HHS Public Access
Author manuscript
J Cogn Neurosci. Author manuscript; available in PMC 2015 May 01.

Published in final edited form as:
J Cogn Neurosci. 2008 October ; 20(10): 1878–1891. doi:10.1162/jocn.2008.20125.

Left-lateralized N170 Effects of Visual Expertise in Reading: Evidence from Japanese Syllabic and Logographic Scripts

Urs Maurer, **Jason D. Zevin**, and **Bruce D. McCandliss**
Weill Medical College of Cornell University, New York

Abstract

The N170 component of the event-related potential (ERP) reflects experience-dependent neural changes in several forms of visual expertise, including expertise for visual words. Readers skilled in writing systems that link characters to *phonemes* (i.e., alphabetic writing) typically produce a left-lateralized N170 to visual word forms. This study examined the N170 in three Japanese scripts that link characters to larger phonological units. Participants were monolingual English speakers (EL1) and native Japanese speakers (JL1) who were also proficient in English. ERPs were collected using a 129-channel array, as participants performed a series of experiments viewing words or novel control stimuli in a repetition detection task. The N170 was strongly left-lateralized for all three Japanese scripts (including logographic Kanji characters) in JL1 participants, but bilateral in EL1 participants viewing these same stimuli. This demonstrates that left-lateralization of the N170 is dependent on specific reading expertise and is not limited to alphabetic scripts. Additional contrasts within the moraic Katakana script revealed equivalent N170 responses in JL1 speakers for familiar Katakana words and for Kanji words transcribed into novel Katakana words, suggesting that the N170 expertise effect is driven by script familiarity rather than familiarity with particular visual word forms. Finally, for English words and novel symbol string stimuli, both EL1 and JL1 subjects produced equivalent responses for the novel symbols, and more left-lateralized N170 responses for the English words, indicating that such effects are not limited to the first language. Taken together, these cross-linguistic results suggest that similar neural processes underlie visual expertise for print in very different writing systems.

INTRODUCTION

Reading words engages specialized visual brain processes that occur within 200 msec of stimulus presentation (Schlaggar & McCandliss, 2007; McCandliss, Cohen, & Dehaene, 2003), and that develop with learning to read (Maurer et al., 2006). A robust marker for such fast, specialized processes is an increased N170 component in the scalp-recorded event-related potential (ERP) in response to visual words compared to low-level visual control stimuli such as strings of symbols or forms (Maurer et al., 2006; Brem et al., 2005; Maurer, Brandeis, & McCandliss, 2005; Maurer, Brem, Bucher, & Brandeis, 2005; Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999).[1]

Reprint requests should be sent to Bruce D. McCandliss, Sackler Institute, Weill Medical College of Cornell University, 1300 York Avenue, New York, NY 10021, or via bdm2001@med.cornell.edu..

This effect may be related to a form of category-specific visual expertise, as a larger N170 component compared to control stimuli is also observed for faces (Bentin, Allison, Puce, & Perez, 1996), and for objects of expertise, for example, in bird experts viewing birds (Tanaka & Curran, 2001) and in car experts viewing cars (Gauthier, Curran, Curby, & Collins, 2003). However, whereas N170 visual expertise effects for faces and objects are typically bilateral or right-lateralized (Blau, Maurer, Tottenham, & McCandliss, 2007; Rossion, Joyce, Cottrell, & Tarr, 2003; Tanaka & Curran, 2001; Bentin et al., 1996), expertise for words results in a left-lateralized effect (Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005; Rossion et al., 2003; Bentin et al., 1999). This pattern may reflect the involvement of language processes during learning to read, such as the association of letters with phonemes that takes place in alphabetic writing systems rather than familiarity of particular visual words (Maurer & McCandliss, 2007).

If the left-lateralization of the N170 for written words is a result of mappings from graphemes to phonemes, this effect should be weaker or nonexistent for writing systems with different types of mappings from spelling to sound. Thus, investigations within languages that do not make associations between characters and phonemes, but rather between characters and entire syllables or words, provide a critical test for understanding the nature of specialized visual processes in reading that are reflected by the left-lateralized N170 for reading expertise. A cross-linguistic approach also opens the possibility of testing whether such left-lateralization is limited to the writing system of the first language, as suggested previously by comparisons between different alphabetic writing systems (Proverbio, Leoni, & Zani, 2004; Proverbio, Cok, & Zani, 2002).

Left-lateralization of the reading network in the brain has been extensively studied with functional neuroimaging methods in alphabetic (e.g., Brem et al., 2006; Cohen et al., 2000; Paulesu et al., 2000; Tagamets, Novick, Chalmers, & Friedman, 2000), but also in nonalphabetic languages, such as Japanese and Chinese (e.g., Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2005; Ischebeck et al., 2004; Thuy et al., 2004; Tan et al., 2001). Two recent meta-analyses of neuroimaging studies on reading aimed at detecting both similarities among different writing systems as well as systematic differences (Bolger, Perfetti, & Schneider, 2005; Tan, Laird, Li, & Fox, 2005). Alphabetic, Japanese, and Chinese scripts all activate a common left-hemisphere network, including inferior frontal, posterior-temporal, and inferior occipito-temporal regions (Bolger et al., 2005). The latter region included the visual word form area, which has been proposed to be involved in visual expertise in reading (McCandliss et al., 2003). Interestingly, according to both meta-analyses, Chinese script activated an additional right hemisphere region in the inferior occipito-temporal cortex (Bolger et al., 2005; Tan et al., 2005), suggesting additional right-hemispheric visual processing of Chinese logographic script.

However, due to the low temporal resolution, functional magnetic resonance imaging and positron emission tomography studies cannot directly measure rapid brain processes that are specialized for reading, and are thus not able to resolve whether lateralization of these processes differs between writing systems during the early aspects of perceptual encoding.

[1]An analogous effect is found in the M170 component of the magnetic field using MEG (Eulitz et al., 2000; Tarkiainen et al., 1999).

A number of electroencephalography (EEG)/magneto-encephalography (MEG) studies have suggested that Japanese, Korean, and Chinese readers demonstrate larger N170/M170 components to visual words than control stimuli (Wong, Gauthier, Woroch, DeBuse, & Curran, 2005; Kim, Yoon, & Park, 2004; Shirahama, Ohta, Takashima, Matsushima, & Okubo, 2004), suggesting that fast brain processes are also tuned for print in nonalphabetic scripts. However, the lateralization of such effects has not been conclusively resolved. Results in native Korean speakers who could read Chinese characters and written English (Kim et al., 2004) suggested that phonographic scripts (Korean, English) elicit a left-lateralized response, whereas logographic scripts elicit a bilateral response.

In contrast, an ERP study by Wong et al. (2005) reported left-lateralized N170 responses in Chinese–English bilinguals viewing either Chinese logographic characters or alphabetic letters, relative to pseudofont stimuli. Similarly, in two MEG studies, no difference between Kana (which codes syllables or moras) and Kanji (which codes words logographically) around 200 msec were found in either of the two hemispheres (Shirahama et al., 2004; Koyama, Kakigi, Hoshiyama, & Kitamura, 1998). Other ambiguous results have been reported for lateralization of early visual processing of Japanese syllabic scripts. Although the MEG sources isolated approximately 200 msec poststimulus in the posterior inferior–temporal cortex were bilateral in response to Kana characters in one study (Koyama et al., 1998), they showed a left-hemispheric dominance in another study (Kuriki, Hirata, Fujimaki, & Kobayashi, 1996).

Additional studies are needed that explicitly assess lateralization of N170 responses in nonalphabetic languages within the same subjects, and assess whether left-lateralized N170 effects are linked to a reader's experience with that writing system. The current study investigates whether stimuli from three Japanese scripts elicit a left-lateralized increase in the N170 in skilled Japanese readers, using naive English readers as controls.

