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An ERP Investigation of Visual Word Recognition in Syllabary Scripts

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Abstract

The bi-modal interactive-activation model has been successfully applied to understanding the neuro-cognitive 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, the current study 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 where the prime and target words were both in the same script (within-script priming, Experiment 1) or were in the opposite script (cross-script priming, Experiment 2). As in previous studies with alphabetic scripts, in both experiments the N250 (sub-lexical 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 where prime and target words shared visual features. Overall, the results provide support for the hypothesis that visual word recognition involves a generalizable set of neuro-cognitive processes that operate in a similar manner across different writing systems and languages, as well as pointing to the viability of the bi-modal interactive activation framework for modeling such processes.

Keywords

erp; priming; lexical

In recent years, much progress in describing the neuro-cognitive processes involved in visual word recognition has been made by a systematic effort to link modulations of ERP components observed in masked repetition priming with component processes in the bi-modal interactive activation model (e.g., Holcomb & Grainger, 2006; see Grainger & Holcomb, 2009, for 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 being 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 neuro-cognitive 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 weight given to mapping orthography onto semantics versus the mapping of orthography onto phonology. In the present study we show how the same method and theoretical framework applied to

understanding reading in alphabetic scripts can be usefully applied to an investigation of reading in syllabary scripts.

Studies combining masked priming with 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 current 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., Holcomb & Grainger, 2006; 2007; Grainger & Holcomb, 2009). Given the precise timing of these three components, it is argued that they reflect three successive 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 would reflect the mapping of letter-level information onto whole-word form (orthographic and phonological) representations, and the N400 would reflect the subsequent mapping of whole-word representations onto meaning.

This tentative mapping of masked repetition priming effects seen in different ERP components onto underlying processes involved in visual word recognition is summarized in Figure 1, which applies the theoretical framework of the bi-modal interactive activation model (BIAM) developed to account for interactions between orthographic and phonological processing during the recognition of printed and spoken words (Grainger & Ferrand, 1994; Grainger, Diependaele, Spinelli, Ferrand, & Farioli, 2003; Grainger & Holcomb, 2009). In the orthographic pathway of the BIAM, a printed word (e.g., CAR) activates a set of visual features which 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 representation (e.g., the sounds k, ä, 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, Midgely, Holcomb, & Grainger, 2010). Therefore, the aim of this study was to investigate whether this framework could be more broadly applied to other languages with a completely different script, such as Japanese.

The Japanese writing system

The Japanese writing system has three different sets of characters, and in any given sentence all three 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 where 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 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 have 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 visually familiar to native Japanese speakers, which means that the two scripts are typically not interchangeable (although in some cases there are words that can be written in both scripts). Finally, it is also important to note that Hiragana occurs more frequently in written Japanese compared to Katakana.

Visual word recognition in Japanese Kana

There are a number of behavioral studies that have used the masked priming paradigm to investigate the processes involved in visual word recognition in Japanese Kana (e.g., Perea & Perez, 2008; Perea, Nakatani, & van Leeuwen, 2011). 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 than 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, Mitarai, & Yoshida, 1991; Yamada, 1992), we might expect word recognition processes to be very different compared with word recognition in alphabetic scripts, and 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 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, where direct visual character processing likely dominates the access of meaning from print). This possibility is illustrated in Figure 2. According to this proposal, the most efficient pathway from print to meaning in Japanese syllabary scripts is from V-features to C-syllables (i.e., character-based syllables) to P-syllables to P-words to semantics. The hypothesis here is that the role of whole-word character-based representations is diminished in the case of syllabary scripts compared with the role of whole-word orthographic representations in alphabetic scripts. The role of whole-word multi-character 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 (50ms and 80ms) in words written with the Katakana and Hiragana syllabaries of Japanese. In Experiment 1 we examined within-script repetition priming effects, and in Experiment 2 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 compared with words written in 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 Figures 1 and 2, the only difference that might emerge is in terms of the relative weight assigned to the phonological pathway as opposed to the direct visuo-orthographic pathway in the BIAM. This might have consequences in terms of the relative timing 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 frequency of usage might impact on the direct character-based route to meaning (C-syllables to C-words to meaning). Finally, the cross-script repetition condition tested in Experiment 2 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, primes and targets referred to the same phonological word in the cross-script condition, but were visually distinct (see Table 1 for examples of characters and Table 3 for examples of stimuli).

