, only one script is

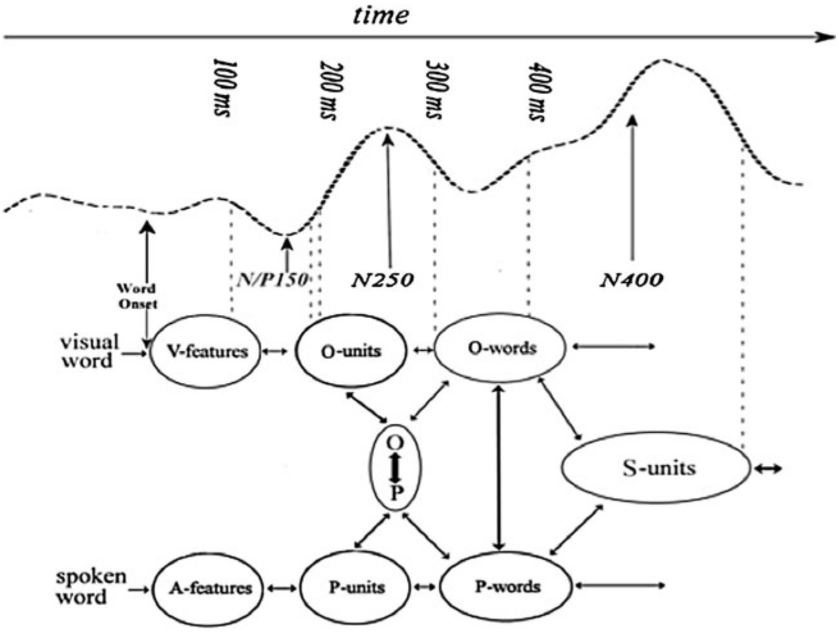

Fig. 1 Event-related potential (ERP) masked repetition-priming effects mapped onto the bimodal interactive-activation model (BIAM). See the main text for details. V, visual; A, auditory; O, orthographic; P, phonological; S, semantic

Table 1 The first five characters of the Japanese syllabary in hiragana (top) and katakana (bottom)

Hiragana	あ	い	う	え	お
Katakana	ア	イ	ウ	エ	オ

visually familiar to native Japanese speakers, which means that the two scripts are typically not interchangeable (although some words can be written in both scripts). Finally, it is also important to note that hiragana occurs more frequently than katakana in written Japanese.

Visual word recognition in Japanese kana

A number of behavioral studies have used the masked-priming paradigm to investigate the processes involved in visual word recognition in Japanese kana (e.g., Perea, Nakatani, & van Leeuwen, 2011; Perea & Pérez, 2009). However, no prior research has combined masked priming with ERP recordings, as in the present study. Although it is clear that processing of words in a logographic script, such as Japanese kanji, necessarily involves processes that are different from those involved in the processing of alphabetic scripts (see Yum et al., 2011, for a recent study comparing Chinese and English) or syllabary scripts (e.g., Bolger, Perfetti, & Schneider, 2005; Iwata, 1984; Sakurai, Yagishita, Goto, Ohtsu, & Mannen, 2006), the extent to which processing in syllabary scripts should differ from processing words in alphabetic scripts is less obvious. However, given the possibility that syllabaries are processed primarily via phonology (e.g., Feldman & Turvey, 1980; Yamada, 1992; Yamada, Mitarai, & Yoshida, 1991), we might expect their word recognition processes to be very different from word recognition with alphabetic scripts, notably in languages like English that have relatively inconsistent mappings between letters and sounds. It is possible that for these shallow orthographies that are closely tied to phonology, readers only use processes akin to the phonological pathway of the BIAM, at least after the initial mapping of visual features onto characters.

As we noted above, the Japanese syllabary scripts were designed to provide an unambiguous link between print and sound, therefore providing a simple route from print to meaning via whole-word phonological representations (note that this contrasts with the large amount of homophony in the kanji writing system, in which direct visual character processing likely dominates the access of meaning from print). This possibility is illustrated in Fig. 2. According to this proposal, the most efficient pathway from print to meaning in Japanese syllabary scripts is from visual (V)-features, to character-based (C)-syllables, to phonological (P)-syllables, to P-words, to semantics (S-units). The hypothesis here is that the role of whole-word character-based representations is diminished in the case of syllabary scripts, as compared with the role of whole-word orthographic representations in alphabetic scripts. The role of whole-word multicharacter representations (C-words) in reading katakana and hiragana words might be further weakened by the fact that the Japanese writing system does not introduce additional spacing to indicate word boundaries.

The present study

In the present study, we test masked repetition priming using two different prime durations (50 and 80 ms) in words written with the katakana and hiragana syllabaries of Japanese. In "Experiment 1: Within-script priming", we examined within-script repetition priming effects, and in "Experiment 2: Cross-script priming", we examined cross-script priming (i.e., the same word written in one script for the prime and the other for the target).

Given the hypothesized similarities in the processing of words in a syllabary script rather than an alphabetic script, we expected to see a qualitatively similar pattern of within-script repetition-priming effects in katakana and hiragana, with respect to what we have previously seen in work with alphabetic scripts. According to the proposed architectures for processing words in these two types of script, described in Figs. 1 and 2, the only difference that might emerge is in terms of the relative weights assigned to the phonological

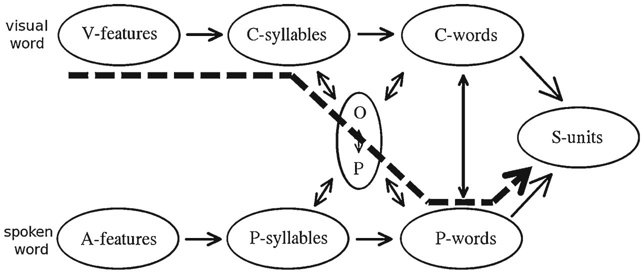

Fig. 2 An adaptation of the BIAM for processing words written in syllabary scripts. The dominant pathway from print to meaning, shown by the dashed arrow, is hypothesized to be via phonological representations. See the main text for details. V, visual; A, auditory; C, character-based; O, orthographic; P, phonological; S, semantic

pathway as opposed to the direct visuo-orthographic pathway in the BIAM. This might have consequences in terms of the relative timings of phonological influences during visual word recognition. We did not expect to see differences between the two Japanese syllabaries themselves in terms of phonological influences on visual word recognition, but it was hypothesized that their different frequencies of usage might impact the direct character-based route to meaning (C-syllables to C-words to meaning). Finally, the cross-script repetition condition tested in "Experiment 2: Cross-script priming" provided a unique means of estimating the time course of phonological processing in the absence of any effects driven by visual or orthographic overlap. Indeed, the primes and targets referred to the same phonological word in the cross-script condition, but were visually distinct (see Table 1 for examples of the characters and Table 3 for examples of the stimuli).