The cross-linguistic approach adopted in the present study extends earlier studies in several important ways: First, it permits between-subjects comparisons of ERP responses to the *same* stimuli in groups of participants *with and without* experience in reading a particular writing system. This is particularly important because the three scripts used in Japanese differ in how they encode spelling-to-sound and spelling-to-meaning mappings, but also in string length and visual complexity. Between-subjects comparisons therefore provide the most direct test of whether N170 lateralization is driven by how a particular script is processed by skilled readers or by lower-level stimulus attributes (see Wong et al., 2005). Second, the two different types of writing systems in Japanese (syllabic Kana[2] and logographic Kanji scripts) allow for the creation of pseudohomophone stimuli that are familiar in their phonology and semantics to real words, but are novel at the visual word form level (see Besner & Hildebrandt, 1987). This allows us to test the role of visual expertise for specific words—as opposed to an entire script—in eliciting left-lateralized N170 responses. Finally, incorporating novel stimuli across groups allows us to rule out the

[2]Japanese Kana actually encode moras rather than syllables. A mora can be a syllable, the second part of a “long” vowel, or a nasal coda. Thus, although many syllables contain only one mora (and thus written with one character), many syllables contain more than one (and are thus written with multiple characters).

potential confound of between-group differences that are unrelated to processing specific scripts.

METHODS

Participants

Native Japanese readers (JL1; $n = 18$) who could also read English, and native English readers who could not read Japanese (EL1; $n = 18$) participated in the study. One of the English speakers did not finish all three experiments, and thus, was excluded from the analyses in this article. The remaining participants were all right-handed and matched between the two groups for age [English: 29.3 years ($SD = 6.7$, range = 20–44); Japanese: 29.8 years ($SD = 6.1$, range = 18–40)], but the sex ratio tended to be different (English: 10 men and 7 women; Japanese: 7 men and 11 women; $p < .1$).[3] The Japanese speakers started to learn English at the age of 9.9 years in average ($SD = 4.0$), and had been living in an English-speaking country for 9.4 years ($SD = 7.1$) at testing. The Japanese speakers had a mean reading age of 19.4 years ($SD = 13.6$) as measured by a standard reading test (Woodcock Johnson-III).

Experiment 1

Stimuli—Forty stimuli for each condition were drawn from a case study using intracranial recordings to record responses to different Japanese scripts (see Tanji, Suzuki, Delorme, Shamoto, & Nakasato, 2005 for more details). These consisted of words written in Hiragana (2 to 3 characters) and words written in Kanji (2 characters). Examples of stimuli are illustrated in Figure 1A. Additionally, pseudowords written in Hiragana and Kanji, also from the Tanji et al. (2005) study, were presented in separate blocks for the purposes of another study, presented elsewhere.

Procedure—The stimuli were presented in black on a gray background, and subtended 1.9 degrees of visual angle horizontally for the Hiragana and 1.4 degrees for the Kanji words. An average stimulus onset asynchrony of 2 sec (±250 msec random jitter) and a fixed stimulus duration of 250 msec were used. The two conditions (Hiragana vs. Kanji words) were presented in separate blocks (4 blocks per condition). All stimuli (40 per condition) were presented twice as nontargets, whereas the second presentation was always in a different block. A subset (12 per condition) was additionally presented once as a target (13.0% of all stimuli). The participants were asked to press a button whenever a stimulus occurred two times in a row (one-back repetition detection).

[3]The different sex ratio did not critically affect the main results of left-lateralized effects of visual expertise in this study. Additional analyses of variance (ANOVAs) with groups matched for sex (7 men and 7 women in each language group) revealed similar effects as in the analyses with the entire groups regarding the “Hemisphere by Group” interactions in Experiment 1 [$F(1, 26) = 5.2$, $p < .05$] and in Experiment 2 [$F(1, 26) = 6.1$, $p < .05$] and regarding the “Hemisphere by Condition” interaction in Experiment 3 [$F(1, 26) = 10.1$, $p < .01$]. However, the sex-matched group N170 latency ANOVA revealed only a non-significant trend toward a group difference in Experiment 2 [$F(1, 26) = 2.6$, $p < .12$].

Experiment 2

Stimuli—The stimuli in Experiment 2 were adapted from Besner and Hildebrandt (1987) and consisted of 45 words per condition written in Japanese Katakana script (see example stimuli in Figure 1A). For Japanese readers, the visual word forms were familiar in one condition because these words are typically written in Katakana (called "regular Katakana" in this article). In the other condition, however, the stimuli had unfamiliar visual word forms because these words are typically written in Kanji script, but were transliterated into Katakana script (called "Kanji Katakana" in this article; see also Figure 1B) for the purpose of this experiment, which was possible due to the highly regular sound-to-character mappings of the Katakana script. This manipulation creates two sets of stimuli that differ in visual word form familiarity to Japanese speakers, yet can be read as meaningful words that have equally familiar phonology and meaning. For the English speakers, both types of stimuli were equally unfamiliar at each of these levels. As the two sets of stimuli were matched for initial character, and number of characters (mean length = 3.3 characters, range = 2–4 characters; see also Besner & Hildebrandt, 1987), we kept the original number of stimuli resulting in a slightly higher number of stimuli presented in Experiment 2 compared to Experiment 1.

Procedure—The task and procedures in Experiment 2 were the same as in Experiment 1, except that 14 stimuli per condition were repeated as targets to keep a similar ratio of targets (13.5%) to nontargets (90 stimuli per condition). The familiar and unfamiliar Katakana word forms subtended 3° of visual angle horizontally.

Experiment 3

Stimuli—Stimuli in Experiment 3 were 40 English words and 40 novel symbol strings (Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005). Words and symbol strings were matched for string length and consisted of three to five characters. The symbol strings were very similar to our earlier work and were made up of eight different geometric symbols (Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005). Although half of the symbols were familiar (circle, triangle, rectangle, diamond), the other half contained "descenders" (as in the lowercase letters "g, j, p, and q"), creating novel characters. Novel visual stimuli were created by combining these symbols to form unfamiliar strings.

Procedure—Task and procedure in Experiment 3 were the same as in Experiment 1. Word and symbol stimuli subtended 1.8° of visual angle.

Data Analysis

The 128-channel EEG was recorded using a geodesic sensor net (Hydrocel, EGI) with a Cz reference. Data were sampled at 500 Hz/channel with filter settings 0.1–100 Hz. Impedance was kept below 50 kΩ, which is a standard procedure that is specific to use with the particular combination of high impedance amplifiers and geodesic sensor nets employed in this study (Ferree, Luu, Russell, & Tucker, 2001). Using BESA software, channels with excessive artifacts were spline interpolated, and eye blinks were corrected (multiple source eye correction method; Berg & Scherg, 1994). The data then were digitally band-pass filtered (0.3–30 Hz), segmented (−150 to 750 msec), artifact rejected (±100 μV), and nontarget stimuli were averaged separately for the two conditions. Using Brain Vision Analyzer software, grand means were computed for groups and conditions separately, after average reference and global field power (GFP) had been computed (Lehmann & Skrandies, 1980).

For each experiment, the N170 segment was selected according to the GFP minima adjacent to the N170 GFP peak in the grand-grand mean (across 2 conditions × 2 groups; as in Brem et al., 2005; Maurer, Brem, et al., 2005). The averaged values across this segment (Experiment 1: 126–210 msec; Experiment 2: 130–216 msec; Experiment 3: 130–232 msec) were analyzed regarding global map strength (GFP), and lateralization by contrasting amplitudes at left and right occipito-temporal electrodes (left: 58 and right: 96). The left and right occipito-temporal channels were selected according to the topographic maxima in the negative field over the left and right hemispheres in the average across all six conditions and two groups.