EXPERIMENT 1: Within- script priming

ERP 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 alphabet language, the current 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 (Kiyonaga, Grainger, Midgley, & Holcomb, 2007; Grainger, Kiyonaga, & Holcomb, 2006) where the phonological nature of the stimuli was emphasized in Roman script languages (English and French) has suggested that cross-activation of phonological representations lags behind purely visuo-orthographic priming effects. To the degree that priming 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 in the current study by also manipulating the duration of the masked primes, employing the traditional 50 ms primes 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 current study should occur only with 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 low-frequency words (Grainger, Lopez, Eddy, Dufau, & Holcomb, 2012). We might expect a similar frequency-like effect between scripts in the current experiment since Katakana occur less often than Hiragana in written Japanese.

Methods

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

Participants self-reported their Japanese language skills on a seven-point Likert scale (1 = unable; 7 = expert), participants 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 self-reported language skill in Japanese was 6.76 (SD = 0.8), where reading skill was 6.70 (SD = 0.82), speaking skill was 6.74 (SD = 0.84) and comprehension

skill was 6.85 ($SD = 0.72$). 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 1051.71 per million (range 1-30479) 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* (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 words were monomorphemic and ranged from 2 to 5 syllables. See Table 2A for detailed psycholinguistic characteristics.

The distinctly Hiragana target words were used in the within-script Hiragana condition (further noted as HH) and the distinctly Katakana target words were used in the within-script Katakana condition (further noted 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 word in the same script (unrelated condition). For 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, KK repeated, and KK unrelated) with each target word appearing only once. Prime words in the unrelated condition never appeared as the target 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 a go/no-go semantic categorization, where participants were asked to press a button as soon as they saw a probe word naming human body part displayed on the screen (Holcomb & Grainger, 2006). For all other words, participants were asked to read passively without responding. 15% of the total targets were probe items, half of which were displayed in Hiragana and the other half in Katakana. A set of 10 probes were used in the prime position to measure prime visibility and provide an objective measure of the effectiveness of the masking procedure. A 10 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 100Hz and located 56 inches in front of the participant. Stimuli were displayed in off-white colored letters in Mincho font (character matrix 20 pixels wide $\times$ 40 pixels tall) on a black background. Each trial began with a fixation cross displayed in the center of the screen for 500ms. Then a forward mask comprised of seven pseudo characters replaced the fixation cross for another 500ms. The pseudo characters were made of parts of Hiragana and Katakana characters (see Figure 3 for an example). The forward mask was then replaced by a prime for either 50ms (24 participants) or 80 ms (24 participants), which was quickly replaced by the backward mask (same string of pseudo characters as the forward mask) for 20ms. The backward mask was then replaced by the target word which remained on the screen for 300ms. Target words were followed by a 900ms blank screen which was replaced by a stimulus [(- -)] indicating that it was OK to blink for 2000ms.

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, USAF. see Supplemental Figure 1). In addition to the 29 scalp sites, additional electrodes were attached to below the left eye (to monitor for vertical eye movement/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 k (impedance for eye electrodes was less than 10 k). 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 re-referenced to the algebraic average of the left and right mastoid electrodes were formed off-line from trials free of ocular and muscular artifact. An average of 88.5% (SD=10.1%) of 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 lowpass filtered at 15Hz and a 100ms 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 amplitude of 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 and 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 (240-300ms), the early portion of the N400 (350-500ms) and a later portion of the N400 (500-600ms).

One set of analyses, which focused on the N/P150, included factors of Repetition (repeated vs. unrelated), Script (Hiragana vs. Katakana) and Prime duration (50 ms. vs. 80 ms.). Following the precedent of a growing number of studies examining the N/P150, we restricted our analyses to the four frontal and posterior sites where this component has been shown to be largest (FP1/FP2 vs. O1/O2 – e.g., Holcomb & Grainger, 2006; Chauncey, Holcomb, & Grainger, 2008). Similarly, following a growing number of studies using 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 Figure 1). This resulted in a three level Laterality factor (left vs. center vs. right) five level Anterior/Posterior factor (frontopolar vs. frontal vs. central vs. parietal vs. occipital), two level Script factor (Hiragana vs. Katakana), two level Prime duration factor (50ms vs. 80ms), and two level Repetition factor (repeated vs. unrelated). The distribution, script and repetition factors were all within-subject while the prime duration factor¹ was between subjects so a mixed between/within ANOVA was used and the Geisser-Greenhouse correction was applied to all contrasts involving more than 1 df in the numerator (Geisser & Greenhouse, 1959).

Results

Behavioral Data—Participants detected on average 93% (SD=8.4%) of 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 post experiment debriefing did they report seeing any of the prime words.

