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Ichi, Ni, 3, 4: Neural Representation of Kana, Kanji, and Arabic Numbers in Native Japanese Speakers

Emily L. Coderre[1], **Christopher G. Filippi**[2], **Paul A. Newhouse**[1], and **Julie A. Dumas**[1],*

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

[2] Department of Radiology, University of Vermont College of Medicine

Abstract

The Japanese language represents numbers in kana digit words (a syllabic notation), kanji numbers and Arabic numbers (logographic notations). Kanji and Arabic numbers have previously shown similar patterns of numerical processing, and because of their shared logographic properties may exhibit similar brain areas of numerical representation. Kana digit words require a larger phonetic component, and therefore may show different areas of numerical representation as compared to kanji or Arabic numbers. The present study investigated behavioral reaction times and brain activation with fMRI during the numerical processing of kana digit words, kanji numbers and Arabic numbers. No differences in behavioral reaction time were found between kanji and Arabic numbers. In contrast, kana digit words produced a longer reaction time as compared to the other two notations. The imaging data showed that kana activated the posterior cingulate cortex when compared to kanji and Arabic numbers. It is suggested that this posterior cingulate activation reflects an additional attentional demand in this script which may be related to the infrequent use of kana digit words, or may reflect an extra step of phonological mediation in converting the visual word form to the verbal word form. Overall, the data suggest that number reading is processed differently in these three notations.

Keywords

number processing; Japanese kana and kanji; symbolic notation; fMRI

Behavioral evidence from previous studies with both humans and animals has supported the idea of a central area of number processing in the brain (Verguts & Fias, 2004; Dehaene, Dehaene-Lambertz & Cohen, 1998) and has generated theories of an internal analogue magnitude representation, similar to a 'mental number line' (Verguts & Fias, 2004; Fias, Lammertyn, Reynvoet, Dupont & Orban, 2003). These suggestions are supported by the well-documented findings of distance and size effects in number comparison. As the distance between two numbers being compared decreases, the reaction time in judging which is larger increases (a *distance effect*); and as the size of numbers being compared increases, reaction time increases (a *size effect*) (Moyer & Landauer, 1967; Dehaene et al., 1998; Verguts & Fias, 2004; Libertus, Woldorff & Brannon, 2007). It has been suggested that the internal representation of numerical magnitude is coded in a notation-independent representation, and

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*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.

is shared by both symbolic (i.e. Arabic numbers) and non-symbolic (i.e. dot arrays) stimuli (Ansari, 2008; Fias et al., 2003; Libertus et al., 2007; Verguts & Fias, 2004; see Dehaene et al., 1998 and Ansari 2008 for reviews).

One of the most prominent models of number processing is Dehaene's Triple Code Model. This model proposes three separate representations of number: the visual number form, verbal word frame, and analogue magnitude representation (Dehaene, 1992). The first two representations are notation-dependent (i.e. based on whether numbers are presented as Arabic numerals, written or spoken words) and function at the identification level. The third is a notation-independent semantic representation, similar to an abstract mental number line. Dehaene posits that these first two representations are automatically translated into the third; that is, written or spoken numbers are automatically translated into an analogue magnitude representation, meaning that numbers automatically activate semanticity (meaning).

Imaging studies have supported such theories of a central number processing area, and have identified the left intraparietal sulcus (IPS) of the parietal lobe as being the central brain area for number representation and processing (Cohen Kadosh, Henik, Rubinsten, Mohr, Dori, van de Ven, Zorzi, Hendler, Goebel & Linden, 2005; Göbel, Johansen-Berg, Behrens & Rushworth, 2004; Dehaene, Piazza, Pinel & Cohen, 2003). The left IPS is particularly active during tasks involving comparison of numbers and number representation, and has also been found to be involved in the representation of numerical magnitude in both symbolic and non-symbolic stimuli (Fias et al., 2003; Ansari 2008). It has also been suggested that within the left IPS there are subtle differences in the methods of processing for symbolic and non-symbolic stimuli (Ansari 2008; Verguts & Fias, 2004). For example, symbolic representations (i.e. Arabic numbers, digit words) may be more precisely coded than non-symbolic representations (dot arrays). Additionally, variations in symbolic representations (i.e. Arabic numbers vs. digit words) may lead to notation-specific symbolic representation within the bilateral IPS (Ansari 2008; Cohen Kadosh, Cohen Kadosh, Kaas, Henik & Goebel, 2007).