The N170 latency was determined using a topographic component recognition procedure (Brem et al., 2006; Brandeis, Naylor, Halliday, Callaway, & Yano, 1992). The N170 segment maps (assessed separately for each group and condition) were normalized and used as templates to find the time point with the highest covariance (map latency) within the borders of the N170 segment in each subject.

For each experiment, multivariate ANOVAs with repeated measures were computed for the N170 measures (GFP, lateralization, and map latency) with the between-subject factor “group” and the within-subject factor “condition.” For the lateralization analysis, there was an additional “hemisphere” within-subject factor.

To facilitate interpretation of the overall analyses and to allow better comparisons with earlier studies, we performed a series of analogous multivariate ANOVAs separately for each group (yielding Hemisphere by Stimulus condition interactions) and separately for each stimulus condition (yielding Hemisphere by Group interactions), as well as *t* tests for lateralization differences (left vs. right occipito-temporal channel) for each stimulus condition in each group.

For each experiment, behavioral responses to targets were analyzed in multivariate ANOVAs with repeated measures on accuracy and reaction time using “group” as between-subject factor and “condition” as within-subject factors. Due to a file error, the behavioral data were lost from one Japanese subject for Experiment 3.

RESULTS

Experiment 1

In Experiment 1, the participants detected immediate repetitions of Japanese Hiragana words and Japanese Kanji words. Both the syllabic Hiragana and the logographic Kanji script were familiar to the Japanese speakers but were unfamiliar to the naive English speakers.

Behavior—In Experiment 1, the Japanese participants were more accurate at detecting targets than the English participants [Table 1; Group: $F(1, 33) = 13.1$, $p < .001$]. For reaction time, there was no significant group difference ($F < 1$), nor any interaction between group and condition ($F < 1.5$). There was, however, a trend toward faster responses for Hiragana repetition than Kanji repetition ($p < .1$). When tested within the groups separately, this difference was significant for the Japanese ($p < .05$), but not for the English participants ($F < 1$).

N170 Analyses

Global field power: The analysis regarding global map strength yielded no significant main effects or interactions.

Occipito-temporal channels: In the overall analysis, the N170 was slightly right-lateralized for the English participants, whereas it was strongly left-lateralized for the Japanese participants (Group × Hemisphere: $p < .05$; Table 2; see also Figures 1 and 2). This lateralization difference between the groups did not significantly differ between Hiragana and Kanji words (Group × Condition × Hemisphere: $p > .16$). In addition, Hiragana words elicited a larger N170 than the Kanji words (Condition: $p < .01$).

The analyses for the language groups separately revealed that the Hiragana words elicited a larger N170 than the Kanji words in the English speakers [Condition: $F(1, 16) = 14.4$, $p < .01$], possibly due to their larger string length. In the Japanese speakers, the N170 was stronger over the left than over the right hemisphere [Hemisphere: $F(1, 17) = 5.5$, $p < .05$], and this lateralization difference tended to be larger for Hiragana than for Kanji words (Condition × Hemisphere: $p < .1$).

The analyses for the two stimulus conditions separately revealed significant Group × Hemisphere interactions [Hiragana: $F(1, 33) = 6.4$, $p < .05$; Kanji: $F(1, 33) = 5.0$, $p < .05$], indicating a more left-lateralized N170 for Japanese subjects compared to a more bilateral N170 for English subjects for both Hiragana and Kanji scripts.

Lateralization *t* tests showed that the N170 was leftlateralized in the Japanese speakers for both Hiragana ($p < .05$) and Kanji ($p < .1$), although slightly less significant for the latter (Table 3). On the other hand, the N170 was bilateral for the English speakers for both conditions (both $0 < t < 1.2$).

Map latency: The N170 tended to occur earlier for Hiragana than Kanji stimuli (Condition: $p < .1$; Table 2). Although the N170 mean latencies were shorter in Japanese than in English subjects, this difference was not significant [Group: $F(1, 33) = 2.0$, $p > .16$].

Planned comparisons for map latency revealed no significant effects, neither in the group comparisons separately for the stimulus conditions nor comparing the stimulus conditions separately within the two groups (all $p > .13$).

Experiment 2

In Experiment 2, the participants detected immediate repetitions of words written in Japanese Katakana script. As in Experiment 1, the syllabic Katakana script was familiar to the Japanese speakers but was unfamiliar to the naive English speakers. For Japanese speakers, the regular Katakana words had familiar visual word forms (combinations of Katakana characters), whereas the "Kanji" Katakana words had unfamiliar visual word forms, as they were words typically written in Kanji, but transcribed into Katakana for this experiment.

Behavior—The behavioral analyses revealed that the Japanese subjects were more accurate at detecting targets than the English subjects [Table 1; group: $F(1, 33) = 6.9$, $p < .05$]. Accuracy, however, was similar for both regular Katakana and "Kanji" Katakana (Condition: $F < 1$; Condition × Group: $F < 1$), which held also for the groups separately (both *Fs* < 1).

There were no reaction time effects (all *Fs* < 1), indicating similar speed in detecting targets for Japanese and English subjects (Table 1), and also for regular and " Kanji" Katakana stimuli (this also held for the groups separately: both *Fs* < 1).

N170 Analyses

Global field power: There were no significant effects regarding N170 map strength.

Occipito-temporal channels: In the overall analysis, the N170 was more negative at the left than at the right occipito-temporal channel (channels 58 and 96; Hemisphere: $p < .05$; see Table 2), mainly due to the Japanese subjects (Group × Hemisphere: $p < .05$; see also Figures 2 and 3). No other effects were significant.

The analyses for the language groups separately revealed no significant effects in the English speakers (all $F < 1.2$). In the Japanese speakers, the N170 was more negative at the left hemisphere channel than at the right hemisphere channel [Hemisphere: $F(1, 17) = 14.9$, $p < .01$]. Notably, the Japanese N170 response showed neither a significant Condition main effect nor a significant Condition × Lateralization interaction (both *Fs* < 1), which would indicate an influence of word form familiarity.

The analyses for the stimulus conditions separately yielded similar main effects of hemisphere [regular Katakana: $F(1, 33) = 5.8$, $p < .05$; "Kanji" Katakana: $F(1, 33) = 6.1$, $p < .05$] that were both mainly due to a left-lateralized increase in the Japanese group [Hemisphere × Group; regular Katakana: $F(1, 33) = 6.5$, $p < .05$; "Kanji" Katakana: $F(1, 33) = 6.4$, $p < .05$].

Lateralization *t* tests revealed strong left-lateralization of the N170 for both types of Katakana stimuli (regular: $p < .01$, "Kanji": $p < .001$) in the Japanese speakers (Table 3), but bilateral responses in the English speakers (both $0 < t < 1$).

Map latency: The N170 map occurred earlier in the Japanese than in the English speakers (Japanese: 160 msec, English: 171 msec; Group: $p < .05$; Table 2; see also Figure 3). No other effects were significant (*Fs* < 1).

Planned comparisons revealed that there was no latency difference between the two types of Katakana stimuli in either of the two groups (both *Fs* < 1), but that the latencies were shorter in the Japanese than in the English for both types of stimuli, although this effect was only marginally significant for the regular Katakana [regular Katakana: $F(1, 33) = 4.0$, $p < .1$; “Kanji” Katakana: $F(1, 33) = 4.4$, $p < .05$].

Experiment 3

In Experiment 3, the participants detected immediate repetitions of English words and novel symbol strings. The English words were familiar to both the native English and the native Japanese speakers (who were also proficient readers of English), whereas the symbol strings were unfamiliar to both groups.