Experiment 1: Within-script priming

ERP-based masked repetition-priming effects of within-script primes on both hiragana and katakana targets were measured in a masked-priming paradigm (i.e., hiragana–hiragana and katakana–katakana repetition priming). In addition to allowing us to make masked ERP priming comparisons in a non-Roman alphabetic language, the present experiment also permitted, for the first time, an examination of the fine-grained time course of word processing in a sound-based script. Previous work in our lab (Grainger, Kiyonaga, & Holcomb, 2006; Kiyonaga, Grainger, Midgley, & Holcomb, 2007) in which the phonological nature of the stimuli was emphasized in Roman-script languages (English and French) had suggested that cross-activation of phonological representations lags behind purely visuo-orthographic priming effects. To the degree that priming effects in hiragana and katakana reflect activation of a phonologically mediated pathway, we would predict a delay in the time course of N250 and N400 priming effects in these scripts. We tested this theory in the present study by also manipulating the duration of the masked primes, employing the traditional 50-ms primes that have been used in most masked-priming studies, as well as a longer, 80-ms prime. If more time with the prime is required to successfully activate a sluggish phonological pathway, then priming in the present study should occur only with the longer-duration primes (i.e., 80 ms). Moreover, in alphabetic languages, high-frequency words have been found to elicit larger and earlier-peaking repetition-priming effects than do low-frequency words (Grainger, Lopez, Eddy, Dufau, & Holcomb, 2012). We might expect to find a similar frequency-like effect between the scripts in the present experiment, since katakana occurs less often than does hiragana in written Japanese.

Method

Participants

A group of 48 (31 female, 17 male; mean age = 24 years, *SD* = 4.46) Japanese speakers residing in Boston, Massachusetts, participated in this experiment. Half of these participants (16 female, eight male; mean age = 24.4 years, *SD* = 4.81) participated in the 50-ms experiment, and the other half (15 female, nine male; mean age = 23.4 years, *SD* = 4.10) participated in the 80-ms experiment. All of the participants were right-handed with normal or corrected-to-normal vision and reported Japanese as their native language. None of them reported a history of language or reading disorders.

Participants self-reported their Japanese language skills on a seven-point Likert scale (1 = *unable*, 7 = *expert*); they reported their abilities to read, speak, and comprehend Japanese, as well as how frequently they read in Japanese (1 = *rarely*, 7 = *very frequently*). The overall average of the self-reported language skill in Japanese was 6.76 (*SD* = 0.8), where reading skill was rated 6.70 (*SD* = 0.82), speaking skill 6.74 (*SD* = 0.84), and comprehension skill 6.85 (*SD* = 0.72). The participants reported their average frequency of reading in Japanese as 5.70 (*SD* = 1.27).

Stimuli

The target stimuli for this experiment were 120 words that were always written in hiragana (*distinctly hiragana* words) and 120 words that were always written in katakana (*distinctly katakana* words). The distinctly hiragana words had a mean frequency of 1,051.71 per million (range 1–30,479), and the distinctly katakana words had a mean frequency of 529.68 per million (range 2–8,842), according to the *Lexical Properties of Japanese* norms (Amano & Kondo, 2003). Imageability ratings were not available for the Japanese words, but we assessed imageability by translating the words to English and then using the MRC Psycholinguistic Database, according to which the English translations did not differ in imageability. All of the words were monomorphemic and ranged from two to five syllables long. See Table 2A for their detailed psycholinguistic characteristics.

The distinctly hiragana target words were used in the within-script hiragana condition (noted hereafter as *HH*), and the distinctly katakana target words were used in the within-script katakana condition (noted hereafter as *KK*). The targets were paired with primes that were either the same word in the same script (repeated condition) or a word that was phonologically, orthographically, morphologically, and semantically unrelated, presented in the same script (unrelated condition). For the purposes of counterbalancing, each participant was presented with one of three lists of prime–target pairings; each list included all four conditions (HH repeated, HH unrelated,

Table 2 Psycholinguistic characteristics of stimuli used in Experiments 1 (A) and 2 (B)

	Hiragana	Katakana
A		
Frequency (range)	1,051.71 (1–30,479)	529.08 (2–8,842)
Imageability (*SD*)	486.32 (67.68)	486.19 (114.91)
Length (*SD*)	3.28 (0.61)	3.78 (0.81)
B		
Frequency (range)	682.54 (16–3,975)	470.74 (37–6,115)
Imageability (*SD*)	443.00 (219.72)	437.28 (207.03)
Length (*SD*)	3.23 (0.73)	3.23 (0.79)

KK repeated, and KK unrelated), with each target word appearing only once. The prime words in the unrelated condition never appeared as targets in the experiment. Most importantly, the prime and target ERPs in the repeated and unrelated conditions were formed from exactly the same physical stimuli across participants, reducing the possibility of ERP effects across conditions due to differences in physical features or lexical properties. Examples of the experimental manipulations are shown in Table 3A.

Task

The task was go/no-go semantic categorization, in which participants were asked to press a button as soon as they saw a probe word naming a human body part displayed on the screen (Holcomb & Grainger, 2006). For all other words, participants were asked to read passively, without responding. Of the total number of targets, 15 % were probe items, half of which were displayed in hiragana and the other half in katakana. A set of ten probes were used in the prime position to measure prime visibility and to provide an objective measure of the effectiveness of the masking procedure. A ten-trial practice session was administered before the main experiment to familiarize the participants with the task (data were not collected during practice).