Though there seems to be a central area of neural processing regardless of stimulus type, behavioral processing differences between symbolic notations have been demonstrated by the robust finding that a longer numerical memory span is possible with Arabic numbers (e.g. 4 5 2) than digit words (e.g. four five two) (Chincotta & Underwood, 1997), a phenomenon known as a “numerical memory span advantage”. This may be due to a variety of different factors, including the role of phonology in digit words which is absent in numerals, the strategy of “chunking” numerals together, or the reduced amount of visual information present in Arabic numbers as compared to digit words (Flaherty & Moran 2000). Most previous studies investigating this trend have focused on languages which share the properties of an alphabetic writing system (e.g. Spanish, English, etc.). However, there is little research taking into consideration the inherent psycholinguistic differences in logographic writing systems (e.g. Chinese, Japanese kanji) and how variations in symbolic notations may affect numerical processing.

It has been shown that logographic and alphabetic writing systems activate different areas of the brain: logographic writing systems activate neural systems primarily in the left middle frontal gyrus, and 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), whereas alphabetic writing systems activate a left temporoparietal system, including the superior temporal gyrus and the inferior parietal cortex (Tan et. al, 2005a; Bolger et al., 2005). It should be mentioned that this literature is quite inconsistent in terms of specific and segregated regions of activation for logographic and alphabetic writing systems; however, these are the most commonly converging areas activated in the literature.

In an investigation of the neural representation of Arabic numerals in Chinese and English native speakers, Tang et al. (2006) found that native English and native Chinese speakers elicited different brain areas during comparison of Arabic numerals (which are also frequently used in Chinese). Specifically, Chinese speakers showed more activation in a premotor association area, and had similar patterns of activation in comparing both non-numerical symbols and Arabic numbers. The authors suggest that Chinese speakers use a visuo-spatial system in representing Arabic numbers. This may stem from their experience with reading Chinese characters, which are also very dependent on visuo-spatial relations. Their findings support the idea that linguistic differences among cultures lead to number processing differences in the brain, even in such shared symbolic representations as Arabic numbers.

Japanese uses both a syllabic (*kana*) and logographic (*kanji*) writing system interchangeably, a characteristic which allows the study of both types of writing systems within one language. Japanese kana allows a direct phonetic reading, as each symbol represents a syllable, and thus for the purposes of this paper are analogous to digit words (i.e. “three”). Japanese kanji are Chinese characters with modified pronunciations, and like Arabic numbers require the pronunciation of each individual character to be memorized (i.e. there are no phonetic clues in the symbol ‘4’ that indicate its pronunciation, ‘four’). Imaging studies have shown that kana are processed, like alphabetic writing systems, in a left temporoparietal system as well as the occipital cortex (Nakamura, Dehaene, Jobert, Bihan & Kouider, 2005; Thuy, Matsuo, Nakamura, Toma, Oga, Nakai, Shibasaki & Fukuyama, 2004; Ischebeck, Indefrey, Usui, Nose, Hellwig & Taira, 2004; Sakurai, Momose, Iwata, Watanabe, Ishikawa & Kanazawa, 1993; Sakurai, Momose, Iwata, Sudo, Ohtomo & Kanazawa, 2000; Coderre, Filippi, Newhouse & Dumas, 2008), whereas kanji, like logographic writing systems, activate the temporal cortex, particularly the fusiform gyrus (Nakamura et al., 2005; Thuy et al., 2004; Sakurai et al., 2000; Coderre et al., 2008). Japanese uses Arabic numbers interchangeably with kanji numbers, and with near-equal frequency, although kanji is the more formal and traditional representation. Kana digit words can also be used, although kana representations are not seen very often in print. Children learn the kana representations early in school, but then switch over to the more frequently-used kanji. Thus, Japanese is unique in its ability to represent numbers in three different notations each having the same pronunciation (see Figure 1). In addition, the shared logographic properties of kanji and Arabic numbers present the possibility that these two notations are processed similarly in the brain.