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

Visual inspection of ERPs—Plotted in Figure 4A are the ERPs for the repeated and unrelated conditions. These ERPs are collapsed across the prime duration and script factors because they did not produce any significant main effects or interactions with the repetition factor.

Epoch Analyses of ERP Data

90-200 ms (N/P150) epoch: In this epoch the main effect of repetition was not significant ($p > 0.34$). However, there was a robust Repetition $\times$ 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 repeated targets, while at frontal-polar sites the opposite pattern was obtained (unrelated were more negative than repeated -- see Figure 4A sites FP1/2, O1/2 and Figure 4B). Importantly, there were no interactions involving the Script or Prime duration factors with the Repetition factor (all $ps > .60$).

240 to 350 ms (N250) epoch: Between 240 and 350ms, there was a significant main effect of Repetition ($F(1, 46) 10.09, p < .001$) indicating that targets following unrelated primes were more negative going than targets that were repetitions of primes. There were also significant Repetition $\times$ Anterior/Posterior ($F(4, 184) 13.53, p < .05$) and Repetition $\times$ Laterality interactions ($F(2, 92) 4.71, p < .05$). Inspection of Figures 4A and 4C suggests that the effects of repetition were larger over more anterior sites than over more posterior sites and over midline than more lateral sites. All other effects involving the Repetition factor including Prime Duration and Script Type were not significant (all $ps > .62$).

350 to 500 ms (early N400) epoch: There were again effects of Repetition in this epoch ($F(1, 46) 6.08, p < .05$) indicating that targets following unrelated primes were more negative going than targets that were repetitions of primes. There were also significant Repetition $\times$ Anterior/Posterior ($F(4, 184) 8.5, p < .001$), and Repetition $\times$ Laterality interactions ($F(2, 92) 5.59, p < .01$). Inspection of Figures 4A and 4C suggests that the effects of repetition were largest over central midline sites. There were no other effects involving the Repetition factor and no effects of the Prime Duration factor (all $ps > .06$).

500 to 600 ms (late N400) epoch: The Repetition $\times$ Anterior/Posterior interaction remained significant in the 500-600ms epoch as well ($F(4, 184) 2.62, p < .05$), however 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 above epoch based analyses with a time course analysis whereby we compared unrelated to repeated targets in 16 consecutive 25ms temporal windows between 200 and 600ms. These results are reported in Table 5A where the first clear evidence of priming started in the 250-275ms window followed by another distinct window of priming that started in the 400-425ms window.

Discussion

Robust masked repetition priming effects were found in Experiment 1 for both Hiragana and Katakana words. These effects were seen on the same three ERP components that have previously been reported to be sensitive to masked repetition priming in languages that use the Roman alphabet² (e.g., Holcomb & Grainger, 2006).

The somewhat later time course of the N250 (250-350 ms vs. 200-300 ms) and N400 (400-450 vs. 350-400) components in Experiment 1 compared with procedurally comparable studies in English and French (e.g., Kiyonaga et al., 2007; Holcomb & Grainger, 2006) 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 Figure 2) where crossing the O-P interface is hypothesized to require extra time resulting in a delay in ERP priming effects. If this is indeed the case, then we should observe similar ERP priming effects when primes and targets are the same word written in a different kana script (cross-script priming). On the other hand, the early N/P150 priming effect seen in Experiment 1 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 the dissimilar pairs during unrelated trials (e.g., Chauncey et al, 2008). Therefore the dissimilarity of visual features between Katakana and Hiragana words even on primed trials should eliminate any N/P150 activity. These predictions were tested in Experiment 2 where the same participants as Experiment 1 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 was procedurally identical to Experiment 1 except primes were now in a different script than the target (Katakana-Hiragana and Hiragana-Katakana cross-script priming). If, as suggested above, the ERP masked priming effects found in Experiment 1 were due to processing of Japanese words following an orthographic-phonological-semantic route, then a similar pattern of N250 and N400 effects to those found in Experiment 1 should be obtained when priming is tested across the two scripts given the shared phonological representations. However, to the degree that priming in Experiment 1 was mediated by a direct visual route (C-Syllables > C-Words > S-units in Figure 2), then the pattern of results in Experiment 2 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 at the longer prime duration condition as in the cross-modal masked priming effect reported by Kiyonaga et al., (2007).

