Published in final edited form as:

Brain Lang. 2008 November ; 107(2): 124–132. doi:10.1016/j.bandl.2008.01.011.

The Stroop Effect in Kana and Kanji Scripts in Native Japanese Speakers: An fMRI Study

Emily L. Coderre¹, Christopher G. Filippi², Paul A. Newhouse¹, and Julie A. Dumas^{1,*}

¹Clinical Neuroscience Research Unit, Department of Psychiatry, University of Vermont College of Medicine

²Department of Radiology, University of Vermont College of Medicine

Abstract

Prior research has shown that the two writing systems of the Japanese orthography are processed differently: kana (syllabic symbols) are processed like other phonetic languages such as English, while kanji (a logographic writing system) are processed like other logographic languages like Chinese. Previous work done with the Stroop task in Japanese has shown that these differences in processing strategies create differences in Stroop effects. This study investigated the Stroop effect in kanji and kana using functional magnetic resonance imaging (fMRI) to examine the similarities and differences in brain processing between logographic and phonetic languages. Nine native Japanese speakers performed the Stroop task both in kana and kanji scripts during fMRI. Both scripts individually produced significant Stroop effects as measured by the behavioral reaction time data. The imaging data for both scripts showed brain activation in the anterior cingulate gyrus, an area involved in inhibiting automatic processing. Though behavioral data showed no significant differences between the Stroop effects in kana and kanji, there were differential areas of activation in fMRI found for each writing system. In fMRI, the Stroop task activated an area in the left inferior parietal lobule during the kana task and the left inferior frontal gyrus during the kanji task. The results of the present study suggest that the Stroop task in Japanese kana and kanji elicits differential activation in brain regions involved in conflict detection and resolution for syllabic and logographic writing systems.

Keywords

Stroop task; Japanese kana and kanji; fMRI

Introduction

Previous research in the field of psycholinguistics has reported differences in the processing of logographic writing systems such as Japanese and Chinese as compared to alphabetic languages such as English. The Japanese orthography is particularly interesting to study because of its unique use of two different writing systems, *kana* and *kanji*. Japanese kana (of which there are two types, *hiragana* and *katakana*) is a syllabic writing system in which each symbol represents a syllable, which in turn allows a direct phonetic reading. Japanese kanji,

*Address for Correspondence (JD): Clinical Neuroscience Research Unit, Department of Psychiatry, University of Vermont College of Medicine, 1 South Prospect St., Burlington, VT 05401, Voice: (802) 847-2523, Fax: (802) 847-7889, Email: Julie.Dumas@uvm.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

in contrast, is a logographic writing system in which each symbol, or 'character', represents a word with a specific meaning. Kanji are Chinese symbols adopted into the Japanese orthography, with some slight alterations. A Chinese character generally consists of two individual parts called 'radicals', one signifying the pronunciation and the other the meaning. While the adoption of Chinese characters into Japanese kanji retained the meaning of the symbol, the pronunciation was changed (eg., the symbol for 'green' is the same in both languages, but pronounced 'lu' in Chinese and 'midori' in Japanese). This important aspect of the orthography means that the pronunciation of each individual kanji character must be memorized. Thus, while syllabic writing systems like kana map visual forms (graphemes) onto phonemes (sounds), logographic writing systems like kanji map forms (characters) onto morphemes (meanings). Recent research has shown that the fundamental linguistic differences between these syllabic and logographic writing systems create variations in how and where each script is processed in the brain (e.g. Nakamura, Dehaene, Jobert, Bihan, & Kouider, 2005; Thuy, Matsuo, Nakamura, Toma, Oga, Nakai, Shibasaki, & Fukuyama, 2004; Sakurai, Momose, Iwata, Sudo, Ohtomo & Kanazawa, 2000). The present study utilized functional magnetic resonance imaging (fMRI) to investigate the neural processing differences between kana and kanji, specifically through the use of a Japanese Stroop task. We first review the relevant literature regarding the psycholinguistic processing of kana and kanji, then present an account of the Stroop effect in Japanese and its differences between the two writing systems.

The combination of kana and kanji in Japanese provides the unique opportunity to study the processing of syllabic and logographic writing systems in the context of one language. Many studies have investigated the differences between logographic and alphabetic writing systems, generally with Chinese and English. Through studies of phonological processing, reading, and deficits due to dyslexia, these writing systems have been found to activate different areas of the brain. Chinese characters activate neural systems primarily in the left middle frontal gyrus, as well as areas of the ventral occipitotemporal system such as the fusiform gyrus (Tan, Spinks, Feng, Siok, Perfetti, Xiong, Fox & Gao, 2003; Tan, Laird, Li & Fox, 2005a; Tan, Spinks, Eden, Perfetti & Siok, 2005b; Siok, Perfetti, Jin & Tan, 2004; Bolger, Perfetti & Schneider, 2005). Alphabetic writing systems, on the other hand, primarily activate a left temporoparietal system including the mid-superior temporal gyri, left inferior parietal cortex and supramarginal gyrus, as well as a ventral occipitotemporal system including the right mid-inferior occipital gyrus (Tan et. al, 2005a; Bolger et.al, 2005). This prior research demonstrates that the fundamental linguistic differences in these writing systems are reflected in different processing regions within the brain.