Flaherty and Moran (2000) examined the differences in processing between kanji and Arabic numbers in native Japanese speakers through the use of a numerical memory span task. They found no differences between memory spans, as subjects could remember just as many numbers presented in Arabic as in kanji. This finding indicated that there is no numerical memory span advantage in Japanese. In a subsequent study of English and Japanese deaf and hearing individuals, Flaherty and Moran (2004) found that English deaf subjects had shorter memory spans than English hearing subjects for both English digit words and Arabic numbers. Because of the importance of phonology in English, deaf individuals often have a harder time with English linguistic materials than hearing individuals. However, Japanese deaf and hearing subjects showed comparable numerical memory spans both for kanji and Arabic numbers. Because kanji are visually-based, as are Arabic numbers, they are better suited to the visual memory strategies of deaf subjects and result in comparable memory spans in deaf and hearing Japanese subjects. These studies illustrate the similarities in processing between kanji and Arabic numbers, and support the theory that these two symbolic representations have similar processing methods.

A study by Ito and Hatta (2003) examined the differences between kana digit words, kanji numbers and Arabic numbers as applied to Dehaene's Triple-Code model. Using a direct numerical task (numerical size judgment), the authors hypothesized that if all three notations shared a common semantic representation of number, then similar distance effects would be found. The results showed that although there were differences in reaction time between the notations (indicating differences in representation at the identification stage), all three symbolic notations showed distance effects, and thus may have a common semantic representation. As expected, this supports Dehaene's idea that notation-dependent numerical representations are translated into a notation-independent semantic representation. In a second experiment, the authors used an indirect numerical task (physical size judgment), to test Dehaene's proposal that semantic number representation is automatically activated for all symbolic notations. The authors hypothesized that if all three scripts have a common semantic representation, and semantics are automatically activated, there would be similar distance and congruity effects across the three notations. A congruity effect occurs when, in a numerical comparison task in which one number is physically larger than the other, reaction time is faster when numerically larger numbers are also physically larger. However, all three notations produced different effects, suggesting that (contrary to Dehaene's proposal) semantics are not *automatically* activated, and there is different semantic processing across the notations in an indirect numerical task. The authors speculated that the connections between the notation-dependent and semantic representations were stronger for Arabic and kanji numbers than for kana digit words. Additionally, even though all three notations have identical pronunciations, the role of phonology may come into play in kana digit words and cause additional delays as the visual number is translated into the verbal number. In other words, in kana digit words the visual number form is translated into the verbal number form, which is then translated into the semantic representation of the number. In contrast, kanji and Arabic numbers, which do not have as strong of a connection to phonology, proceed from the visual form straight to the semantic number representation.

The present study investigated the numerical processing of kanji numbers and kana digit words as compared to Arabic numbers both in behavioral reaction time and with fMRI while subjects performed a number naming task. This is the first study of its kind to utilize fMRI to investigate all three symbolic notations found in Japanese: kana digit words, kanji numbers and Arabic numbers. Due to their syllabic properties, we expected kana digit words to show similar results as other alphabetic digit words (Flaherty & Moran, 2004). Kana should elicit longer reaction times in the behavioral data and produce different patterns of brain activation as compared to kanji or Arabic numbers. Because of a larger effect of phonology and reading in kana, as in other alphabetic languages (Flaherty & Moran, 2004; Ito & Hatta, 2003), we hypothesized that areas related to kana processing would be activated in the kana digit word condition, specifically areas of the temporal and parietal cortices including the inferior parietal cortex and the superior temporal gyrus (Coderre et al., 2008; Tan et al., 2005a; Nakamura et al., 2005; Thuy et al., 2004; Ischebeck et al., 2004; Sakurai et al., 1993; 2000). Because of the logographic similarities between kanji and Arabic numbers, as well as evidence from numerical memory span research (Flaherty & Moran, 2000, 2004) and applications of Dehaene's Triple-Code model (Ito & Hatta, 2003), we expected to find evidence that these two symbolic notations are processed in a similar manner as compared to kana, which may require a different processing strategy or more attentional demands than kanji or Arabic numbers. This may be reflected in similar patterns of reaction times in the behavioral data relative to kana and similar areas of brain activation in the imaging data.