Behavior—Repetitions of English words were more accurately detected than repetition of symbol strings [Table 1; Condition: $F(1, 32) = 11.6$, $p < .01$]. This pattern did not differ between the two groups (Group, Group × Condition, *Fs* < 1). Reaction time again showed no difference between groups or condition (all *Fs* < 1).

N170 Analyses

Global field power: As in the other two experiments, GFP yielded no significant effects.

Occipito-temporal channels: In the overall analysis, words elicited a larger N170 than symbol strings (Condition: $p < .05$; Table 2), mainly over the left hemisphere (Hemisphere × Condition: $p < .001$), but this interaction did not differ between the two groups ($p = .3$). In addition, the overall N170 was larger in Japanese than in the English participants for words, but similar for symbol strings (Group × Condition: $p < .05$).

The analyses for the groups separately revealed that in the English speakers the N170 was left-lateralized for words, but right-lateralized for symbols [Hemisphere × Condition: $F(1, 16) = 16.9$, $p < .001$]. In the Japanese speakers, the N170 was generally larger for words than for symbols [Condition: $F(1, 17) = 8.8$, $p < .01$], which tended to be more pronounced over the left hemisphere (Hemisphere × Condition: $p < .1$).

The analyses for the conditions separately revealed that the N170 was left-lateralized for words [Hemisphere: $F(1, 33) = 9.0$, $p < .01$], but that this left-lateralization did not differ between the groups (Hemisphere × Group: $F < 1$). For symbols, there were no significant effects at all (all *Fs* < 1).

Lateralization *t* tests yielded left-lateralized N170 topographies in response to English words for both language groups, although this effect was slightly more robust in the English ($p < .05$) than in the Japanese speakers ($p < .1$; Table 3). Both groups showed no significant lateralization for the symbol condition (both $-1 < t < +1$).

Map latency: There were no significant effects regarding map latency (all *Fs* < 1).

DISCUSSION

The main goal of the study was to test whether the finding of left-lateralized N170 effects that reflect expertise for visual words in alphabetic writing systems would extend to

Japanese scripts that link characters with syllables or with morphemes rather than with phonemes, and thus, apply a different level of association between visual code and language.

The cross-linguistic approach in the present study further complements earlier results on N170 expertise effects for words (Brem et al., 2005; Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005; Eulitz et al., 2000; Bentin et al., 1999; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999; Schendan, Ganis, & Kutas, 1998). These studies relied on the assumption that control stimuli sufficiently match a given writing system for low-level visual features, yet it is often unclear what dimensions of similarity are most critical to control for from one writing system to the next, and tests of visual similarity on any low-level visual property are rarely reported. We addressed this issue directly by contrasting ERP responses to the same stimuli in groups of participants who differ in their experience with a particular writing system (see also Wong et al., 2005), although such contrasts can also introduce new potential confounds, such as differences in ERP topographies across groups which must also be addressed.

Expertise in a Syllabic Writing System Produces a Left-lateralization of the N170

Our results show that the left-lateralization of the N170 in response to visual word forms depends upon the experience a participant has with the writing system used: Only the Japanese readers showed a left-lateralized N170 to word forms written in Japanese Katakana and Hiragana script, whereas the native English speakers who could not read the script showed a bilateral N170 topography. Moreover, the same Japanese subjects showed a left-lateralized N170 only in response to scripts with which they had experience, but not in response to novel symbol strings, which elicited an equally bilateral N170 in both groups.

Left-lateralization has been shown to be characteristic of visual expertise for words written in alphabetic scripts (Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005; Rossion et al., 2003; Bentin et al., 1999), as opposed to N170 expertise effects for faces and objects which typically have a bilateral or right-lateralized topography (Rossion et al., 2003; Tanaka & Curran, 2001; Bentin et al., 1996). Previous studies have reported an enhanced N170 for words in syllabic writing systems compared to control stimuli, but did not explicitly test left-lateralization (Kim et al., 2004; Shirahama et al., 2004). The current results suggest that similar processes underlie the left-lateralized N170 in alphabetic writing systems and writing systems that associate characters with larger phonological units, such as syllables.

Expertise in a Logographic Script Also Produces a Left-lateralization of the N170

An important question of the present study was whether the N170 was also left-lateralized in response to words written in the logographic Kanji script. One previous study suggested that left-lateralization was limited to scripts using grapheme-phoneme conversion rules (Kim et al., 2004), whereas another study found a left-lateralized expertise effect for single logographic characters (Wong et al., 2005), which raised the question of whether such left-lateralized effects would also extend to whole words composed of more than one character.

In the present study, the N170, in response to logo-graphic Kanji words, was more left-lateralized in Japanese participants compared to English participants without reading experience in that script. This result confirms and extends the study by Wong et al. (2005)

by showing that the left-lateralized N170 expertise effect in logographic scripts also extends to entire words composed by a combination of two characters.

In contrast, a study of Korean participants reading Chinese characters (Kim et al., 2004) did not find evidence for a left-lateralized response. A number of factors may have led to this discrepancy. Importantly, Chinese characters are encountered less frequently by Korean readers than by readers of Japanese. It is also possible that task differences played a role. The study by Kim et al. (2004) employed a semantic task, whereas the present study and the study by Wong et al. (2005) used a one-back repetition detection task. Semantic processing of logographic characters thus may increase processing in the right hemisphere leading to a more bilateral topography. It is important to note, however, that there was a trend toward a *weaker* left-lateralization for the logo-graphic than the syllabic scripts in the current study, although the topography for the logographic script was still more left-lateralized when compared to the naive English participants. This may suggest that subtle differences in lateralization based on script properties could be revealed in more sensitive designs.

Expertise in a Syllabic Writing System May Also Shorten the N170 Latency

The current results also present some evidence that reading expertise is associated with shorter N170 latencies in addition to the lateralization effects. This latency effect, however, seems to be less robust than the left-lateralized amplitude effects, as the group comparison revealed shorter latencies only for the Katakana stimuli in Experiment 2, but not for the Hiragana and Kanji stimuli in Experiment 1. Moreover, the effect was not significant when smaller groups, matched for sex, were used. Latency effects of visual expertise would be in agreement with an earlier study finding shorter N170 latencies for Japanese syllabic words compared to visual control stimuli (Shirahama et al., 2004). In alphabetic writing systems, some studies did not find latency differences (Eulitz et al., 2000; Bentin et al., 1999), whereas others focused on map topographies rather than on latencies (Brem et al., 2005; Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005). One study with adolescents and adults in an alphabetic writing system, however, reported a latency interaction with age, suggesting that faster N170 latencies for words compared to control stimuli is a relatively late developing effect in reading acquisition (Brem et al., 2006). This suggests that effects of visual expertise on the N170 latency are small and not very robustly detected across different studies, but it remains unclear whether such effects could be characteristic for syllabic scripts.

Script Familiarity rather than Familiarity with Specific Visual Word Forms Drives the N170 Expertise Effect in Japanese Katakana Reading

Another important goal of the present study was to investigate whether familiarity of visual word forms, that is, familiarity with particular *combinations* of characters, would affect the N170. Earlier studies on visual word form familiarity effects in the N170 can be grouped into two main approaches either contrasting words with visually novel, but pronounceable pseudowords (e.g., Maurer, Brandeis, et al., 2005; Bentin et al., 1999), or contrasting high-frequency words with low-frequency words (e.g., Hauk & Pulvermuller, 2004; Proverbio, Vecchi, & Zani, 2004). In both these approaches, the visual word form familiarity manipulation is confounded with additional familiarity differences in sound and meaning, which may help explain the inconsistent results within and between the two approaches (for a discussion, see Maurer, Brandeis, et al., 2005). The approach taken in the present study aims to control for additional familiarity differences by comparing word forms that differ only in visual familiarity as phonological and semantic familiarity is kept constant: The unfamiliar "Kanji" Katakana word forms in the present study acted as familiar words at the phonological and semantic level, but as novel regular "pseudowords" at the visual level, and thus, allowed us to isolate effects of visual word form familiarity when compared to words that are typically written in Katakana script. In Experiment 2, nearly identical responses were found to visually familiar words and pseudohomophones (Figures 2 and 3). This finding of equivalence, in the context of a strong, language-experience-specific left-lateralization for all Katakana stimuli, suggests that there is no influence of word form familiarity within the Japanese group, but a strong influence of script familiarity across groups.