Prior imaging studies of the Japanese language have shown dissociations between brain regions involved in kana and kanji processing across a range of tasks in monolingual speakers. Kana and kanji differences have been found specifically in semantic processing (Nakamura et al., 2005), phonological processing (Seki, Okada, Koeda & Sadato, 2004; Sekiguchi, Koyama & Kakigi, 2004), orthographic processing (Uchida, Kikyo, Nakajima, Konishi, Sekihara & Miyashita, 1999; Ischebeck, Indefrey, Usui, Nose, Hellwig & Taira, 2004), implicit and explicit word processing (Thuy et al., 2004), and word-reading in kanji and kana words and non-words (Sakurai et al, 2000; Sakurai, Momose, Iwata, Watanabe, Ishikawa & Kanazawa, 1993; Sakurai, Momose, Iwata, Watanabe, Ishikawa, Takeda & Kanazawa, 1992). Despite variability in tasks, methods, and imaging technologies, there are some consistent findings specific to kana and kanji that can be seen in this prior literature. Kana tends to activate the occipital, temporal, and parietal cortices (Nakamura et al., 2005; Thuy et al., 2004; Ischebeck et al., 2004; Sakurai et al., 1993; 2000). Kanji seems to primarily activate the temporal cortex, particularly the fusiform gyrus (Nakamura et al., 2005; Thuy et al., 2004; Sakurai et al., 2000). Though kana is a syllabic writing system, a comparison of these brain areas with the prior literature on alphabetic writing systems suggests that kana and alphabetic writing systems activate a similar temporoparietal system of processing (i.e. Nakamura et al., 2005; Thuy et

al., 2004; Ischebeck et al., 2004; Sakurai et al., 1993; 2000; Tan et. al, 2005a; Bolger et.al, 2005). A comparison of kanji with logographic writing systems suggests a similar recruitment of an occipitotemporal system, particularly the fusiform gyrus (i.e. Nakamura et al., 2005; Thuy et al., 2004; Sakurai et al., 2000; Tan et. al, 2003, 2005a, 2005b; Siok et. al, 2004; Bolger et al., 2005).

The Stroop phenomenon is potentially interesting in Japanese linguistics due to the processing differences between kana and kanji. In Stroop's original 1935 experiment performed in English, subjects were presented with color words printed colored ink and asked to name the color of the ink. Color words printed in an incongruent color (e.g., 'blue' printed in red ink) produced a slower reading time than simply naming blocks of color. This slower reading time is due to the conflict of two cognitive processes: naming the color and reading the word. According to various hypotheses, the dual stimuli of word and color are processed at the same speed up to the 'locus of interference' (Moriguchi & Morikawa, 1998). If the irrelevant stimulus (the word in the color-naming condition) reaches the locus of interference at the same time as or quicker than the relevant stimulus (the color), an extra cognitive effort will be needed to ignore the irrelevant information. Subjects must inhibit the more automatic process of word-reading and instead focus on the color, producing a slower reaction time known as the Stroop Effect.

Relatively little work has been done with the Stroop task in Japanese, though prior research has shown that there are differences in Stroop effects between kana and kanji. Studies of behavioral reaction time by Morikawa (1981) and Moriguchi and Morikawa (1998) have reported a greater Stroop effect in kanji than kana. In both studies these findings are explained by models of the Stroop effect and kana and kanji processing which propose that hemispheric processing differences exist between the scripts. Kana, along with color-names, are processed in the left hemisphere, resulting in less interference in kana color-naming because both words are processed in the same hemisphere. Kanji, along with the concept of colors, are processed in the right hemisphere, resulting in more interference because a hemispheric switch must be made in order to access the color name in the kanji condition (Sasanuma, Itoh, Mori & Kobayashi, 1977; Dyer, 1973). However, most recent imaging research indicates that there are no effects of laterality between the scripts (Nakamura et al., 2005; Seki et al., 2004; Sekiguchi et al., 2004; Uchida et al., 1999; Ischebeck et al., 2004; Thuy et al., 2004; Sakurai et al., 1992; 1993; 2000), and so such theories of hemispheric processing differences between kana and kanji have since been refuted.

The relationship between phonology and reading in kana and kanji may have implications for observing differences in patterns of Stroop effects between these two writing systems. Research on logographic languages like Chinese has found that Chinese processing requires both phonological and visuospatial information (Siok et. al, 2004; Spinks, Liu, Perfetti & Tan, 2000; Tan et. al, 2003, 2005a, 2005b; Perfetti & Liu, 2005; Perfetti, Liu & Tan, 2005). However, the role that phonology plays in Chinese seems to be different than in alphabetic languages, both in the neural representation of phonology (Tan et. al, 2003; Siok et. al, 2004; Tan et. al, 2005a) and the role of phonological awareness in reading (Tan et. al, 2005b; Spinks et. al, 2000). Perfetti et. al (2005) suggest a universal model of reading in which orthography, phonology and semantics are all directly linked, but the differences between writing systems depends on the graphic input units (letters or radicals). Thus, it appears that phonology is universally and cross-linguistically activated in reading processes, but the particular role of phonology differs between writing systems (Bolger et. al, 2005; Perfetti & Liu, 2005; Perfetti et. al, 2005).