Methods and Procedures

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 35 years (*SD*=9.4). Participants had an average of 17.3 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, kanji and Arabic tasks before they took place in the scanner. The subjects were given instructions on the task and allowed to practice the keyboard button responses. Subjects also performed two Stroop tasks in the scanner, the results of which have been published elsewhere (Coderre et al., 2008) and are not presented here.

Number Task—In this task subjects saw blocks of Arabic numbers, kanji numbers or kana digit words for numbers 1 through 5. Each block was presented three times and consisted of eight stimuli of either Arabic, kana, or kanji numbers. Each block lasted 17.5 seconds, and blocks were presented in a counterbalanced order. The subject was asked to press a button on the keyboard corresponding to the number on the computer screen using five fingers on the right hand. The entire number task lasted 4.95 minutes, and was part of a larger experiment lasting approximately 45 minutes.

fMRI Scan Procedure and Preprocessing

Structural and functional MRI scans were acquired using the University of Vermont Research Imaging Facility which includes a Philips Achieva 3.0 Tesla full-body scanner with an 8-channel phased array head coil. 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 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 X 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 mm × 2.8 mm × 5.0 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 random 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 using a trilinear interpolation 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, 148.75 seconds) 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 analyses involved deriving one mean image per individual for each relevant contrast in the activation task (e.g., kana > kanji) after accounting for the hemodynamic response function. These contrast images were further analyzed using standard paired *t*-test procedures in Brain Voyager. In an effort to correct for multiple comparisons, we used the cluster-level statistical threshold estimator from Brain Voyager QX to estimate a minimum cluster size threshold based on the approach of Forman, Cohen, Fitzgerald, Eddy, Mintun, and Noll (2005). The starting *p*-value used in this procedure was $p < 0.03$. This procedure estimated a minimum cluster size of 21 at an alpha level of 0.05. Given the small sample size, the use of random effects analysis, and the preliminary nature of this study, this was the most conservative starting *p*-value in the cluster size estimation procedure at which we were able to observe results.

Results

Behavioral Data

There was a difference in the median reaction times for all three number conditions: kana (*M*=631.1 ms, *SD*=95.3), kanji (*M*=569.9 ms, *SD*=66.7), and Arabic (*M*=564.8 ms, *SD*=78.2). A one-way ANOVA showed a significant effect of number condition ($F(2, 16) = 11.8$, $p < 0.01$). A paired-samples *t*-test showed differences between the kana and kanji conditions ($t(8) = 3.7$, $p<0.01$) and the kana and Arabic conditions ($t(8)=-4.1$, $p<0.01$), but no difference between the kanji and Arabic conditions ($t(8)=0.4$, $p>0.5$; see Figure 2).