A related approach was used in one other ERP study (Sauseng, Bergmann, & Wimmer, 2004) in German, which, contrary to the findings of the current study, demonstrated a stronger N170 to familiar versus novel visual word forms. In that study, unfamiliar word forms were created by altering some letters within a word (e.g., "Kwantität" instead of "Quantität"). Although this approach contrasts the familiarity of the visual word forms while preserving the familiarity of the letters and the phonological and semantic features of known words, such manipulations may introduce less familiar spellings of familiar syllables within words, and thus, changing the focus of spelling-to-sound mapping to such inconsistencies. Unfamiliar letter combinations in word forms have been shown to influence word processing in alphabetic languages within the first 200 msec (Hauk et al., 2006). Thus, the present result may suggest that visual word form familiarity effects in the N170 only occur in alphabetic, but not in syllabic, scripts.

The current set of findings appears to directly contradict the conclusion from N170 research on English that claims that left-lateralized N170 responses are modulated by visual word form familiarity (Maurer, Brandeis, et al., 2005). One potential explanation for this contrast between findings across languages is that the impact of visual word form familiarity on encoding mechanisms likely varies as a function of orthographic depth of the writing system (i.e., the regularity of grapheme–phoneme mappings). This explanation was originally put forth to by Maurer, Brandeis, et al. (2005) to account for the finding of equivalently left-lateralized N170 responses for words and pseudowords in German, in contrast to the findings in English.

According to this explanation, as mappings between orthography and phonology become less consistent, as in the case of English relative to German, there is increased pressure to encode orthographic patterns at a larger grain size (Ziegler & Goswami, 2006). Increasing the grain size of orthographic patterns also results in an increase of the number of grapheme–phoneme correspondences that need to be learned (Ziegler & Goswami, 2006), which may lead to a lesser degree of automaticity in grapheme–phoneme mapping (Maurer, Brandeis, et al., 2005). As pronunciation of pseudowords is somewhat ambiguous in English (Zevin & Seidenberg, 2006), the decreased automaticity may bias subjects against using phonological information for processing pseudowords especially when the pseudowords are presented in blocks in an implicit language task (Maurer, Brandeis, et al., 2005).

Based on such an explanation, one would predict that, given the very shallow nature of the Katakana script, familiarity effects during encoding of visual words would not necessarily accrue beyond the level of the individual character, which is precisely what we found in the left-lateralized N170 results and in the absence of an N170 difference between familiar and unfamiliar Katakana visual word forms. Thus, the hypothesis that orthographic depth dictates the grain size of familiarity effects for the left-lateralized N170 response appears to account for findings across English, German, and Katakana scripts. Unfortunately, the precisely analogous experiments in Kanji or Hiragana that might help to test the limits of this hypothesis are not logically plausible.

Together, the present results suggest that visual word form familiarity in this orthographically shallow syllabic writing system does not affect the N170 when confounding effects of familiarity differences in phonology and semantics are controlled for. Additional studies are needed to clarify whether word form familiarity effects in the N170 depend on the level of organization of a script, or whether familiarity accrues at the level of syllables similarly across different scripts.

Left-lateralized N170 is Not Restricted to the First Language

One further goal of the present study was to test whether left-lateralized expertise effects were limited to the first language (L1), as has been previously suggested (Proverbio, Leoni, et al., 2004; Proverbio, Vecchi, et al., 2004; Proverbio et al., 2002), or whether they would also occur for the L2 language. The participants in the present study showed a more left-lateralized N170 response to English words compared to novel symbol strings. Although this effect has been shown in many previous studies (e.g., Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005; Bentin et al., 1999), a critical result was the absence of a significant interaction with the group factor (meaning L1 vs. L2).

Although the left-lateralization was less significant in the Japanese group, when tested alone, this suggests that left-lateralized expertise effects in the N170 also occurs for the L2 language. This differs from two earlier studies with bilinguals and with simultaneous interpreters reporting a left-lateralized N170 for the L1 language, but a bilateral N170 for the L2 language (Proverbio, Leoni, et al., 2004; Proverbio, Vecchi, et al., 2004; Proverbio et al., 2002). Again, effects of second-language learning on the N170 lateralization might be task dependent, as certain language processes may not become fully engaged in a one-back task (Maurer, Brandeis, et al., 2005), and thus, may occur only in tasks that require reading explicitly (Proverbio, Leoni, et al., 2004; Proverbio, Vecchi, et al., 2004; Proverbio et al., 2002). Alternatively, differences in lateralization of the word N170 between first- and second-language learning may be restricted to cases in which both languages use alphabetic scripts, and may play out differently if the two languages use different ways to map characters to word sounds.

Although there were no lateralization differences between the two groups, there were group differences that occurred similarly over the left and over the right hemispheres: The

Japanese speakers showed a bilateral increase of the N170 in response to English words compared to the English speakers, whereas the two groups did not differ for the symbol N170. This wordspecific but bilateral effect may reflect “novice versus expert learning” of a new script (Maurer et al., 2006; Palmeri, Wong, & Gauthier, 2004), indicating high sensitivity of the Japanese speakers' neural network to the more recently learned English script. This is in agreement with developmental results showing bilaterally increased N170 tuning for print in second-graders compared to skilled adult readers (Maurer et al., 2006). In Japanese readers learning English, as well as in children learning to read for the first time, an extensive neural network may become sensitive to a novel script in an early phase of learning, while later sensitivity for some visual aspects of the script may decrease in parts of this network with more reading experience, resulting in a more selective tuning (Maurer et al., 2006). Moreover, decrease of sensitivity may be stronger in the right hemisphere than in the left hemisphere because of feedback from left-lateralized language regions (Zevin & McCandliss, 2005) eventually leading to a left-lateralization of the word N170 (Maurer et al., 2007). This could also explain why the left-lateralization of the N170 in response to English words was slightly less significant in Japanese speakers ($p < .1$) than in English speakers ($p < .05$).

N170 Expertise Effects and Visual Complexity

Earlier studies in alphabetic writing systems investigated N170 expertise effects within a single-subject group using word and low-level control stimuli such as symbol strings, forms, and false fonts (Maurer, Brandeis, et al., 2005, Maurer, Brem, et al., 2005; Eulitz et al., 2000; Bentin et al., 1999; Schendan et al., 1998), similar to those used in Experiment 3 of the present study. Such designs run the risk that any low-level visual difference between the experienced script and the control script (e.g., visual complexity) would be confounded with experience differences, and thus, weaken claims that the N170 is modulated by experience (Eulitz et al., 2000; Schendan et al., 1998). In the present cross-linguistic study, we were able to use the same exact stimuli with two different groups who differed in their experience with the writing system, thus keeping visual complexity constant within each script condition, and varied instead the experience level of particular groups of subjects. The pattern of N170 effects across the two groups when considering Japanese, English, and Symbol scripts converges well with previously reported results for contrasts between words and control stimuli, suggesting that those N170 effects are indeed linked to experience.