Methods

Participants—The same 48 participants who participated in Experiment 1 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 (typically Hiragana words) and 120 words that could be written in either script but were more frequently written in Katakana (typically Katakana words). 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* (Amano & Kondo, 2003). All words were monomorphemic, 2 to 5 syllables, and matched for imageability (See

²Although in keeping with previous studies reporting the N/P150 we quantified this effect at the sites typically showing the largest such effects (O1/O2 and FP1/FP2). Note however (Figure 4B) that the anterior part of the N/P150 effect in this study was actually largest at sites somewhat posterior to what we have found in previous studies using roman scripts (i.e., central and centro-frontal rather than fronto-polar). One possibility for this are differences in the distribution of low-level visual features (e.g., shape, configuration and size) between Roman and Kana scripts which might have subtly altered the spatial configuration of underlying neural sources of the effect.

Table 2B for detailed psycholinguistic characteristics). 15% of the total targets were probe items that were human body parts, half of which were displayed in Hiragana and the other half in Katakana. A set of 10 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 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 was the same as Experiment 1.

Data analysis—An average of 88.4% (SD=8.7%) of trials per participant were used in the analysis and were evenly distributed across conditions. The percentages of valid trials per condition are listed in Table 4B. The same approach to data analysis as Experiment 1 was used for Experiment 2.

Results

Behavioral Data—Participants detected on average 94% (SD=7.5%) of 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 post experiment debriefing

Visual inspection of ERPs—The ERPs time locked to targets for the cross-script related and unrelated priming conditions are plotted in Figure 5.

Epoch Analyses of ERP Data

90 to 200ms (N/P150) epoch: In this epoch, an ANOVA did not reveal a significant main effect of Repetition ($F(1, 46)=0.06$, $p=0.81$) nor interactions of Repetition with any other variable (all $ps > .26$ – see Figure 4A sites FP1/2, O1/2 and Figure 4B).

240 to 350ms (N250) epoch: An omnibus ANOVA on the mean amplitudes in this epoch showed a trend in the main effect of Repetition ($F(1, 46)=3.21$ $P=.08$) and a significant Repetition $\times$ Ant/Post interaction ($F(4, 184)=3.12$ $p < .05$). Inspection of Figures 5B and 5C suggests that this interaction was due to a larger effect of Repetition over more frontal sites. All other effects involving the Repetition factor, including Prime Duration, were not significant (all $ps > .22$).

350 to 500ms (late N250/early N400) epoch: While there was not a significant main effect of Repetition ($p=0.12$) in this epoch, there was a significant Repetition $\times$ Anterior/Posterior interaction ($F(4, 184)=4.54$ $p < .005$). Examination of the ERPs in Figures 5B and 5C suggests that the effects of repetition were larger over more central regions. This priming effect did not interact with Script or Prime Duration (all $ps > 0.15$).

500 to 600ms (late N400) epoch: There was a main effect of Repetition 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 Figures 5B and 5C). All other effects in this epoch involving the Repetition factor did not reach significance (all p s > 0.1).

Time-Course Analysis—As in Experiment 1 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 16 consecutive 25ms temporal windows between 200 and 600. These results are reported in Table 5B.

Discussion

Experiment 2 revealed a pattern of cross-script priming that was quite similar to what had been observed in the within-script conditions of Experiment 1, 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, primes and targets were written with physically different characters in the repetition condition.¹ On the other hand, priming effects on the N250 and N400 components in Experiment 2 showed the same overall pattern as Experiment 1. This suggests that much of the priming seen on the same components in Experiment 1 was driven by phonological and semantic overlap in the repetition condition, rather than orthographic overlap. It is important to note, however, that priming effects on the N250 component were topographically less widely distributed in Experiment 2 compared with Experiment 1, with effects appearing mostly in frontal electrode sites (compare Figures 4B and 4C to Figures 4B and 5C). Furthermore, these Figures suggest that the bulk of N400 priming effects emerge later in Experiment 2 compared with Experiment 1 (also compare Table 5A to Table 5B). This pattern fits with the idea that some of the priming effects on the N250 and N400 components seen in Experiment 1 are being driven by orthographic overlap in the repetition condition, which is absent in Experiment 2.

GENERAL DISCUSSION

The present study examined within-script and between-script priming with words written in one of 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 in a syllabary script using a methodology that has provided important information about the time-course of neuro-cognitive 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 bi-modal interactive-activation model (BIAM) of word recognition (see Figure 1). In the present study, we proposed an account of word recognition in Japanese Kana using the theoretical framework of the BIAM (see Figure 2), and we put this proposal to test in two experiments. In what follows we first discuss the within-script priming effects seen in Experiment 1 before discussing the implications of the cross-script priming effects of Experiment 2. 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., Holcomb & Grainger, 2006; Grainger & Holcomb, 2009; Midgely, 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 on 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 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 in the processes involved in reading words in Japanese Kana and those that are involved in reading words written in Roman script. One possible difference with respect to prior findings is that the time course of the N250 and N400 components was slightly later in the current 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 is similar to the phonological priming effect reported by Grainger et al. (2006) and obtained using comparable methodology.