Procedure

Visual stimuli were presented on a 19-in. monitor with a refresh rate of 100 Hz and located 56 in. in front of the participant. Stimuli were displayed in off-white-colored letters in Mincho font (character matrix 20 pixels wide × 40 pixels tall) on a black background. Each trial began with a fixation cross displayed in the center of the screen for 500 ms. Then, a forward mask composed of seven pseudocharacters replaced the fixation cross for another 500 ms. The pseudocharacters were made of parts of hiragana and katakana characters (see Fig. 3 for an example). The forward mask was then replaced by a prime for either 50 ms (24 participants) or 80 ms (24 participants), which was quickly replaced by the backward mask (same string of pseudocharacters as the forward mask) for 20 ms. The backward mask was then replaced by the target word, which remained on the screen for 300 ms. Target words were followed by a 900-ms blank screen, which was replaced by a stimulus [(− −)] indicating that it was OK to blink, for 2,000 ms.

EEG recording procedure

Participants were seated in a comfortable chair in a sound-attenuated, darkened room. The electroencephalogram (EEG) was recorded from 29 electrodes held in place on the scalp by an elastic cap (Electro-Cap International, Inc., Eaton, OH, USA; see Supplemental Fig. 1). In addition to the 29 scalp sites, additional electrodes were attached below the left eye (to monitor for vertical eye movements/ blinks), to the right of the right eye (to monitor for horizontal eye movements), over the left mastoid bone (reference), and over the right mastoid bone (recorded actively to monitor for differential mastoid activity). All EEG electrode impedances were maintained below 5 kΩ (the impedance for the eye electrodes was less than 10 kΩ). The EEG was amplified by an SA Bioamplifier (San Diego, CA, USA) with a bandpass of 0.01 and 40 Hz, and the EEG was continuously sampled at a rate of 200 Hz throughout the experiment.

Data analysis

Averaged ERPs, time-locked to target onset and rereferenced to the algebraic average of the left and right mastoid electrodes, were formed offline from trials free of ocular and muscular artifacts. An average of 88.5 % (*SD* = 10.1 %) of the trials per participant were used in the analysis and were evenly distributed across conditions. The average percentages of valid trials per condition are listed in Table 4A. The averaged ERPs were low-pass filtered at 15 Hz, and a 100-ms epoch immediately before target onset was used as the baseline. For each participant, four types of targets were formed from the two levels of script (hiragana and katakana) and two levels of repetition (repeated and unrelated). The mean amplitudes of the target ERPs were measured in each of these conditions in epochs identified in previous masked-priming ERP experiments to be sensitive to three qualitatively distinct ERP components (see Grainger & Holcomb, 2009, for a review of the literature making a case for the independence of these ERP effects). These included the N/P150 (90–200 ms), the N250 (240–300 ms), the early portion of the N400 (350–500 ms), and a later portion of the N400 (500–600 ms).

One set of analyses, which focused on the N/P150, included the factors Repetition (repeated vs. unrelated), Script (hiragana vs. katakana), and Prime Duration (50 vs. 80 ms).

Table 3 Examples of experimental stimuli by conditions for Experiments 1 (A) and 2 (B)

		Prime/**Target**	*Prime*/**Target**
A	**Experiment 1: Within-Script**		
Repeated	Script	*H*/**H**	*K*/**K**
	Example	*いのち*/**いのち**	*ズック*/**ズック**
	Translation	*life*/**life**	*shoes*/**shoes**
Unrelated	Script	*H*/**H**	*K*/**K**
	Example	*とけい*/**いのち**	*アニメ*/**シジミ**
	Translation	*clock*/**life**	*anime*/**clam**
B	**Experiment 2: Cross-Script**		
Repeated	Script	*K*/**H**	*H*/**K**
	Example	*ツヅラ*/**つづら**	*へちま*/**ヘチマ**
	Translation	*box*/**box**	*loofah*/**loofah**
Unrelated	Script	*K*/**H**	*H*/**K**
	Example	*トケイ*/**つづら**	*あにめ*/**ヘチマ**
	Translation	*clock*/**box**	*anime*/**clam**

Presentation formats: H, hiragana; K, katakana

Following the precedent of a growing number of studies in which the N/P150 has been examined, we restricted our analyses to the four frontal and posterior sites at which this component has been shown to be largest (FP1/FP2 vs. O1/O2; see, e.g., Chauncey, Holcomb, & Grainger, 2008; Holcomb & Grainger, 2006). Similarly, following a growing number of studies that have used the ERP masked-priming paradigm (e.g., Grainger et al., 2012; Massol, Grainger, Midgley, & Holcomb, 2012) analyses focusing on the N250 and N400 used 15 electrode sites, arranged in three columns and five rows (see Supplemental Fig. 1). This resulted in a three-level Laterality factor (left vs. center vs. right), a five-level Anterior/Posterior factor (frontopolar vs. frontal vs. central vs. parietal vs. occipital), a two-level

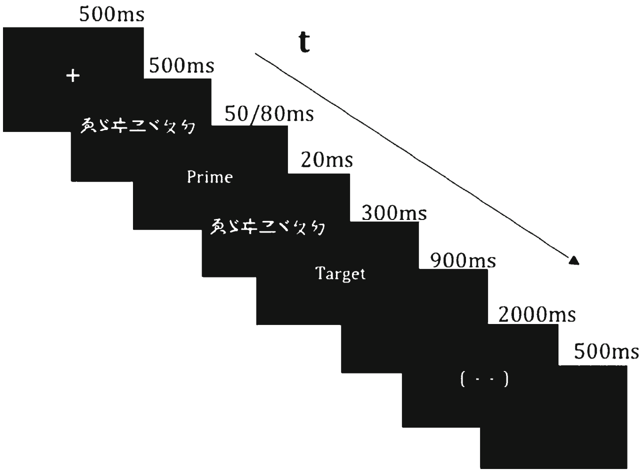

Fig. 3 Schematic of a sample trial

Table 4 Average percentage of valid trials and standard deviations for each condition in Experiments 1 (A) and 2 (B)

	Average %	*SD*
A		
HH repeated	88.33	11.28
HH unrelated	88.48	11.43
KK repeated	88.67	8.55
KK unrelated	88.60	9.34
B		
KH repeated	87.96	9.33
KH unrelated	89.04	9.31
HK repeated	87.80	9.04
HK unrelated	88.81	7.19

HH, hiragana–hiragana condition; KK, katakana–katakana condition

Script factor (hiragana vs. katakana), a two-level Prime Duration factor (50 vs. 80 ms), and a two-level Repetition factor (repeated vs. unrelated). The factors related to distribution and the Script and Repetition factors were all manipulated within subjects, while the Prime Duration factor[1] was between subjects, so a mixed between/within analysis of variance (ANOVA) was used, and the Greenhouse–Geisser correction was applied to all contrasts involving more than 1 *df* in the numerator (Greenhouse & Geisser, 1959).