Absent or smaller differences between words and closely matched control stimuli, such as false fonts, may be due to generalization of the effects of visual expertise to stimuli resembling a particular script. Some degree of flexibility of the expertise system for reading seems to be necessary given that writing differs with different font types or with different samples of hand writing.

Generalization to other stimuli may also explain the finding that naive Italian readers showed a left-lateralized N170 in response to unfamiliar Greek words and pseudo-words in an earlier study (Proverbio, Del Zotto, & Zani, 2006). Greek letters are similar to Roman letters in some aspects and participants may be able to make use of an existing expertise network to process those stimuli more efficiently. Although naive readers might be able to recruit their expertise network through generalization, they still seem to process the unfamiliar script differently from native readers, as indicated by an N170 difference for target stimuli between Greeks and naive Italians viewing Greek letter strings (Proverbio et al., 2006).

In the present study, we could avoid the problem of generalization, as Japanese characters differ more strongly from alphabetic letters. It remains to be elucidated in future studies, however, what the critical factors are for potential generalization of such expertise effects across stimulus classes.

Effects of Visual Expertise on Behavioral Target Detection

Across all three experiments, participants were more accurate at detecting repetitions of stimuli written in a script with which they were familiar than at detecting repetitions of stimuli in an unfamiliar script or of novel symbol string stimuli. No such effects, however, were found for reaction time. Visual expertise effects on accuracy—but not on reaction time—are commonly observed when adults detect repetitions of words and unfamiliar symbol strings presented in separate blocks (Brem et al., 2006; Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005).

The present cross-linguistic study extends previous within-group comparisons using blocked presentation and a repetition detection task by showing that groups who differ in visual expertise for a script also differ mainly in accuracy and not in reaction time when detecting immediate repetitions of words written in that script.

Visual expertise, however, may also affect reaction time as shown in another study comparing Greek and naive Italian speakers detecting target letters in Greek letter strings (Proverbio et al., 2006). Greek speakers responded faster to target letters in Greek words than naive Italian speakers, whereas the two groups did not differ for target letters in Greek pseudowords (Proverbio et al., 2006). As the stimulus categories were randomly interspersed in that study in contrast to the blocked presentation in the present study, and as the two studies also employed different tasks (letter detection vs. word repetition detection), this suggests that behavioral effects of visual expertise are modulated by the mode of stimulus presentation and by the nature of the task.

Conclusions

Our results suggest that left-lateralized N170 effects indexing visual expertise for reading extend to writing systems linking characters with syllables or with morphemes. Furthermore, this study provides a unique test of visual word form familiarity versus script-familiarity effects on the N170 to reveal that within Katakana, N170 effects reflect familiarity with Katakana characters as a script rather than their configuration into specific visual word forms. Furthermore, the similarity of responses across groups to novel stimuli serves to rule out potential group differences in ERP responses that reflect factors unrelated to specific scripts. Therefore, the group effects appear to be genuinely dependent on experience, as the responses to the identical stimuli differed between participants depending on their experience with Japanese script, and, further, as the responses in the same subjects depended on subjects' experience with the stimuli.

Acknowledgments

This research was supported by the Swiss National Science Foundation (Fellowship for Prospective Researchers: U. M.), NIH/NIDCD (F32-DC006352: J. D. Z.; R01-DC007694: B. D. M.), and the U.S. National Science Foundation (NSF 529112: B. D. M.). We thank Eva Hulse for helping collecting the data. We also would like to thank Kazuyo Tanji for sharing his unpublished stimuli.

REFERENCES

Bentin S, Allison T, Puce A, Perez E. Electrophysiological studies of face perception in humans. Journal of Cognitive Neuroscience. 1996; 8:551–565. [PubMed: 20740065]

Bentin S, Mouchetant-Rostaing Y, Giard MH, Echallier JF, Pernier J. ERP manifestations of processing printed words at different psycholinguistic levels: Time course and scalp distribution. Journal of Cognitive Neuroscience. 1999; 11:235–260. [PubMed: 10402254]

Berg P, Scherg M. A multiple source approach to the correction of eye artifacts. Electroencephalography and Clinical Neurophysiology. 1994; 90:229–241. [PubMed: 7511504]

Besner D, Hildebrandt N. Orthographic and phonological codes in the oral reading of Japanese kana. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1987; 13:335–343.

Blau VC, Maurer U, Tottenham N, McCandliss BD. The face-specific N170 component is modulated by emotional facial expression. Behavioral and Brain Functions. 2007; 3:7. [PubMed: 17244356]

Bolger DJ, Perfetti CA, Schneider W. Cross-cultural effect on the brain revisited: Universal structures plus writing system variation. Human Brain Mapping. 2005; 25:92–104. [PubMed: 15846818]

Brandeis D, Naylor H, Halliday R, Callaway E, Yano L. Scopolamine effects on visual information processing, attention, and event-related potential map latencies. Psychophysiology. 1992; 29:315–336. [PubMed: 1626042]

Brem S, Bucher K, Halder P, Summers P, Dietrich T, Martin E, et al. Evidence for developmental changes in the visual word processing network beyond adolescence. Neuroimage. 2006; 29:822–837. [PubMed: 16257546]

Brem S, Lang-Dullenkopf A, Maurer U, Halder P, Bucher K, Brandeis D. Neurophysiological signs of rapidly emerging visual expertise for symbol strings. NeuroReport. 2005; 16:45–48. [PubMed: 15618888]

Cohen L, Dehaene S, Naccache L, Lehericy S, Dehaene-Lambertz G, Henaff MA, et al. The visual word form area: Spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. Brain. 2000; 123:291–307. [PubMed: 10648437]

Eulitz C, Eulitz H, Maess B, Cohen R, Pantev C, Elbert T. Magnetic brain activity evoked and induced by visually presented words and nonverbal stimuli. Psychophysiology. 2000; 37:447–455. [PubMed: 10934903]

Ferree TC, Luu P, Russell GS, Tucker DM. Scalp electrode impedance, infection risk, and EEG data quality. Clinical Neurophysiology. 2001; 112:536–544. [PubMed: 11222977]

Gauthier I, Curran T, Curby KM, Collins D. Perceptual interference supports a non-modular account of face processing. Nature Neuroscience. 2003; 6:428–432.

Hauk O, Patterson K, Woollams A, Watling L, Pulvermuller F, Rogers TT. [Q] When would you prefer a SOSSAGE to a SAUSAGE? [A] At about 100 msec. ERP correlates of orthographic typicality and lexicality in written word recognition. Journal of Cognitive Neuroscience. 2006; 18:818–832. [PubMed: 16768380]

Hauk O, Pulvermuller F. Effects of word length and frequency on the human event-related potential. Clinical Neurophysiology. 2004; 115:1090–1103. [PubMed: 15066535]

Ischebeck A, Indefrey P, Usui N, Nose I, Hellwig F, Taira M. Reading in a regular orthography: An FMRI study investigating the role of visual familiarity. Journal of Cognitive Neuroscience. 2004; 16:727–741. [PubMed: 15200701]

Kim KH, Yoon HW, Park HW. Spatiotemporal brain activation pattern during word/picture perception by native Koreans. NeuroReport. 2004; 15:1099–1103. [PubMed: 15129153]

Koyama S, Kakigi R, Hoshiyama M, Kitamura Y. Reading of Japanese Kanji (morphograms) and Kana (syllabograms): A magnetoencephalographic study. Neuropsychologia. 1998; 36:83–98. [PubMed: 9533391]

Kuriki S, Hirata Y, Fujimaki N, Kobayashi T. Magnetoencephalographic study on the cerebral neural activities related to the processing of visually presented characters. Brain Research, Cognitive Brain Research. 1996; 4:185–199. [PubMed: 8924047]