Imaging Data

Three contrasts of interest were examined with the imaging data. For both kana > kanji and kana > Arabic, we expected more activation for kana, specifically in the temporal and parietal cortices including the inferior parietal cortex and the superior temporal gyrus. For Arabic > kanji, we expected similar processing for these two notations and predicted few areas of activation would remain after this subtraction. In the contrast of kana > kanji, kana activated the left posterior cingulate (BA 30; See Table 1, Figure 3). The line graph in Figure 3 displays percent BOLD signal change in the left posterior cingulate over time and shows that there was less deactivation in kana compared to kanji number reading. In the contrast of kana > Arabic, kana also activated the left posterior cingulate (BA 29; see Figure 4). In general, Arabic numbers activated areas of the frontal and parietal lobes. In the contrast of Arabic > kanji, Arabic numbers activated the right inferior parietal lobe (BA 40). In the kana > Arabic comparison, areas more active under Arabic numbers included the frontal lobe, specifically the left middle frontal gyrus (BA 9) and right medial frontal gyrus (BA 10). In general, kanji numbers activated areas of the frontal and occipital lobes. In the contrast of kana > kanji, kanji numbers activated the left anterior cingulate (BA 32). In the comparison of Arabic > kanji, kanji numbers activated areas of the occipital lobe, including the left fusiform gyrus (BA 19) and the left inferior occipital gyrus (BA 17).

In order to examine the relationship between reaction time (RT) and the corresponding brain activation, correlation analyses were performed. The main correlations of interest were the relationship of kana RT to brain areas activated in the kana > kanji and kana > Arabic comparisons. The reaction time for kana was not correlated with any of the regions identified from these comparisons in Table 1. Other correlations were examined between brain regions identified in Table 1 and kanji and Arabic RTs. Again, no significant correlations were found (largest $r = 0.66$, smallest $p > 0.054$). Thus, the reaction times for reading and responding to numbers in each of the three notations were not related to the brain activation found for those three notations. Additionally, the longer reaction time in kana was not related to increased brain activation during this condition. However, the small sample size in this study may make this lack of correlation uncertain.

In addition to basic comparisons of the three notations, we also performed conjunction analyses. When used in neuroimaging, this method identifies brain areas activated by the logical conjunction of task A AND task B (Nichols, Brett, Andersson, Wager & Poline, 2005). We performed three conjunction analyses on these data. The conjunction of (kana > kanji) & (kana > Arabic) combines significant areas of activation from both the (kana > kanji) and (kana > Arabic) contrasts, and thus identifies areas specific to only kana. Similarly, (kanji > kana) & (kanji > Arabic) combines areas of activation common to both of these contrasts, and so identifies areas specific to only kanji; (Arabic > kana) & (Arabic > kanji) identifies areas specific to only Arabic numbers. The kana conjunction analysis yielded activation in the left posterior cingulate (BA 29; see Table 2 and Figure 5). The kanji conjunction analysis did not show any significant areas of activation. The Arabic conjunction analysis yielded activation in the right inferior parietal lobe (40). Interpretations of these data are discussed below.

Discussion

The current study investigated numerical processing with kana digit words, kanji and Arabic numbers with both behavioral reaction times and fMRI. In contrast to kanji and Arabic numbers, we hypothesized that kana numbers would elicit results similar to those of alphabetic digit words in previous studies (Ito & Hatta, 2003; Flaherty & Moran, 2004), based on the syllabic nature of kana. We expected a longer reaction time for kana digit words in comparison to kanji and Arabic numbers, and hypothesized that areas of kana processing would be activated in the imaging data, notably areas of the temporal and parietal cortices including the inferior parietal cortex and the superior temporal gyrus (Coderre et al., 2008; Tan et al., 2005a; Nakamura et al., 2005; Thuy et al., 2004; Ischebeck et al., 2004; Sakurai et al., 1993; 2000). The behavioral data showed a significantly longer median reaction time for kana as compared to both kanji and Arabic numbers. This supports the present hypothesis and indicates that kana digit words may require a different processing strategy or more attentional demands than either kanji or Arabic numbers.