Such differences between writing systems in the role of phonology on reading implies differences in the role of phonology in Japanese kana and kanji (see Bolger et. al, 2005 for a

meta-analysis). In the Japanese literature, Yamada et al. (1999) has found that kanji have a much stronger tie to meaning than phonology, since the characters are mapped onto morphemes (meanings) rather than phonemes (sounds), as in the syllabic kana. We hypothesize that native Japanese speakers should perform better on the incongruent color-naming task in kanji because it will be easier to ignore the phonology of the character and respond to the color of the ink. The kana incongruent color-naming task, however, should produce more conflict, as readers need to inhibit the automatic response of reading the word in order to name the color, as in English. This hypothesis, hereafter referred to as the Phonological Interference Hypothesis, would produce a greater Stroop effect for kana than kanji, reflected in a longer reaction time in the incongruent condition of kana relative to kanji.

The present study investigated the Phonological Interference Hypothesis of kana and kanji processing in a Japanese Stroop task, predicting a greater Stroop effect in kana than kanji. As the Stroop task requires inhibition of automatic responses, we expected to find increased activation in brain areas related to inhibition of cognitive functions, specifically the anterior cingulate cortex, which is reliably activated in such conflict tasks (Peterson, Skudlarski, Gatenby, Zhang, Anderson & Gore, 1999; Peterson, Kane, Alexander, Lacadie, Skudlarski, Leung, May & Gore, 2002). The activation of the anterior cingulate should be greater in the incongruent versus congruent conditions of the Stroop task. Though much work has been done investigating the differences between kana and kanji in other linguistic areas, this is the first study of its kind to use functional MRI to look at writing system differences in a Japanese Stroop task.

Methods

Participants

There were nine participants in this study (seven female), ages 18 and over and all right-handed native Japanese speakers who were also proficient in English. The mean age was 36 years ($SD=9.4$). Participants had an average of 17.2 years of education ($SD = 1.7$). Requirements for participation included self-reports of good health, normal or corrected-to-normal vision, and having Japanese as their native language. Exclusion criteria included a history of neurological and psychiatric disorders or other major illnesses that may affect cognitive functioning, current use of psychoactive medications, and consumption of more than three alcoholic drinks per day.

Procedure

Participants came to the University of Vermont Functional Brain Imaging Facility for an appointment that lasted approximately two hours. Subjects were paid \$50 for their participation. Informed consent was first obtained by the investigators. Subjects were then trained on the kana and kanji tasks before they took place in the scanner. The subjects were given instructions on the task and allowed to practice the keyboard button responses.

Kana Stroop Task—The Stroop task was used as a test of controlled and automatic processing. In this task a subject was presented with the words ‘red’, ‘green’ or ‘blue’ in kana in a random order, each printed in either red, green or blue ink. In the congruent condition the kana symbol being presented was congruent with the color of the ink, while in the incongruent condition the subject saw kana symbols printed in incongruent colors. In the control condition, subjects saw kana symbols that are not symbols for colors (‘telephone’, ‘dictionary’, and ‘clock’) printed in red, green or blue. While performance in the congruent condition may be facilitated by the matching color word, and performance in the incongruent condition may be impaired by the contrasting color word, a non-color control word should be neutral in regards to these influences. In all conditions the subject was asked to respond to the color of the symbols by pressing a button with their right hand to indicate the color (right index finger for red, right

middle finger for green, and right ring finger for blue). All words used in the Kana Stroop task were *hiragana* (the more commonly used script in modern Japanese) as opposed to *katakana* (which is generally used in specific circumstances, such as with words imported from other languages).

Kanji Stroop Task—This task was identical to the kana task except kanji symbols were used. It should be mentioned that each Japanese kanji can have more than one pronunciation depending on the context in which it is used. The character for ‘green’, for example, when seen by itself is pronounced with the Japanese pronunciation “midori”. However, if combined with other characters to form a new word, this character is pronounced “ryoku”, which is taken from the ancient Chinese pronunciation. The same is true for all kanji in Japanese. However, in this study we show only the color characters alone, and so we assume each is pronounced with the Japanese pronunciation (i.e. “aka” / red, “ao” / blue, and “midori” / green).

Each Stroop task contained blocks of congruent, incongruent, control or rest, each presented three times. Each block consisted of eight stimuli each of congruent, incongruent, and control stimuli. Blocks were presented in a counterbalanced order.

fMRI Scan Procedure and Preprocessing

Structural and functional MRI scans were acquired using the University of Vermont Functional Brain Imaging Facility which includes a Philips Achieva 3.0 Tesla scanner. All subjects received the following MR sequences as part of the imaging protocol: (1) A sagittal T1-weighted spoiled gradient volumetric sequence oriented perpendicular to the long axis of the temporal lobes and anterior commissure (AC)-posterior commissure (PC) line using a repetition time (TR) of 9.9 ms, echo time (TE) of 4.6 ms, a flip angle of 8 degrees, number signal averages (NSA) 1.0, a field of view (FOV) of 256 mm, a 256×256 matrix, and 1.0 mm slice thickness with no gap for 140 contiguous slices. (2) An axial T2-weighted gradient spin echo (GRASE) sequence using the AC-PC line for slice positioning. Twenty eight contiguous slices of 5 mm slice thickness and no gap were acquired using TR 2466 ms, TE 80 ms, NSA 3.0 and FOV of 230 mm. All images were reviewed by a board-certified neuroradiologist to exclude intracranial pathology. fMRI was performed using EpiBOLD (echoplanar blood oxygenation level dependent) imaging. For the fMRI sequences, a single-shot, gradient-echo, echoplanar pulse sequence was used (TR 2500 ms/TE 35 ms/flip angle 90 degrees/1 NSA). Resolution was $2.5 \text{ mm} \times 2.8 \text{ mm} \times 5.0 \text{ mm}$. Thirty contiguous slices of 5mm thickness with no gap were obtained in the axial oblique plane, parallel to the AC-PC line using a FOV of 240 mm and a matrix size of 128×96 . Field map correction for magnetic inhomogeneities was accomplished by acquiring images with offset TE at the end of the functional series.