Results

Behavioral data

Participants detected on average 93 % ($SD = 8.4$ %) of the human body part probes in the target position, but importantly, no participant (in either prime duration condition) pressed to any body part probes in the prime position, nor in a postexperiment debriefing did they report seeing any of the prime words.

Visual inspection of the ERPs

Plotted in Fig. 4A are the ERPs for the repeated and unrelated conditions. These ERPs are collapsed across the Prime Duration and Script factors because those factors did not produce any significant main effects or interactions with the Repetition factor.

Epoch analyses of the ERP data

90- to 200-ms (N/P150) epoch In this epoch, the main effect of repetition was not significant ($p > .34$). However, we found a robust Repetition × Anterior/Posterior interaction [$F(1, 46) = 13.06$, $p < .001$], suggesting that the effects of repetition over the occipital sites resulted in unrelated targets producing more positive-going ERPs than did repeated targets, while at frontopolar sites, the opposite pattern was obtained (i.e., unrelated more negative than repeated; see Fig. 4A [sites FP1/2, O1/2] and Fig. 4B). Importantly, no interactions of the Script or Prime Duration factors with the Repetition factor were revealed (all $ps > .60$).

240- to 350-ms (N250) epoch Between 240 and 350 ms, we found a significant main effect of repetition [$F(1, 46) = 10.09$, $p < .001$], indicating that targets following unrelated primes were more negative-going than were targets that were repetitions of primes. We also found significant Repetition × Anterior/Posterior [$F(4, 184) = 13.53$, $p < .05$] and Repetition × Laterality [$F(2, 92) = 4.71$, $p < .05$] interactions. Inspection of Fig. 4A and C suggests that the effects of repetition were larger over more anterior than more posterior sites, and over midline than more lateral sites. All of the other interactions involving the Repetition factor, including those with prime duration and script type, were not significant (all $ps > .62$).

350- to 500-ms (early N400) epoch Again, effects of repetition emerged in this epoch [$F(1, 46) = 6.08$, $p < .05$], indicating that targets following unrelated primes were more negative-going than were targets that were repetitions of the primes. Significant Repetition × Anterior/Posterior [$F(4, 184) = 8.5$, $p < .001$] and Repetition × Laterality [$F(2, 92) = 5.59$, $p < .01$] interactions also emerged. Inspection of Fig. 4A and C suggests that the effects of repetition were largest over central midline sites. We found no other interactions involving the Repetition factor, and no effects or interactions of the Prime Duration factor (all $ps > .06$).

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[1] We chose to manipulate prime duration between rather than within subjects because of the limited number of items that fit the rest of the design constraints (e.g., words that could be written in both scripts for Exp. 2).

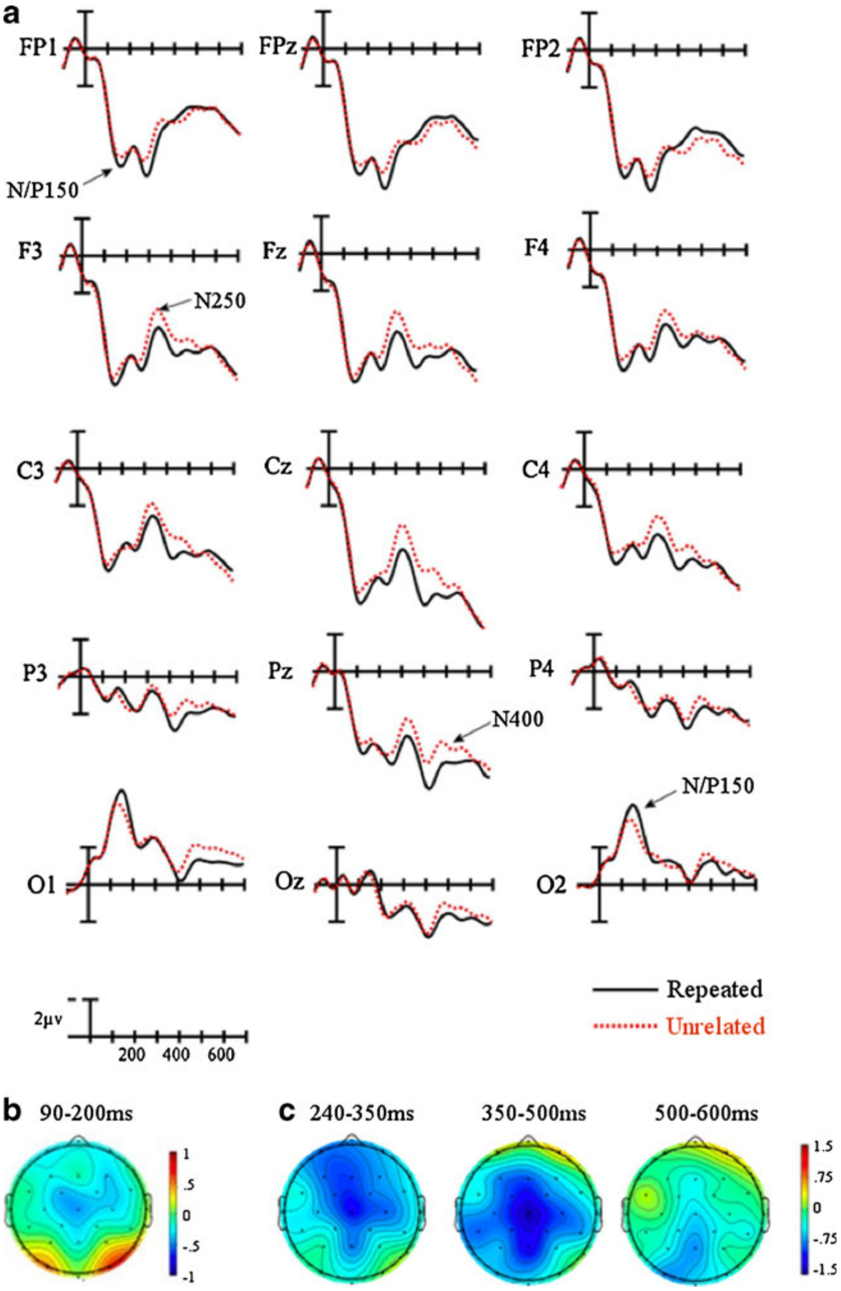

Fig. 4 (A) ERPs from all repeated (solid lines) and unrelated (dotted lines) targets in the within-script experiment at 15 sites collapsed across scripts and prime durations. FP1/2 and O1/2 were the sites used in the N/P150 analysis, and all 15 were used in the N250 and N400 analyses. (B) Voltage map from all scalp sites, based on the average activity of unrelated minus repeated target ERPs averaged across 90–200 ms. Note that, as is typical for the N/P150, the small priming effect peaking near 150 ms is of opposite polarity at anterior and posterior sites. (C) Voltage map from all scalp sites, based on the average activity of unrelated minus repeated target ERPs averaged across the latency ranges indicated. Nondifference voltage maps used to create these difference voltage maps are included in the supplements