Lehmann D, Skrandies W. Reference-free identification of components of checkerboard-evoked multichannel potential fields. Electroencephalography and Clinical Neurophysiology. 1980; 48:609–621. [PubMed: 6155251]

Maurer U, Brandeis D, McCandliss B. Fast, visual specialization for reading in English revealed by the topography of the N170 ERP response. Behavioral and Brain Functions. 2005; 1:13. [PubMed: 16091138]

Maurer U, Brem S, Bucher K, Brandeis D. Emerging neurophysiological specialization for letter strings. Journal of Cognitive Neuroscience. 2005; 17:1532–1552. [PubMed: 16269095]

Maurer U, Brem S, Bucher K, Kranz F, Benz R, Steinhausen H-C, et al. Impaired tuning of a fast occipito-temporal response for print in dyslexic children learning to read. Brain. 2007; 130:3200–3210. [PubMed: 17728359]

Maurer U, Brem S, Kranz F, Bucher K, Benz R, Halder P, et al. Coarse neural tuning for print peaks when children learn to read. Neuroimage. 2006; 33:749–758. [PubMed: 16920367]

Maurer, U.; McCandliss, BD. The development of visual expertise for words: The contribution of electrophysiology. In: Grigorenko, EL.; Naples, AJ., editors. Single-word reading: Biological and behavioral perspectives. Erlbaum; Mahwah, NJ: 2007. p. 43-64.

McCandliss BD, Cohen L, Dehaene S. The visual word form area: Expertise for reading in the fusiform gyrus. Trends in Cognitive Sciences. 2003; 7:293–299. [PubMed: 12860187]

Nakamura K, Dehaene S, Jobert A, Le Bihan D, Kouider S. Subliminal convergence of Kanji and Kana words: Further evidence for functional parcellation of the posterior temporal cortex in visual word perception. Journal of Cognitive Neuroscience. 2005; 17:954–968. [PubMed: 15969912]

Palmeri TJ, Wong AC, Gauthier I. Computational approaches to the development of perceptual expertise. Trends in Cognitive Sciences. 2004; 8:378–386. [PubMed: 15335465]

Paulesu E, McCrory E, Fazio F, Menoncello L, Brunswick N, Cappa SF, et al. A cultural effect on brain function. Nature Neuroscience. 2000; 3:91–96.

Proverbio AM, Cok B, Zani A. Electrophysiological measures of language processing in bilinguals. Journal of Cognitive Neuroscience. 2002; 14:994–1017. [PubMed: 12419124]

Proverbio AM, Del Zotto M, Zani A. Greek language processing in naive and skilled readers: Functional properties of the VWFA investigated with ERPs. Cognitive Neuropsychology. 2006; 23:355–375. [PubMed: 21049335]

Proverbio AM, Leoni G, Zani A. Language switching mechanisms in simultaneous interpreters: An ERP study. Neuropsychologia. 2004; 42:1636–1656. [PubMed: 15327931]

Proverbio AM, Vecchi L, Zani A. From orthography to phonetics: ERP measures of grapheme-to-phoneme conversion mechanisms in reading. Journal of Cognitive Neuroscience. 2004; 16:301–317. [PubMed: 15068599]

Rossion B, Joyce CA, Cottrell GW, Tarr MJ. Early lateralization and orientation tuning for face, word, and object processing in the visual cortex. Neuroimage. 2003; 20:1609–1624. [PubMed: 14642472]

Sauseng P, Bergmann J, Wimmer H. When does the brain register deviances from standard word spellings?—An ERP study. Brain Research, Cognitive Brain Research. 2004; 20:529–532. [PubMed: 15268930]

Schendan HE, Ganis G, Kutas M. Neurophysiological evidence for visual perceptual categorization of words and faces within 150 ms. Psychophysiology. 1998; 35:240–251. [PubMed: 9564744]

Schlaggar BL, McCandliss BD. Development of neural systems for reading. Annual Review of Neuroscience. 2007; 30:475–503.

Shirahama Y, Ohta K, Takashima A, Matsushima E, Okubo Y. Magnetic brain activity elicited by visually presented symbols and Japanese characters. NeuroReport. 2004; 15:771–775. [PubMed: 15073512]

Tagamets MA, Novick JM, Chalmers ML, Friedman RB. A parametric approach to orthographic processing in the brain: An fMRI study. Journal of Cognitive Neuroscience. 2000; 12:281–297. [PubMed: 10771412]

Tan LH, Laird AR, Li K, Fox PT. Neuroanatomical correlates of phonological processing of Chinese characters and alphabetic words: A meta-analysis. Human Brain Mapping. 2005; 25:83–91. [PubMed: 15846817]

Tan LH, Liu HL, Perfetti CA, Spinks JA, Fox PT, Gao JH. The neural system underlying Chinese logograph reading. Neuroimage. 2001; 13:836–846. [PubMed: 11304080]

Tanaka JW, Curran T. A neural basis for expert object recognition. Psychological Science. 2001; 12:43–47. [PubMed: 11294227]

Tanji K, Suzuki K, Delorme A, Shamoto H, Nakasato N. High-frequency gamma-band activity in the basal temporal cortex during picture-naming and lexical-decision tasks. Journal of Neuroscience. 2005; 25:3287–3293. [PubMed: 15800183]

Tarkiainen A, Helenius P, Hansen PC, Cornelissen PL, Salmelin R. Dynamics of letter string perception in the human occipitotemporal cortex. Brain. 1999; 122:2119–2132. [PubMed: 10545397]

Thuy DH, Matsuo K, Nakamura K, Toma K, Oga T, Nakai T, et al. Implicit and explicit processing of kanji and kana words and non-words studied with fMRI. Neuroimage. 2004; 23:878–889. [PubMed: 15528088]

Wong AC, Gauthier I, Woroch B, DeBuse C, Curran T. An early electrophysiological response associated with expertise in letter perception. Cognitive, Affective & Behavioral Neuroscience. 2005; 5:306–318.

Zevin JD, McCandliss BD. Dishabituation of the BOLD response to speech sounds. Behavioral and Brain Functions. 2005; 1:4. [PubMed: 15953396]

Zevin JD, Seidenberg MS. Simulating consistency effects and individual differences in nonword naming. Journal of Memory and Language. 2006; 54:145–160.

Ziegler JC, Goswami U. Becoming literate in different languages: Similar problems, different solutions. Developmental Science. 2006; 9:429–436. [PubMed: 16911438]

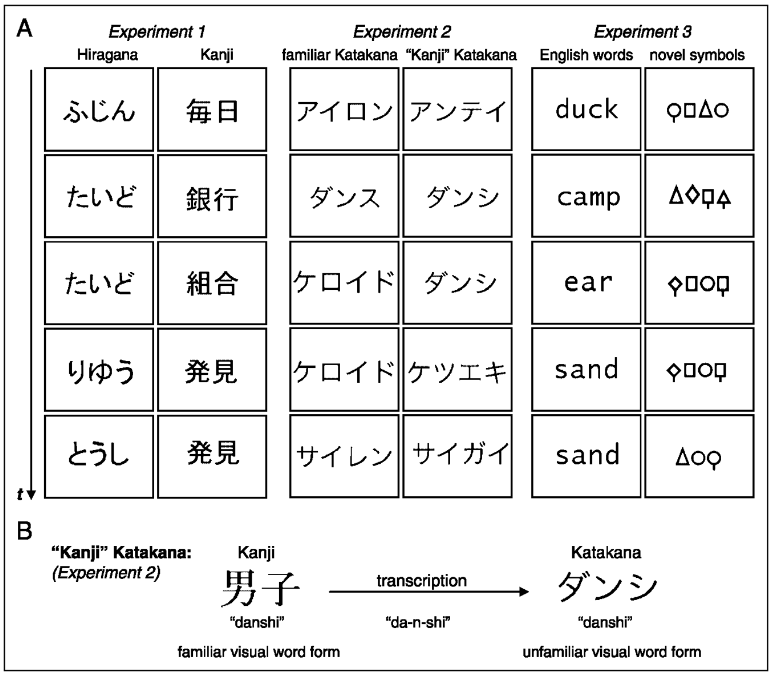

Figure 1.