Preprocessing and fixed effects analyses of the functional data were performed with Brain Voyager QX software (Brain Innovation, Maastricht, The Netherlands). Before the analyses were completed the following preprocessing steps were performed. Three-dimensional motion correction to correct for small head movements was completed by alignment of all volumes to the first volume. Estimated translation and rotation movements never exceed 2 mm for any subject in these analyses. Further data preprocessing comprised of linear trend removal and filters for spatial (4 mm full-width half-maximum isotropic Gaussian kernel) as well as temporal (high pass filter: 2 cycles/run) smoothing to remove aliased signal correlated with background respiration and heart rate. Anatomical and functional images were co-registered and normalized to Talairach space. Statistical analysis was performed by multiple linear regression of the signal time course in each voxel. The expected BOLD signal change for each condition within a run was modeled by a canonical hemodynamic response function.

fMRI Analyses

fMRI analysis involved deriving one mean image per individual for each relevant contrast in the activation task (e.g., incongruent > congruent) after accounting for the hemodynamic response function. These contrast images were further analyzed using standard paired *t*-test procedures in Brain Voyager. Given the small sample size, the critical significance level for group-level analyses was based on clusters of activated voxels with the probability threshold set at $p_{corr} < 0.05$.

Results

Performance Data

Kana versus Kanji processing—In order to examine reaction time differences in color naming between writing systems, paired-sample *t*-tests were performed on the median reaction times between kana and kanji in the congruent, incongruent and control conditions (i.e. kana congruent vs. kanji congruent, kana incongruent vs. kanji incongruent, kana control vs. kanji control). Though the overall pattern of means suggests faster processing times for kanji versus kana, none of the results from these comparisons were statistically significant (congruent: $t(7) = -1.6, p > 0.2$; incongruent: $t(7) = -1.4, p > 0.2$; control: $t(7) = -1.8, p > 0.1$; see Figure 1).

The Stroop Effect—In an effort to analyze the behavioral data and the functional imaging data using the same analytic strategy, we first computed the Stroop effects as defined by the incongruent condition minus the congruent or control conditions. Further comparisons across the two writing systems were then computed with paired sample *t*-tests. Stroop effects were found in the reaction time data for both kana and kanji. A one-sample *t*-test showed that this Stroop effect (defined as the incongruent condition minus the congruent condition) was significant in the kana condition ($t(7) = 2.9, p < 0.05$), indicated by a greater median reaction time in the incongruent condition ($M = 658.4$ ms, $SD = 89.4$) than the congruent condition ($M = 563.7$ ms, $SD = 46.3$). Kanji also produced a significant Stroop effect ($t(7) = 2.6, p < 0.05$), with a greater median reaction time in the incongruent condition ($M = 523.0$ ms, $SD = 328.8$) than the congruent condition ($M = 426.1$ ms, $SD = 239.2$). However, a within-subject comparison with a paired *t*-test of the Stroop effect in kana with the Stroop effect in kanji yielded no significant differences ($t(7) = 0.1, p > 0.9$). To eliminate potential facilitation effects from the congruent condition, the control condition was also compared to the incongruent condition to calculate Stroop effects in both kana and kanji. While the pattern of means suggested Stroop effects existed when examining the incongruent – the control conditions, the one sample *t*-tests yielded no significant differences (kanji incongruent – control: $t(7) = 2.0, p > 0.08$; kana incongruent – control: $t(7) = 1.1, p > 0.3$).

Neuroimaging Data

Kana versus kanji processing—First, we examined basic language processing by comparing the control conditions of each writing system through a subtraction of the activation for the kanji control condition from the kana control condition. Kana was found to activate the left inferior parietal lobe (BA 40) and left superior parietal lobe (BA 7), as well as the right postcentral gyrus (BA 2) in the parietal lobe (Table 1). Kanji activated the left superior and right medial frontal gyrus (BA 9), as well as a large occipital area including the lingual gyrus bilaterally (BA 18), and the left fusiform gyrus (BA 19).

The Stroop Effect—Next we examined the brain activity related to Stroop interference in kana and kanji in two different ways. First we subtracted the activation for congruent condition from the activation from the incongruent condition. For the comparison of the incongruent condition relative to the congruent condition in kana and kanji separately, similar areas of activation were found for both writing systems in regions of the cingulate gyrus and anterior

cingulate gyrus (BA 32, 24; Table 2). However, differences in activation in more peripheral brain areas were observed in the Stroop effects between the two writing systems. The Stroop effect in kana uniquely activated the left inferior parietal lobe (BA 40, Figure 2), while the Stroop effect in kanji uniquely activated the left inferior frontal gyrus (BA 9, Figure 3). A larger subtraction of the Stroop effect (incongruent – congruent) of kanji from the Stroop effect of kana was performed to directly analyze differences between writing systems in the amount of interference during the Stroop task (Table 3). Kana activated areas of the frontal lobe (BA 10), the precentral gyrus (BA 9) and the middle temporal gyrus (BA 37), as well as two small regions in the right anterior cingulate gyrus (BA 32/24). However, an area of deactivation in the left anterior cingulate (BA 32) suggests that kanji also activated this area. Because of the nature of this large subtraction, it is difficult to attribute these areas of activation and deactivation to the Stroop effect; that is, deactivation could be the result of the kana congruent or kanji incongruent conditions, rather than a larger writing system effect.