In comparisons to both the kanji and Arabic conditions, kana activated the left posterior cingulate (BA 30). Additionally, in the conjunction analyses of (kana > kanji) & (kana > Arabic), which identifies areas of activation specific to kana processing, the only significant area of activation was the left posterior cingulate (BA 29). It appears that the posterior cingulate is involved in the number word reading of only kana numbers, as it is not active in kanji or Arabic numbers. The posterior cingulate has been implicated in a number of different tasks, including motivation (Mohanty, Gitelman, Small & Mesulam, 2008; Small, Gitelman, Gregory, Nobre, Parrish & Mesulam, 2003), visuospatial processing (Cavanna & Trimble 2006; Gobbelé, Lamberty, Stephan, Stegelmeyer, Buchner, Marshall, Fink & Waberski, 2008; Antal, Baudewig, Paulus & Dechent, 2008), and processing of emotional words (Posner, Russell, Gerber, Gorman, Colibazzi, Yu, Wang, Kangarlu, Zhu & Peterson, 2008), and is also thought to be a part of the default network (Gaab, Gabrieli & Glover, 2008; Bluhm, Osuch, Lanius, Boksman, Neufeld, Théberge & Williamson, 2008). In addition to these diverse functions, however, the primary function of this area seems to be attention (Ng, Noblejas, Rodefer, Smith & Poremba, 2007; Hahn, Ross & Stein, 2006; Hahn, Ross & Stein, 2007; Small et al., 2003; Antal et al., 2008; Mohanty et al., 2008; Lawrence, Ross, Hoffmann, Garavan & Stein, 2003). Thus, the numerical processing of kana numbers seems to require additional attentional resources, localized in the left posterior cingulate, which kanji and Arabic numbers do not utilize to the same degree.

As can be seen in the graph of percent BOLD signal change in Figure 3, there was less deactivation in the posterior cingulate in kana relative to kanji in the kana > kanji comparison. We interpret this as a greater engagement of attentional resources required for kana relative to kanji in this brain area. The additional attention required to process kana digit words could be related to the relatively low frequency of kana words in the Japanese language. As mentioned previously, kanji and Arabic numbers are used with near-equal frequency (though kanji are more traditional). Kana numbers, however, are learned during childhood but are not seen often in print. Although the pronunciation is the same between all three scripts, the relative unfamiliarity of kana digit words as compared to kanji and Arabic numbers could account for the additional attentional demands, as subjects had to pay more attention to reading the unfamiliar word. If kana digit words are less familiar, this would also explain the longer reaction time for kana as compared to kanji or Arabic. In addition, the complexity of kana number words differs between numbers, and some contain two characters compared to the one-character kanji and Arabic numbers (see Figure 1). These more complex characters may explain the increased demand for attentional resources in this script.

Additional attentional resources associated with posterior cingulate activation may also be recruited for phonological mediation in kana digit words. As suggested by Ito & Hatta (2003), Dehaene's Triple-Code Model may function differently in Japanese, since in kana digit words the visual number form (digit word) is translated into the verbal number form (pronunciation of digit word) and then into the semantic number representation. Kanji and Arabic numbers, in contrast, do not have such a strong phonological connection, and proceed directly from the visual form to the semantic representation. This extra step of phonological mediation in kana would explain the longer reaction time in responding to kana digit words than kanji or Arabic numbers, as additional attentional control is required in kana to read the word presented, pronounce it and translate it into a numerical representation, then respond accordingly. Though we must stress that more research is needed to investigate the specific function of the posterior cingulate in kana number processing, the activation of the posterior cingulate in kana number processing suggests that there is an additional attentional demand in this notation that causes it to be processed differently than kanji or Arabic numbers.

Based on previous studies which suggested that kanji and Arabic numbers, because of their shared logographic properties, may be processed in a similar way (Flaherty & Moran, 2000, 2004; Ito & Hatta, 2003), we expected to find few differences either in reaction times or in areas of brain activation between kanji and Arabic numbers. The behavioral results showed no significant differences in reaction times between these notations, as hypothesized. However, the imaging data did show some differences in brain areas in the comparison of kanji and Arabic numbers. In the contrast of Arabic > kanji, Arabic numbers activated the right inferior parietal lobe (BA 40), whereas kanji activated the left middle occipital gyrus (BA 19), the left inferior occipital gyrus (BA 17), and the left fusiform gyrus (19). Previous studies have found the fusiform gyrus to be activated for kanji in a variety of tasks (Nakamura et al., 2005; Thuy et al., 2004; Sakurai et al., 2000), and so the activation of this area may reflect the reading of kanji words in this condition. In the contrast of kana > kanji, kanji activated the left anterior cingulate (BA 32), an area which has been implicated in attention and cognitive control, specifically for tasks of conflict resolution (Peterson, Skudlarski, Gatenby, Zhang, Anderson & Gore, 1999; Peterson, Kane, Alexander, Lacadie, Skudlarski, Leung, May & Gore, 2002). This may represent a different level of attentional control that is required for logographic number processing in kanji numbers as compared to Arabic numerals.