Experimental stimuli. (A) The participants were presented words written in Hiragana and Kanji (Experiment 1), words written in Katakana with familiar and unfamiliar visual word form (Experiment 2), English words, and novel symbol strings (Experiment 3). In all three experiments, the task was to detect immediate repetitions, which could be done also for words written in an unfamiliar script and for novel symbol strings. The stimuli were presented for 250 msec separated by a fixation cross lasting for 1750 msec on average. ERPs were computed for nontarget stimuli only. (B) In Experiment 2, unfamiliar visual word forms were created by transcribing the word sound of words typically written in Kanji into Katakana script, which was possible because of the consistent phoneme-to-grapheme mapping of that script.

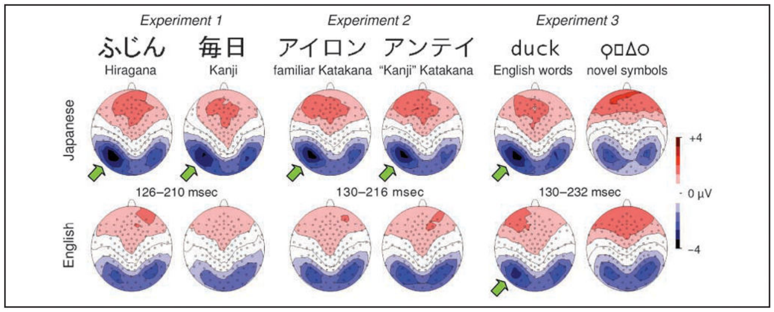

Figure 2.

N170 ERP maps. The N170 ERP maps elicited by words written in one of the three Japanese scripts (Hiragana, Katakana, Kanji) show increased amplitudes over left posterior channels in participants who can read Japanese (Japanese, first row) compared to participants who cannot read Japanese (English, second row). Familiar word forms (familiar Katakana, third column) elicit similar N170 maps as unfamiliar word forms (“Kanji” Katakana) in both Japanese and English participants. In both English and Japanese participants, who also could read English, English words elicited a left-lateralized N170 map compared to novel symbols.

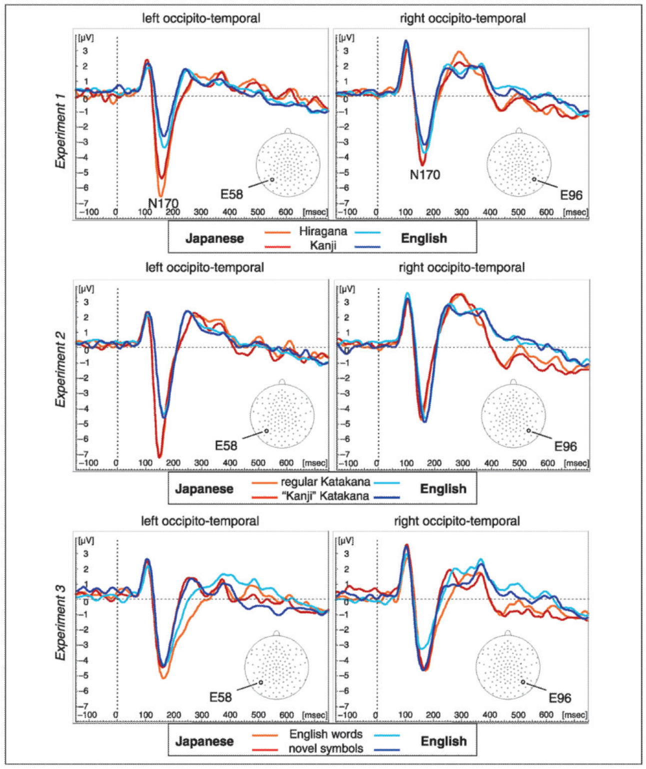

Figure 3.

N170 waveshapes. The waveshapes at the topographic peak channels over the left and right hemisphere show the increased N170 amplitudes for Japanese words (Hiragana, Katakana, Kanji) over the left hemisphere (left panel) in the Japanese participants (light and dark red lines) compared to the English participants (light and dark lines). Familiar and unfamiliar word forms (regular and "Kanji" Katakana) elicit almost identical waveshapes in the N170 range. The N170 in response to English words was more left-lateralized than for novel symbols in both groups because of an increase over the left hemisphere (Japanese) and a decrease over the right hemisphere (English).

Table 1

Behavioral Results [Mean (*SD*)]

	Accuracy (%)		***Reaction Time (msec)***	
	Japanese	***English***	***Japanese***	***English***
Experiment 1				
Hiragana	95.8 (11.0)	88.8 (12.9)	600 (101)	622 (83)
Kanji	96.3 (7.7)	83.4 (7.7)	637 (100)	630 (99)
Experiment 2				
Regular Katakana	96.9 (6.9)	89.7 (7.4)	632 (102)	625 (86)
“Kanji” Katakana	95.7 (7.3)	91.2 (10.3)	636 (98)	625 (85)
Experiment 3				
English words	97.1 (5.0)	96.7 (5.1)	640 (77)	613 (82)
Novel symbols	87.3 (20.3)	87.4 (14.5)	627 (102)	601 (93)

Table 2

N170 Analyses

	Map Strength (GFP)	*Occipito-temporal Channels*	*Map Latency*
Experiment 1	C: $F(1, 33) = 3.2^{\dagger}$	C: $F(1, 33) = 9.9^{**}$	C: $F(1, 33) = 3.6^{\dagger}$
		G: $F(1, 33) = 3.8^{\dagger}$	
		H × C: $F(1, 33) = 3.8^{\dagger}$	
		H × G: $F(1, 33) = 6.1^{*}$	
Experiment 2	–	H: $F(1, 33) = 6.2^{*}$	G: $F(1, 33) = 5.3^{*}$
		H × G: $F(1, 33) = 6.7^{*}$	
Experiment 3	–	C: $F(1, 33) = 4.3^{*}$	–
		H × C: $F(1, 33) = 14.6^{***}$	
		C × G: $F(1, 33) = 5.7^{*}$	

C = condition; G = group; H = hemisphere.

$^{*}p < .05$.

$^{**}p < .01$.

$^{***}p < .001$.

$^{\dagger}p < .1$.

Table 3

N170 Lateralization Tests (Left vs. Right)

	Japanese	***English***
Hiragana	$t(1, 17) = -\mathbf{2.5}^{*}$	$t(1, 16) = +0.8$
Kanji	$t(1, 17) = -\mathbf{2.0}^{\dagger}$	$t(1, 16) = +1.1$
Katakana (regular)	$t(1, 17) = -\mathbf{3.5}^{**}$	$t(1, 16) = +0.1$
Katakana (“Kanji”)	$t(1, 17) = -\mathbf{4.1}^{***}$	$t(1, 16) = +0.0$
English words	$t(1, 17) = -\mathbf{2.0}^{\dagger}$	$t(1, 16) = -\mathbf{2.2}^{*}$
Novel symbols	$t(1, 17) = -0.2$	$t(1, 16) = +0.9$

− = left > right; + = right > left.

* $p < .05$.

** $p < .01$.

*** $p < .001$.

† $p < .1$.