Second, as the matching color name and color ink in the congruent condition may result in a facilitation effect, we also compared the incongruent to the control conditions in kana and kanji (Table 4). Kana produced significant activation in the cingulate gyrus (BA 32), middle frontal gyrus (BA 6) and left inferior parietal lobule (BA 40), as well as the right superior temporal gyrus (BA 39) and right lingual gyrus (BA 17). Kanji produced significant activation in the cingulate gyrus (BA 24) and left medial frontal gyrus (BA 6), as well as the right superior temporal gyrus (BA 13) and the lingual gyrus (BA 17/18).

Discussion

The present study utilized fMRI to investigate the differences in brain activation between the two writing systems of Japanese, kana and kanji, as well as the effects of these writing systems on Stroop performance. Word processing in kana and kanji was examined by comparing the activation of the control condition in each writing system (Table 1). As the control words used in these tasks were color-neutral, this condition is the best approximation of reading without the interference or facilitation of the incongruent or congruent conditions. Kana mainly activated regions in the parietal lobe, including the left inferior parietal lobe (BA 40), left superior parietal lobe (BA 7), and the right postcentral gyrus (BA 2). Kanji activated the left superior and right medial frontal gyrus (BA 9) and the left fusiform gyrus (BA 19), as well as a large occipital system. These results are in keeping with previous research investigating the processing of kana and alphabetic languages (Tan et al., 2005a; Bolger et al., 2005; Nakamura et al., 2005; Thuy et al., 2004; Ischebeck et al., 2004; Sakurai et al., 1993, 2000), as well as kanji and logographic languages (Tan et al., 2003, 2005a, 2005b; Bolger et al., 2005; Siok et al., 2004; Nakamura et al., 2005; Thuy et al., 2004; Sakurai et al., 2000).

The Phonological Interference Hypothesis of Stroop performance in Japanese predicts less interference in the Stroop task for kanji because of a stronger tie to meaning than phonology, and thus a larger Stroop effect for kana than kanji. The results of the present study did not support this hypothesis. The Stroop task produced the expected effects in the behavioral reaction time data within each writing system; i.e. a greater reaction time for the incongruent relative to the congruent conditions for both kana and kanji. However, a direct comparison of the Stroop effect in kana to the Stroop effect in kanji did not show any significant differences in reaction time. Similarly, the imaging data showed individual Stroop effects in each writing system, evident in the activation of the cingulate gyrus in a subtraction of the congruent condition from the incongruent condition (Table 2). A direct comparison between the Stroop effects of kana and kanji resulted in activation of the cingulate and anterior cingulate gyri by both kana and kanji, as well as other frontal and temporal regions activated by kana (Table 3); however, all areas of significant activation were fairly small. It appears that there is no difference in the cingulate gyrus during the Stroop performance in kana and kanji. Though

some previous research has indicated a stronger tie of kanji to phonology than to meaning (Yamada et. al, 1999), recent research indicates that Chinese character reading involved phonological as well as semantic information (Perfetti et. al, 2005; Perfetti & Liu, 2005; Tan et. al, 2003, 2005a,b; Spinks et. al, 2000; Siok et. al, 2004). More generally, phonology is universally activated in word reading in both logographic and phonetic writing systems, though the particular role of phonology differs between them (Bolger et. al, 2005; Perfetti & Liu, 2005; Perfetti et. al, 2005). The lack of a difference between the Stroop effects of kana and kanji and the contradiction of the Phonological Interference Hypothesis suggest that perhaps the role of phonology in kana and kanji processing is not as different as previously thought. More work needs to be done in this particular area of the Stroop Effect in Japanese to draw any further conclusions.

Though the expected cingulate gyrus difference was not observed, there were two distinctly different fMRI activations in kana and kanji Stroop performance. An analysis of the Stroop effect in kana showed significant activation in the left inferior parietal lobe (BA 40; Figure 2). In contrast, the Stroop effect in kanji showed activation in the left inferior frontal gyrus (BA 9; Figure 3). These activations were exclusive to each writing system. There are several possible explanations for this observation. First, the left parietal and left frontal lobes have been associated with the processing of alphabetic and logographic writing systems, respectively (Tan et al., 2003, 2005a,b; Siok et al., 2004; Bolger et al., 2005). Though it is tempting to attribute the differences observed here to the underlying differences between kana, which are processed syllabically, and kanji, which are processed logographically, research is conflicting in this area. For example, Tan et al. (2005a) found the left inferior parietal lobe to be activated during phonological processing of Chinese characters, and the left inferior frontal gyrus to be involved in alphabetic word processing. It appears that there are large networks of processing for each type of writing system, with many overlapping areas, as has been demonstrated by Bolger et al. (2005), who suggested that all writing systems share similar cortical systems and differ only in their localization within these systems. Much more extensive research is required to identify the specific locations of kana and kanji, or alphabetic and logographic writing systems, in the brain.