500- to 600-ms (late N400) epoch The Repetition × Anterior/Posterior interaction remained significant in the 500- to 600-ms epoch [$F(4, 184) = 2.62$, $p < .05$], but all other effects involving the Repetition and Prime Duration factors were not significant.

Time-course analysis

To get a more fine-grained temporal picture of the priming effects, we supplemented the epoch-based analyses above with a time-course analysis, whereby we compared unrelated to repeated targets in the 16 consecutive 25-ms temporal windows between 200 and 600 ms. These results are reported in Table 5A, where the first clear evidence of priming started in the 250- to 275-ms window, followed by another distinct window of priming that started in the 400- to 425-ms window.

Discussion

Robust masked repetition-priming effects were found in “Experiment 1: Within-script priming” for both hiragana and katakana words. These effects were seen on the same three ERP components that have previously been reported to

Table 5 Time-course analyses of the main effect of repetition priming in "Experiment 1: Within-script priming", within-script priming (A), and "Experiment 2: Cross-script priming", cross-script priming (B)

A. Experiment 1: Within-Script Priming								
Epoch	200–225	225–250	250–275	275–300	300–325	325–350	350–375	375–400
p value			**	***	****	**		
Epoch	400–425	425–450	450–475	475–500	500–525	525–550	550–575	575–600
p value	**	**						
B. Experiment 2: Cross-Script Priming								
Epoch	200–225	225–250	250–275	275–300	300–325	325–350	350–375	375–400
p value			**	**				
Epoch	400–425	425–450	450–475	475–500	500–525	525–550	550–575	575–600
p value				***	*****	*****	*****	****

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .005$. $^{****}p < .001$

be sensitive to masked repetition priming in languages that use the Roman alphabet[2] (e.g., Holcomb & Grainger, 2006).

The somewhat later time courses of the N250 (250–350 vs. 200–300 ms) and N400 (400–450 vs. 350–400 ms) components in "Experiment 1: Within-script priming", as compared with procedurally comparable studies in English and French (e.g., Holcomb & Grainger, 2006; Kiyonaga et al., 2007), is in line with our proposal that visual word recognition in Japanese syllabary scripts (kana) primarily reflects processing along the orthographic–phonological–semantic route of the BIAM (see Fig. 2), where crossing the orthographic–phonological interface is hypothesized to require extra time, resulting in a delay in ERP priming effects. If this is indeed the case, we should observe similar ERP priming effects when the primes and targets are the same word written in a different kana scripts (cross-script priming). On the other hand, the early N/P150 priming effect seen in "Experiment 1: Within-script priming" should not occur in cross-script repetition priming, because the N/P150 effect has been shown to reflect processing at the level of visual features, where the visually similar prime and target pairs during repetition elicit a larger N/P150 than do the dissimilar pairs during unrelated trials (e.g., Chauncey et al., 2008). Therefore, the dissimilarity of the visual features between katakana and hiragana words, even on primed trials, should eliminate any N/P150 activity. These predictions were tested in "Experiment 2: Cross-script priming", in which the same participants from "Experiment 1: Within-script priming" were presented with a new set of Japanese words that could be written in either the katakana or hiragana script.

Experiment 2: Cross-script priming

"Experiment 2: Cross-script priming" was procedurally identical to "Experiment 1: Within-script priming", except that the primes were now in a different script than the targets (katakana–hiragana and hiragana–katakana cross-script priming). If, as suggested above, the ERP masked-priming effects found in "Experiment 1: Within-script priming" were due to processing of Japanese words following an orthographic–phonological–semantic route, then a pattern of N250 and N400 effects similar to those found in "Experiment 1: Within-script priming" should be obtained when priming was tested across the two scripts, given the shared phonological representations. However, to the degree that priming in "Experiment 1: Within-script priming" was mediated by a direct visual route (C-syllables → C-words → S-units in Fig. 2), then the pattern of results in "Experiment 2: Cross-script priming" should differ, given the different orthographic representations across scripts. Furthermore, there should not be a comparable N/P150 priming effect, due to the lack of physical feature overlap between primes and targets presented in the two different scripts (i.e., no V-feature to C-syllable overlap). We might also predict that with only the C-syllable → P-word route being available, this route might result in a more sluggish priming effect than the direct visual route and produce a delay in the N400 priming. Likewise, due to this sluggishness, priming might only occur in the longer prime duration condition, as in the cross-modal masked-priming effect reported by Kiyonaga et al. (2007).

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[2] Although this effect is in keeping with previous studies reporting the N/P150, we quantified it at the sites typically showing the largest such effects (O1/O2 and FP1/FP2). Note, however (Fig. 4B), that the anterior part of the N/P150 effect in this study was actually largest at sites somewhat posterior to the ones we have found in previous studies using Roman scripts (i.e., central and centrofrontal rather than frontopolar). One possible source for this difference is differences in the distributions of low-level visual features (e.g., shape, configuration, and size) between Roman and kana scripts, which might have subtly altered the spatial configurations of the underlying neural sources of the effect.

Method

Participants

The same 48 participants who participated in "Experiment 1: Within-script priming" also served in this experiment.