Furthermore, although we expected to see differences in the time course of effects between scripts (Hiragana vs. Katakana) due to the differences in frequency of occurrence 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 where 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 produce very similar priming effects. Similarly, in an fMRI study, Ino, Nakai, Azuma, Kimura, & 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) examining 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 characters forming words. This finding is therefore in line with the absence of any difference in priming effects for the familiar Hiragana words 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

Experiment 2 of the present study tested cross-script priming in the same conditions as Experiment 1 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 component³. 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, Schmidt, & 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 the results of the Grainger et al. study, is what appears to be a more anterior distribution of the N250 cross-script priming effects compared with the within-script priming effect. This can be shown statistically by contrasting the anterior-posterior distribution of N250 priming effects for the two experiments. While there were 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 - $t(47) = 1.9$, $p = 0.032$; Pz - $p > .43$). A straightforward explanation of this pattern is that the effects seen in Experiment 1 are being driven by both orthographic and phonological overlap, whereas the effects seen in Experiment 2 are more limited in distribution since only phonological prime-target overlap is having an influence here. 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.

There was significant cross-script repetition priming on the N400 component, although these effects appear to peak later than the within-script priming effects. Indeed, while there was a main effect of repetition in the early N400 window (350-500 ms) in Experiment 1, this effect only emerged in the late N400 window (500-600 ms) in the cross-script priming conditions of Experiment 2. In line with our explanation of 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 ms and 80 ms). This contrasts with the pattern of cross-modal (visual prime – auditory target) repetition priming reported by Kiyonaga et al. (2007), where priming effects were only found at the longer prime duration (67 ms), and not at the shorter (50 ms) prime duration tested in that study. This suggests that the computation of phonology from orthography might be more efficient in syllabary scripts compared with alphabetic scripts (Kiyonaga et al.'s 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.

³Because this conclusion is partially based on a null effect in Experiment 2 we also conducted a further analysis contrasting the within and between script data in the N/P150 epoch by adding a factor of Experiment. As expected there was 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 the Experiment 1.

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 proposed in the Introduction (see Figure 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 weight 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, Zieler, & Zorzi, 2007). Our conclusions therefore also hold for this generic approach, with the idea that the relative weight 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 basic mechanisms involved in reading in alphabetic scripts. The present study highlights the potential for this framework to provide a general understanding of the neuro-cognitive processes involved in reading words in different languages. It will be important in future studies to further test this conclusion by examining additional language/writing systems that exploit other visual, orthographic and lexical properties.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

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

Table 2

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

A	HH	KK
Frequency (range)	1051.71 (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 (.81)
B	HH	KK
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 (.79)

Table 3

Examples of experimental stimuli by Conditions for Experiment 1 (A) and 2 (B).

A		Experiment 1: Within Script	
		Hiragana (Prime/Target)	Katakana (Prime/Target)
Repeated	Script	<i>H/H</i>	<i>K/K</i>
	Example	いのち/いのち	ズック/ズック
	Translation	<i>life/life</i>	<i>shoes/shoes</i>
Unrelated	Script	<i>H/H</i>	<i>K/K</i>
	Example	とけい/いのち	アニメ/シジミ
	Translation	<i>clock/life</i>	<i>anime/clam</i>

B		Experiment 2: Cross Script	
		Hiragana (Prime/Target)	Katakana (Prime/Target)
Repeated	Script	<i>K/H</i>	<i>H/K</i>
	Example	ツヅラ/つづら	へちま/へチマ
	Translation	<i>box/box</i>	<i>loofah/loofah</i>
Unrelated	Script	<i>K/H</i>	<i>H/K</i>
	Example	トケイ/つづら	あにめ/へチマ
	Translation	<i>clock/box</i>	<i>anime/clam</i>

Table 4

Average percentage of valid trials and standard deviations for each condition in Experiment 1 (A) and 2 (B).

A	Average %	SD
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		
HH repeated	87.96	9.33
HH unrelated	89.04	9.31
KK repeated	87.80	9.04
KK unrelated	88.81	7.19

Table 5

Time-course analyses of the main effect of repetition priming in Experiment 1: Within-script priming (A) and Experiment 2: Crossscript priming (B).

A	Experiment 1: Within-script priming									
	200-225	225-250	250-275	275-300	300-325	325-350	350-375	375-400		
Epoch										
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									
	200-225	225-250	250-275	275-300	300-325	325-350	350-375	375-400		
Epoch										
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