Another interpretation may relate to an association between these areas of activation and the anterior cingulate gyrus. The additional areas activated in the analysis of the Stroop effect in each writing system included Brodmann's areas 40, 9 and 6. These areas have all been shown in previous studies to be involved in conflict and interference tasks (van Veen & Carter, 2005; Peterson et al., 2002; Kemmotsu, Villalobos, Gaffrey, Courchesne & Muller, 2005; Brown, Kindermann, Siegle, Granholm, Wong & Buxton, 1999; Fan, Flombaum, McCandliss, Thomas & Posner, 2003), and appear to be part of a network of attention and conflict resolution that includes the anterior cingulate gyrus. Though the anterior cingulate gyrus is known to be involved in conflict tasks and the inhibition of automatic responses, the exact function of this area is largely unknown. One view, known as the conflict monitoring hypothesis, suggests that the anterior cingulate gyrus plays a more passive role by detecting cognitive conflict, then sending a signal to other regulative networks, including frontal and parietal regions, that are responsible for resolving that conflict (Botvinick, Braver, Barch, Carter & Cohen, 2001; Botvinick, Cohen & Carter 2004; Roelofs, van Turennout & Coles, 2006; Fan et al., 2003). Though no differences were found in the anterior cingulate gyrus between writing systems, the differences in peripheral cortical activation between kana and kanji in the current study suggest that there may be different underlying neural attention and control networks that contribute to the mediation of conflict and interference.

We also examined the incongruent minus control conditions for kana and kanji (Table 4). Kana produced activation in the cingulate gyrus, right middle frontal gyrus and left inferior parietal lobe: areas that are identical to the results from the Stroop Effect subtraction of incongruent –

congruent conditions. Kanji produced activation in the cingulate gyrus and left medial frontal gyrus, areas that again are similar to those in the incongruent – congruent conditions. However, both writing systems also produced activation in the right superior temporal gyrus (BA 39) and lingual gyrus (BA 17/18), which were not found in the incongruent – congruent analysis. This additional activation could be attributed to the involvement of reading processes in the control conditions. Though we had chosen the control words because of their neutrality with regards to color words, and though the subjects are meant to be focusing on the color of ink, automatic reading processes are still recruited. Future research on the Stroop task in Japanese should control for this reading effect by presenting colored blocks instead of color-neutral words.

One important distinction to be made when discussing language processing is that of monolingualism versus bilingualism. Almost all language processing literature previously reviewed was performed on monolingual Japanese (Ischebeck et al., 2004; Moriguchi & Morikawa, 1998; Morikawa 1981; Nakagawa 1994; Nakamura et al., 2005; Sakurai et al., 1992, 1993, 2000; Seki et al., 2004; Sekiguchi et al., 2004; Thuy et al., 2004; Uchida et al., 1999; Yamada et al., 1999) or Chinese speakers (Siok et al., 2004; Tan et al., 2005b). Only one study investigated bilingual participants (Tan et al., 2003), and this research suggested that language experience, both native and second, influences the processing of other languages in the bilingual brain. In the present study all subjects were native Japanese speakers, though some had been raised bilingual. Because the study was carried out in the United States, all subjects also had at least a basic degree of proficiency in English and sometimes other alphabetic languages. Though alphabetic language experience was not specifically examined in the present study, experience with other alphabetic languages could lead to a more alphabetic way of reading, and should be considered further in future studies.

Although this is the first study to examine the Japanese Stroop task with fMRI, and while further research on the processing of kana and kanji and on the Stroop task in Japanese is needed to clarify the neural circuitry and processing of these writing systems, there appear to be significant differences in the processing of kana and kanji. Significant areas of activation were observed in the left inferior parietal lobe for kana and in the left inferior frontal lobe for kanji. Differences were also found in the networks of conflict monitoring and resolution that mediate Stroop task performance. These observations lend support to many previous studies that have investigated differences between kana and kanji, and suggest that these alphabetic and logographic writing systems are organized and processed differently in the brain.

References

- 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]
- Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD. Conflict monitoring band cognitive control. *Psychological Review* 2001;108(3):624–652. [PubMed: 11488380]
- Botvinick MM, Cohen J, Carter CS. Conflict monitoring and anterior cingulate cortex: an update. *Trends in Cognitive Sciences* 2004;8(12):539–546. [PubMed: 15556023]
- Brown G, Kindermann S, Siegle G, Granholm E, Wong E, Buxton R. Brain activation and pupil response during covert performance of the Stroop Color Word task. *Journal of the International Neuropsychological Society* 1999;5(4):308–319. [PubMed: 10349294]
- Dyer FN. Interference and facilitation for color naming with separate bilateral presentations of the word and color. *Journal of Experimental Psychology* 1973;99(3):314–317. [PubMed: 4742545]
- Fan J, Flombaum J, McCandliss B, Thomas K, Posner M. Cognitive and brain consequences of conflict. *Neuroimage* 2003;18(1):42–57. [PubMed: 12507442]