Stimuli

The target stimuli for this experiment were 120 words that could be written in either script but were more frequently written in hiragana and 120 words that could be written in either script but were more frequently written in katakana. The typically hiragana words had a mean frequency of 682.54 (range 16–3,975), and the typically katakana words had a mean frequency of 470.74 (range 37–6,115), according to the *Lexical Properties of Japanese* norms (Amano & Kondo, 2003). All of the words were monomorphemic, two to five syllables long, and matched for imageability (see Table 2B for their detailed psycholinguistic characteristics). The typically hiragana target words were used in the cross-script hiragana condition (noted hereafter as KH), and the typically katakana target words were used in the cross-script katakana condition (noted hereafter as HK). Of the total number of targets, 15 % were probe items that were human body parts, half of which were displayed in hiragana and the other half in katakana. A set of ten probes were used in the prime position, to detect prime visibility and provide an objective measure of the effectiveness of the masking procedure.

Each of the target words was paired with a prime in a different script. These primes either referred to the same phonological realization as the target (cross-script repetition condition) or were phonologically and lexically unrelated to the target (unrelated condition). For the purposes of counterbalancing, each participant was presented with one of three lists of prime–target pairings; each list included all four conditions (KH repeated, KH unrelated, HK repeated, and HK unrelated), with each target word appearing only once. Most importantly, the prime and target ERPs in the cross-script related and unrelated conditions were formed from exactly the same physical stimuli across participants, reducing the possibility of ERP effects across conditions due to differences in physical features or lexical properties. Examples of the experimental manipulations are shown in Table 3B.

Task and procedure

The task and procedure were the same as in "Experiment 1: Within-script priming".

Data analysis

An average of 88.4 % (*SD* = 8.7 %) of the trials per participant were used in the analysis, and these were evenly distributed across conditions. The percentages of valid trials per condition are listed in Table 4B. The same approach to data analysis as in "Experiment 1: Within-script priming" was used for "Experiment 2: Cross-script priming".

Results

Behavioral data

The participants detected on average 94 % (*SD* = 7.5 %) of the human body part probes in the target position, but no participant pressed to any body part probes in the prime position. Also, no participant reported seeing any prime words during a postexperiment debriefing.

Visual inspection of the ERPs

The ERPs time-locked to the targets for the cross-script related and unrelated priming conditions are plotted in Fig. 5.

Epoch analyses of the ERP data

90- to 200-ms (N/P150) epoch In this epoch, an ANOVA did not reveal a significant main effect of repetition [$F(1, 46) = 0.06$, $p = .81$], nor any interactions of repetition with any other variable (all *ps* > .26; see Fig. 4A [sites FP1/2, O1/2] and Fig. 4B).

240- to 350-ms (N250) epoch An omnibus ANOVA on the mean amplitudes in this epoch showed a trend toward a main effect of repetition [$F(1, 46) = 3.21$ $p = .08$] and a significant Repetition × Anterior/Posterior interaction [$F(4, 184) = 3.12$ $p < .05$]. Inspection of Fig. 5B and C suggests that this interaction was due to a larger effect of repetition over more frontal sites. All other interactions involving the Repetition factor, including those with prime duration, were not significant (all *ps* > .22).

350- to 500-ms (late N250/early N400) epoch While we did not find a significant main effect of repetition ($p = .12$) in this epoch, a significant Repetition × Anterior/Posterior interaction was revealed [$F(4, 184) = 4.54$ $p < .005$]. Examination of the ERPs in Fig. 5B and C suggests that the effects of repetition were larger over more central regions. This priming effect did not interact with script or prime duration (all *ps* > .15).