Though there were no behavioral reaction time differences between the processing of Arabic and kanji numbers, the imaging results suggest that there are differences in the neural processing between the notations. In the Arabic > kanji contrast, Arabic numbers activated the right inferior parietal lobe (BA 40). In the conjunction analysis (Arabic > kana) & (Arabic >

kanji), which identified areas specific to only Arabic number processing, the right inferior parietal lobe (BA 40) was found to be the only significant area of activation. This area was not found for kanji processing in any of the comparisons. In the number processing literature, the parietal lobe is often activated bilaterally. Although the left IPS is the region most commonly identified, the right IPS is also somewhat involved in numerical processing (Ansari, 2008; Cohen Kadosh et al., 2007). Cohen Kadosh et al. (2007) suggest that the right parietal lobe is specified more for processing the quantity of digits than for number words, and that there may be laterality differences between types of notation within the parietal lobe and the IPS. Though we had predicted that kanji and Arabic numbers would activate similar neural processing areas, the activation of the inferior parietal lobe only for Arabic may indicate a different processing strategy. It may be the case that kanji numbers are not processed logographically like Arabic numbers, and instead occupy some middle ground between the language-like processing of kana digit words and the symbolic notation of Arabic numbers.

One important caveat regarding the design of this study is the absence of a control condition. Other studies have examined counting and calculation in number processing, typically using a dot array as a control condition. Our primary interest was in examining the reading of numbers in different scripts. However, it was difficult in this study to design a control task which would be matched on the basis of visual characteristics and response selection but would still allow a reading process to take place. In addition, as illustrated in Figure 1, all three notations have the same pronunciation in Japanese, though they are written differently. This presents a problem for having a matching control condition, as the phonology of the written number or digit word would have to be taken into account. Nevertheless, future studies may want to include a suitable control condition to allow for format-specific comparisons between the three notations used here.

These results should be interpreted with caution given the small sample size in this study. We used a cluster-level correction in an attempt at a stringent correction for multiple comparisons. In order to estimate the appropriate cluster size, the starting p-value used in the estimation procedure was $p < 0.03$. While this is a liberal threshold, it was the most conservative threshold that resulted in any activation in our random effects analysis. This limits our ability to detect small effects and reinforces the need for these results to be replicated in the future.

The present study supports previous research suggesting that kanji and Arabic numbers, because of their shared logographic characteristics, require similar processing times by demonstrating that there are no differences in reaction times between the two notations. The imaging data were not fully supportive of our hypotheses, as we did find differences in brain activation between kanji and Arabic numbers, specifically activation of the inferior parietal lobe unique to Arabic numbers. Kana digit words showed a longer median reaction time as compared to kanji or Arabic numbers, supporting previous findings of digit words in alphabetic writing systems. The finding of posterior cingulate activation in kana digit word processing suggests an additional attentional demand in this script which could be related to the relatively low frequency of kana number words in everyday life, or may reflect an extra step of phonological mediation in the conversion from the visual to the verbal word form. As this was the first study of its kind to use fMRI to investigate differences in number processing between kana, kanji and Arabic numbers, more research is needed to support the present findings of posterior cingulate activation in kana digit words, as well as to identify specific areas of number processing in each notation. However, the current study demonstrates that differences do exist between the numerical processing of kana, kanji and Arabic numbers in the brain, and provides a strong basis of support for further investigations of numerical processing in Japanese kana and kanji.