- 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(5):727–741. [PubMed: 15200701]
- Kemmotsu N, Villalobos M, Gaffrey M, Courchesne E, Muller R. Activity and functional connectivity of inferior frontal cortex associated with response conflict. *Cognitive Brain Research* 2005;24(2):335–342. [PubMed: 15993771]
- Moriguchi K, Morikawa Y. Time course analysis of the reverse-stroop effect in Japanese kanji. *Perceptual and Motor Skills* 1998;87:163–174. [PubMed: 9760643]
- Morikawa Y. Stroop phenomena in the Japanese language: The case of ideographic characters (*kanji*) and syllabic characters (*kana*). *Perceptual and Motor Skills* 1981;53:67–77. [PubMed: 7290886]
- Nakagawa A. Visual and semantic processing in reading kanji. *Journal of Experimental Psychology: Human Perception and Performance* 1994;20(4):864–875. [PubMed: 8083640]
- Nakamura K, Dehaene S, Jobert A, 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(6):954–968. [PubMed: 15969912]
- Perfetti CA, Liu Y. Orthography to phonology and meaning: Comparisons across and within writing systems. *Reading and Writing* 2005;18:193–210.
- Perfetti CA, Liu Y, Tan LH. The Lexical Constituency Model: Some Implications of Research on Chinese for General Theories of Reading. *Psychological Review* 2005;112(1):43–59. [PubMed: 15631587]
- Peterson B, Kane M, Alexander G, Lacadie C, Skudlarski P, Leung H, May J, Gore J. An event-related functional MRI study comparing interference effects in the Simon and Stroop tasks. *Cognitive Brain Research* 2002;13(3):427–440. [PubMed: 11919006]
- Peterson B, Skudlarski P, Gatenby J, Zhang H, Anderson A, Gore J. An fMRI Study of Stroop Word-Color Interference: Evidence for Cingulate Subregions Subserving Multiple Distributed Attentional Systems. *Biological Psychiatry* 1999;45:1237–1258. [PubMed: 10349031]
- Roelofs A, van Turenout M, Coles MGH. Anterior cingulate cortex activity can be independent of response conflict in Stroop-like tasks. *Proceedings of the National Academy of Sciences* 2006;103(37):13884–13889.
- Sakurai Y, Momose T, Iwata M, Watanabe T, Ishikawa T, Takeda K, Kanazawa I. Kanji word reading process analyzed by positron emission tomography. *NeuroReport* 1992;3:445–448. [PubMed: 1633284]
- Sakurai Y, Momose T, Iwata M, Watanabe T, Ishikawa T, Kanazawa I. Semantic process in kana word reading: activation studies with positron emission tomography. *Neuroreport* 1993;4(3):327–330. [PubMed: 8477056]
- Sakurai Y, Momose T, Iwata M, Sudo Y, Ohtomo K, Kanazawa I. Different cortical activity in reading of Kanji words, Kana words and Kana nonwords. *Cognitive Brain Research* 2000;9(1):111–115. [PubMed: 10666563]
- Sasanuma S, Itoh M, Mori K, Kobayashi Y. Tachistoscopic recognition of kana and kanji words. *Neuropsychologia* 1977;15(4–5):547–553. [PubMed: 896010]
- Seki A, Okada T, Koeda T, Sadato N. Phonemic manipulation in Japanese: an fMRI study. *Cognitive Brain Research* 2004;20:261–272. [PubMed: 15183397]
- Sekiguchi T, Koyama S, Kakigi R. The effect of phonological repetition on cortical magnetic responses evoked by visually presented words. *Journal of Cognitive Neuroscience* 2004;16(7):1250–1261. [PubMed: 15453977]
- Siok WT, Perfetti CA, Jin Z, Tan LH. Biological abnormality of impaired reading is constrained by culture. *Nature* 2004;431:71–76. [PubMed: 15343334]
- Spinks JA, Liu Y, Perfetti CA, Tan LH. Reading Chinese characters for meaning: the role of phonological information. *Cognition* 2000;76:B1–B11. [PubMed: 10822044]
- 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* 2005a;25:83–91. [PubMed: 15846817]
- Tan LH, Spinks JA, Feng CM, Siok WT, Perfetti CA, Xiong J, Fox PT, Gao JH. Neural Systems of Second Language Reading Are Shaped by Native Language. *Human Brain Mapping* 2003;18:158–166. [PubMed: 12599273]

- Tan LH, Spinks JA, Eden GF, Perfetti CA, Siok WT. Reading depends on writing, in Chinese. *Proceeds of the National Academy of Sciences* 2005b;102(24):8781–8785.
- Thuy D, Matsuo K, Nakamura K, Toma K, Oga T, Nakai T, Shibasaki H, Fukuyama H. Implicit and explicit processing of kanji and kana words and non-words studied with fMRI. *NeuroImage* 2004;23:878–889. [PubMed: 15528088]
- Uchida I, Kikyo H, Nakajima K, Konishi S, Sekihara K, Miyashita Y. Activation of lateral extrastriate areas during orthographic processing of Japanese characters studied with fMRI. *NeuroImage* 1999;9:208–215. [PubMed: 9927549]
- van Veen V, Carter C. Separating semantic conflict and response conflict in the Stroop task: a functional MRI study. *Neuroimage* 2005;27(3):497–504. [PubMed: 15964208]
- Yamada J, Kayamoto Y, Morita A. Japanese kanji as a semantically based orthography. *Psychological Reports* 1999;84:637–642.

Figure 1. Median reaction times of congruent, incongruent and control conditions of the Stroop task in kana and kanji scripts (with standard error bars).

Figure 2.
Incongruent minus congruent condition in the Kana Stroop task, showing activation of the inferior parietal lobe.