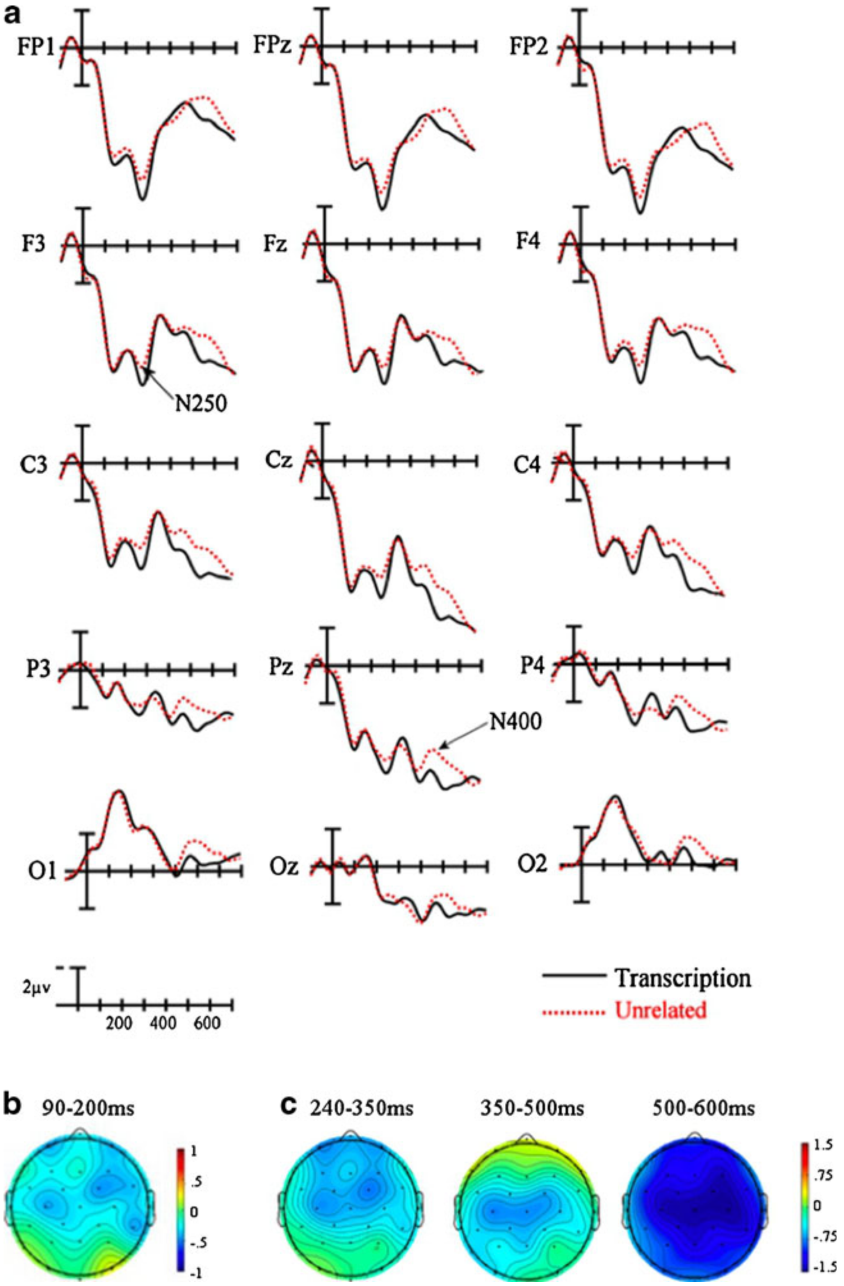

Fig. 5 (A) ERPs from all repeated (solid lines) and unrelated (dotted lines) targets in the cross-script experiment at 15 sites collapsed across scripts and prime durations. FP1/2 and O1/2 were the sites used in the N/P150 analysis, and all 15 were used in the N250 and N400 analyses. (B) Voltage map from all scalp sites, based on the average activity of unrelated minus repeated target ERPs averaged across 90–200 ms. Note that the small priming effect peaking near 150 ms seen in the ERPs in Fig. 4B is not present at the occipital sites in this figure. (C) Voltage map from all scalp sites, based on the average activity of unrelated minus repeated target ERPs averaged across the latency ranges indicated. Nondifference voltage maps used to create these difference voltage maps are included in the supplements

500- to 600-ms (late N400) epoch A main effect of repetition emerged in this epoch [$F(1, 46) = 17.57$ $p < .001$], indicating that targets following unrelated primes were much more negative-going than targets that were repetitions of primes (see Fig. 5B and C). All other interactions in this epoch involving the Repetition factor did not reach significance (all $ps > .1$).

Time-course analysis

As in "Experiment 1: Within-script priming", to get a more fine-grained temporal picture of the priming effects, we also ran a time-course analysis by comparing ERPs in the unrelated and related conditions in the 16 consecutive 25-ms temporal windows between 200 and 600 ms. These results are reported in Table 5B.

Discussion

"Experiment 2: Cross-script priming" revealed a pattern of cross-script priming that was quite similar to what had been observed in the within-script conditions of "Experiment 1: Within-script priming", with the exception of the absence of a significant N/P150 effect. The latter finding was to be expected under the hypothesis that the N/P150 effect reflects the mapping of visual features onto characters when reading katakana and hiragana words. In the cross-script priming conditions of "Experiment 2: Cross-script priming", the primes and targets were written with physically different characters in the repetition condition (see note 1). On the other hand, priming effects on the N250 and N400 components in "Experiment 2: Cross-script priming" showed the same overall pattern as in "Experiment 1: Within-script priming". This suggests that much of the priming seen on the same components in "Experiment 1: Within-script priming" was driven by phonological and semantic overlap in the repetition condition, rather than by orthographic overlap. It is important to note, however, that priming effects on the N250 component were topographically less widely distributed in "Experiment 2: Cross-script priming" than in "Experiment 1: Within-script priming", with the effects appearing mostly at frontal electrode sites (cf. Fig. 4B and C with Fig. 5B and C). Furthermore, these figures suggest that the bulk of N400 priming effects emerged later in "Experiment 2: Cross-script priming" than in "Experiment 1: Within-script priming" (cf. also Table 5A and B). This pattern fits with the idea that some of the priming effects on the N250 and N400 components seen in "Experiment 1: Within-script priming" were being driven by orthographic overlap in the repetition condition, which was absent in "Experiment 2: Cross-script priming".

General discussion

In the present study, we examined within-script and between-script priming with words written in the two syllabary scripts of Japanese kana (hiragana and katakana) using the masked-priming paradigm and ERP recordings. As such, the present study provides the first investigation of word recognition with syllabary scripts, using a methodology that has provided important information about the time course of neurocognitive processes in word recognition in languages that use the Roman alphabet (see Grainger & Holcomb, 2009, for review). In particular, this prior research has enabled a tentative mapping of a set of component processes onto priming effects seen in the ERP waveforms at different moments in time during visual word recognition. These component processes are described within the general framework of a bimodal interactive-activation model (BIAM) of word recognition (see Fig. 1). In the present study, we proposed an account of word recognition in Japanese kana using the theoretical framework of the BIAM (see Fig. 2), and we put this proposal to the test in two experiments. In what follows, we will first discuss the within-script priming effects seen in "Experiment 1: Within-script priming", before discussing the implications of the cross-script priming effects of "Experiment 2: Cross-script priming". The implications with respect to the specific framework of the BIAM will be discussed, as well as the more general implications with respect to reading in a syllabary script.

Masked repetition priming in a syllabary script

On the basis of our prior work combining masked priming and ERPs (e.g., Grainger & Holcomb, 2009; Holcomb & Grainger, 2006; Midgley, Holcomb, & Grainger, 2009) we expected to observe within-script repetition effects on the N/P150 component—thought to reflect the mapping of visual features onto parts of words such as letters or characters—as well as on the N250 component—thought to reflect sublexical orthographic and phonological processing—and the N400 component—thought to reflect the mapping of form representations onto meaning. The key question was whether or not the pattern of priming effects seen on these components with words written in Japanese kana would resemble the pattern seen in prior work testing words in English and French. This would provide some indication as to the extent to which the processes involved in word recognition in a syllabary script are comparable to the processes involved in word recognition in an alphabetic script.

The results of "Experiment 1: Within-script priming" revealed a pattern of priming effects on the N/P150, N250, and N400 components that indeed resembled effects seen in our prior work on word recognition in English and French. Robust priming effects were found on all three components for both katakana and hiragana scripts. This suggests that there is likely to be considerable overlap between the processes involved in reading words in Japanese kana and those involved in reading words written in Roman script. One possible difference with respect to the prior findings was that the time courses of the N250 and N400 components were slightly later in the present study. This could be due to the relatively greater use of phonological information when processing words written in a syllabary script, given that these scripts were specifically designed to facilitate such phonological processing. In line with this reasoning, it is important to note that the timing and topographical distribution of the within-script N250 priming effect were similar to those of the phonological priming effect reported by Grainger et al. (2006) and obtained using a comparable methodology.