Figure 3. Incongruent minus congruent condition in the Kanji Stroop task, showing activation of the inferior frontal gyrus.

Table 1

Writing system comparisons between kana and kanji¹

Contrast	Coordinates			Cluster Extent	Region Description	t value	p value
	x	y	z				
Kana control > kanji control	-30	-34	34	980	Left inferior parietal lobe (BA 40)	4.323	<0.00002
	-21	-58	58	575	Left superior parietal lobe (BA 7)	4.308	<0.00002
	-19	41	10	197	Left medial frontal gyrus (BA 10)	3.335	<0.00087
	45	-19	28	129	Right postcentral gyrus (BA 2)	4.209	<0.00003
	15	-67	49	150	Right precuneus (BA 7)	3.673	<0.00025
	6	32	31	2615	Right medial frontal gyrus (BA 9)	-4.68	<0.000003
	-15	44	31	1225	Left superior frontal gyrus (BA 9)	-4.474	<0.00001
	12	-80	1	27424	Right lingual gyrus (BA 18)	-4.702	<0.000003
	-12	-76	4	2968	Left lingual gyrus (BA 18)	-5.866	<5.19e-9
	-21	-58	-9	2968	Left fusiform gyrus (BA 19)	-5.329	<1.10e-7

¹ Condition comparisons, Talairach coordinates, cluster size, region descriptions (Brodmann's areas, BA), t values and p values.

Table 2
Individual Stroop Effect comparisons for kana and kanji²

Contrast	Coordinates			Cluster Extent	Region Description	t value	p value
	x	y	z				
Kana Incongruent > congruent	9	14	34	1151	Right cingulate gyrus (BA 32)	2.917	<0.0036
	-6	20	43	1151	Left cingulate gyrus (BA 32)	3.296	<0.0010
	-6	47	3	643	Left anterior cingulate (BA 32)	-3.013	<0.0026
	39	2	25	1082	Right precentral gyrus (BA 6)	3.744	<0.0002
	-45	-46	40	461	Left inferior parietal lobe (BA 40)	3.466	<0.0006
Kanji Incongruent > congruent	-6	20	37	1171	Left cingulate gyrus (BA 32)	3.402	<0.0007
	9	23	37	311	Right cingulate gyrus (BA 32)	3.456	<0.0006
	-7	35	4	5635	Left anterior cingulate (BA 24)	-3.862	<0.0001
	-6	2	52	380	Left medial frontal gyrus (BA 6)	3.21	<0.0014
	-48	5	31	2000	Left inferior frontal gyrus (BA 9)	3.595	<0.0003

²Condition comparisons, Talairach coordinates, cluster size, region descriptions (Brodmann's areas, BA), t values and p values.

Table 3
Stroop Effect (defined as incongruent > congruent) comparisons between kana and kanji.³

Contrast	Coordinates			Cluster Extent	Region Description	t value	p value
	x	y	z				
(Kana incongruent > congruent) > (kanji incongruent > congruent)	12	28	22	448	Right anterior cingulate (BA 32)	2.367	<0.01803
	-18	23	34	209	Left cingulate gyrus (BA 32)	-3.104	<0.00194
	3	23	19	176	Right anterior cingulate (BA 24)	2.568	<0.01030
	-36	23	34	285	Left precentral gyrus (BA 9)	3.027	<0.00250
	42	-4	25	715	Right inferior frontal gyrus (BA 9)	3.991	<0.00007
	12	59	19	771	Right superior frontal gyrus (BA 10)	3.3	<0.00098
	-42	-55	-5	378	Left middle temporal gyrus (BA 37)	3.865	<0.00011

³ Condition comparisons, Talairach coordinates, cluster size, region descriptions (Brodmann's areas, BA), t values and p values.

Table 4

Incongruent and control comparisons for kana and kanji.⁴

Contrast	Coordinates			Cluster Extent	Region Description	<i>t</i> value	<i>p</i> value
	x	y	z				
Kana incongruent > control	7	17	42	3461	Right cingulate gyrus (BA 32)	3.815	<0.00014
	36	-1	39	1310	Right middle frontal gyrus (BA 6)	3.328	<0.00091
	-45	-52	40	2047	Left inferior parietal lobe (BA 40)	3.559	<0.00039
	-45	11	37	3609	Left middle frontal gyrus (BA 8)	3.77	<0.00017
	-4	17	49	3461	Left superior frontal gyrus (BA 8)	3.531	<0.00043
	39	-49	28	1460	Right superior temporal gyrus (BA 39)	2.834	<0.00468
Kanji incongruent > control	12	-88	4	2765	Right lingual gyrus (BA 17)	3.988	<0.00007
	-15	2	36	1325	Left cingulate gyrus (BA 24)	3.489	<0.00051
	9	5	31	1398	Right cingulate gyrus (BA 24)	2.907	<0.00372
	-10	8	52	369	Left medial frontal gyrus (BA 6)	3.406	<0.00068
	43	-46	20	771	Right superior temporal gyrus (BA 13)	2.868	<0.00422
	-9	-82	-11	11950	Left lingual gyrus (BA 18)	-6.217	<7.26e-10
	12	-82	1	11165	Right lingual gyrus (BA 17)	-6.892	<9.46e-12

⁴ Condition comparisons, Talairach coordinates, cluster size, region descriptions (Brodmann's areas, BA), *t* values and *p* values.