Furthermore, although we expected to see differences in the time courses of effects between scripts (hiragana vs. katakana) due to differences in the frequencies of occurrence of the scripts in the language, we found no evidence of such effects in either experiment. It is difficult to draw strong conclusions for such null effects, but it is tempting to speculate that at least in this type of priming paradigm, the two scripts are processed very similarly. This conclusion is in line with some prior research in which hiragana and katakana have been compared. For example, Hatta and Ogawa (1983) looked at facilitation effects in a repetition paradigm and concluded that while the lexical representations of the two scripts may not entirely overlap, they seem to share many common processing aspects and to produce very similar priming effects. Similarly, in an fMRI study, Ino, Nakai, Azuma, Kimura, and Fukuyama (2009) found no neural activation differences during the processing of hiragana and katakana in reading-aloud and word recognition tasks.

More directly related to the present work is the ERP study of Maurer et al. (2008), in which they examined N170 effects during word recognition in Japanese kanji, katakana, and hiragana scripts. These authors found a left-lateralized N170 in all three Japanese scripts. Most important is that N170 amplitude was modulated by familiarity with the script, but not by familiarity with particular combinations of the characters forming words. This finding is therefore in line with the absence of any difference in priming effects for the familiar hiragana words as compared with the relatively unfamiliar katakana words in the present study, and points once again to the predominant role for phonology in reading words in syllabary scripts.

Cross-script priming

In "Experiment 2: Cross-script priming" of the present study, we tested cross-script priming in the same conditions as in "Experiment 1: Within-script priming", and with the same participants. This provided the opportunity for examining effects of shared phonology and semantics in the absence of any visual or orthographic overlap, thus permitting further insights into precisely which factors modulate priming effects on the ERP components known to be sensitive to masked repetition priming. This experiment revealed significant priming effects on the N250 and N400 components, and no priming on the N/P150 component.[3] The latter finding provides further support for the hypothesis that the N/P150 reflects the mapping of visual features onto sublexical orthographic representations during visual word recognition (Holcomb & Grainger, 2006, 2007; Kiyonaga et al., 2007), and the mapping of visual features onto object parts in general (Eddy, Schmid, & Holcomb, 2006; Petit, Midgley, Holcomb, & Grainger, 2006).

The fact that the N250 component was modulated by cross-script priming suggests that this component is sensitive to processing beyond a purely visual or orthographic code, and is in line with the hypothesis that the N250 also reflects sublexical phonological processing (Grainger et al., 2006). Consistent with this argument, and with the results of Grainger et al. (2006), is what appears to be a more anterior distribution of the N250 cross-script priming effect, as compared with the within-script priming effect. This can be shown statistically by contrasting the anterior–posterior distributions of N250 priming effects for the two experiments. While we found clear priming effects at both anterior [FPz, $t(47) = 3.36$, $p < .0008$] and posterior [Pz, $t(47) = 2.56$, $p < .007$] sites in the within-script experiment, only the anterior site revealed priming effects in the between-script experiment [FPz, $t(47) = 1.9$, $p = .032$; Pz, $p > .43$]. A straightforward explanation of this pattern is that the effects seen in "Experiment 1: Within-script priming" were being driven by both orthographic and phonological overlap, whereas the effects seen in "Experiment 2: Cross-script priming" were more limited in distribution, since only phonological prime–target overlap was having an influence there. This provides an estimate of the time course of activation of sublexical phonological codes in masked repetition priming with Japanese kana that is perfectly in line with the estimate provided by Grainger et al. (2006) for English—that is, around 300-ms post-target-onset.

Significant cross-script repetition priming emerged in the N400 component, although these effects appeared to peak later than the within-script priming effects. Indeed, while we found a main effect of repetition in the early N400 window (350–500 ms) in "Experiment 1: Within-script priming", this effect only emerged in the late N400 window (500–600 ms) in the cross-script priming conditions of "Experiment 2: Cross-script priming". In line with our explanation of the priming effects seen in the N250 component, this points to a combination of orthographic and phonological prime–target overlap leading to faster activation of semantic representations when primes and targets are in the same script.

Finally, the cross-script priming effects of the present study were obtained independently of prime duration (50 and 80 ms). This contrasts with the pattern of cross-modal (visual prime–auditory target) repetition priming reported by Kiyonaga et al. (2007), in which priming effects were only found at the longer prime duration (67 ms), and not at the shorter prime duration (50 ms) tested in that study. This suggests that the computation of phonology from orthography might be more efficient in syllabary scripts than in alphabetic scripts (Kiyonaga et al.'s, 2007, study used French words), thus enabling priming effects to emerge with shorter prime durations in the present study. In order to further clarify these issues, our future work will investigate cross-modal priming in Japanese, with visual katakana and hiragana primes and auditory targets.

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[3] Because this conclusion is partially based on a null effect in "Experiment 2: Cross-script priming", we conducted a further analysis contrasting the within- and between-script data in the N/P150 epoch by adding the factor Experiment. As expected, this yielded an interaction involving the Experiment and Repetition factors ($p < .026$), which is consistent with the conclusion that this component was only sensitive to priming in "Experiment 1: Within-script priming".

Conclusions

The results of the present study show that processing words in a syllabary script can be understood in terms of the same basic mechanisms thought to be involved in word recognition in alphabetic scripts. Interpreting our results using the theoretical framework for processing Japanese kana that we proposed in the introduction (see Fig. 2), it would appear that both the orthographic and phonological routes of the BIAM are involved in processing words written in a syllabary script. The only difference with respect to visual word recognition in an alphabetic script would be in terms of the relative weights assigned to each of these two routes, with more weight assigned to phonological processing in a syllabary script. Of course, the BIAM represents one possible implementation of a generic dual-route approach to visual word recognition that draws a distinction between the direct mapping of orthography onto semantics and the indirect mapping of orthography onto semantics via phonological representations (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Perry, Ziegler, & Zorzi, 2007). Our conclusions therefore also hold for this generic approach, with the idea that the relative weights assigned to the direct and indirect pathways would vary as a function of script. The precise nature of the mappings from orthography to meaning and from orthography to phonology varies across scripts, and this likely determines the relative efficiency of each processing route.

Put even more generally, reading, whatever the language or script, is both a linguistic skill, building on prior knowledge of spoken language, and a visual skill, building on prior competence in visual object processing. The BIAM provides one particular instantiation of this general approach that has been successfully applied to understanding the basic mechanisms involved in reading alphabetic scripts. The present study highlights the potential for this framework to provide a general understanding of the neurocognitive processes involved in reading words in different languages. It will be important in future studies to test this conclusion further by examining additional language/writing systems that exploit other visual, orthographic, and lexical properties.

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