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pronunciation	Kana	Kanji	Arabic
“ichi”	いち	一	1
“ni”	に	二	2
“san”	さん	三	3
“shi”	よん	四	4
“go”	ご	五	5

Figure 1.

Japanese kana, Japanese kanji, and Arabic numbers one through five with pronunciation.

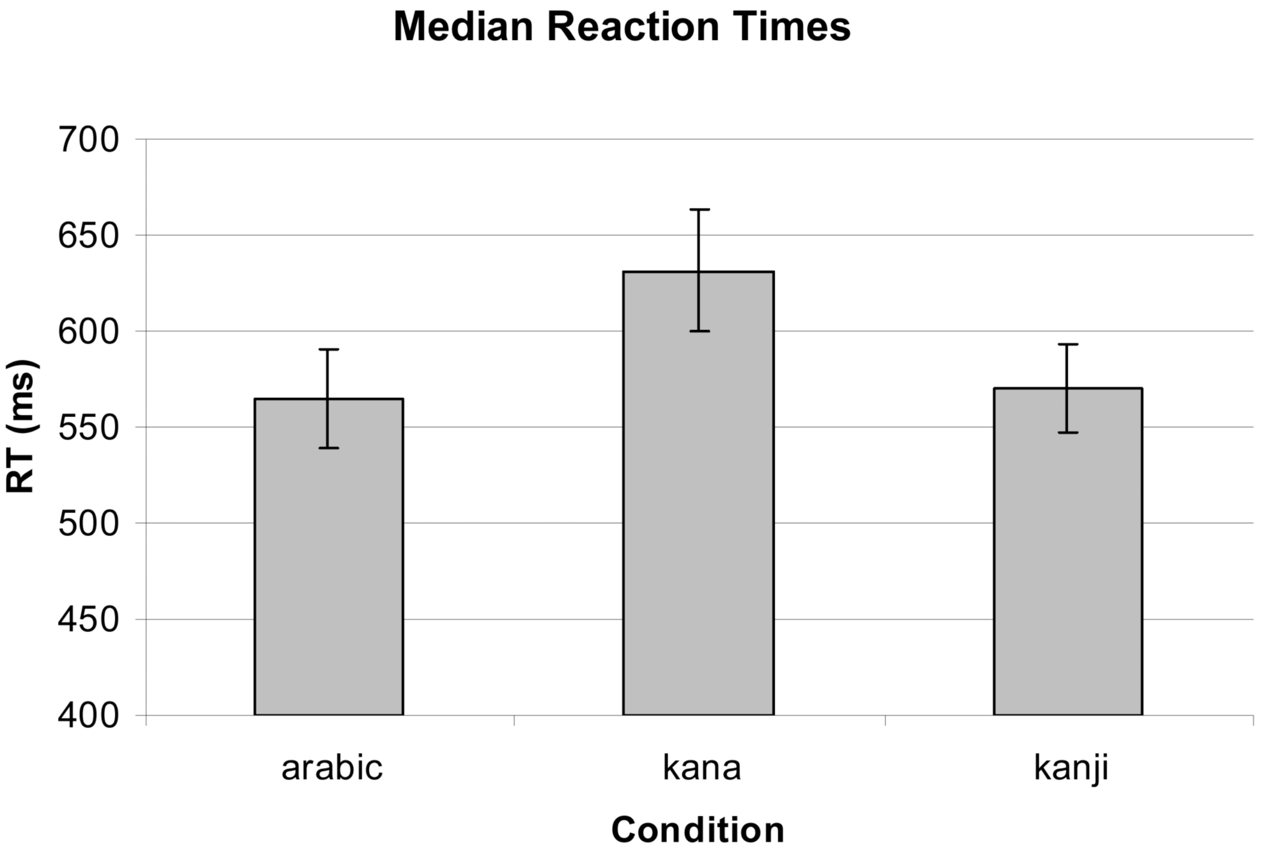

Figure 2.
Median reaction times for reading numbers in the Arabic, kana and kanji conditions (with standard error bars).

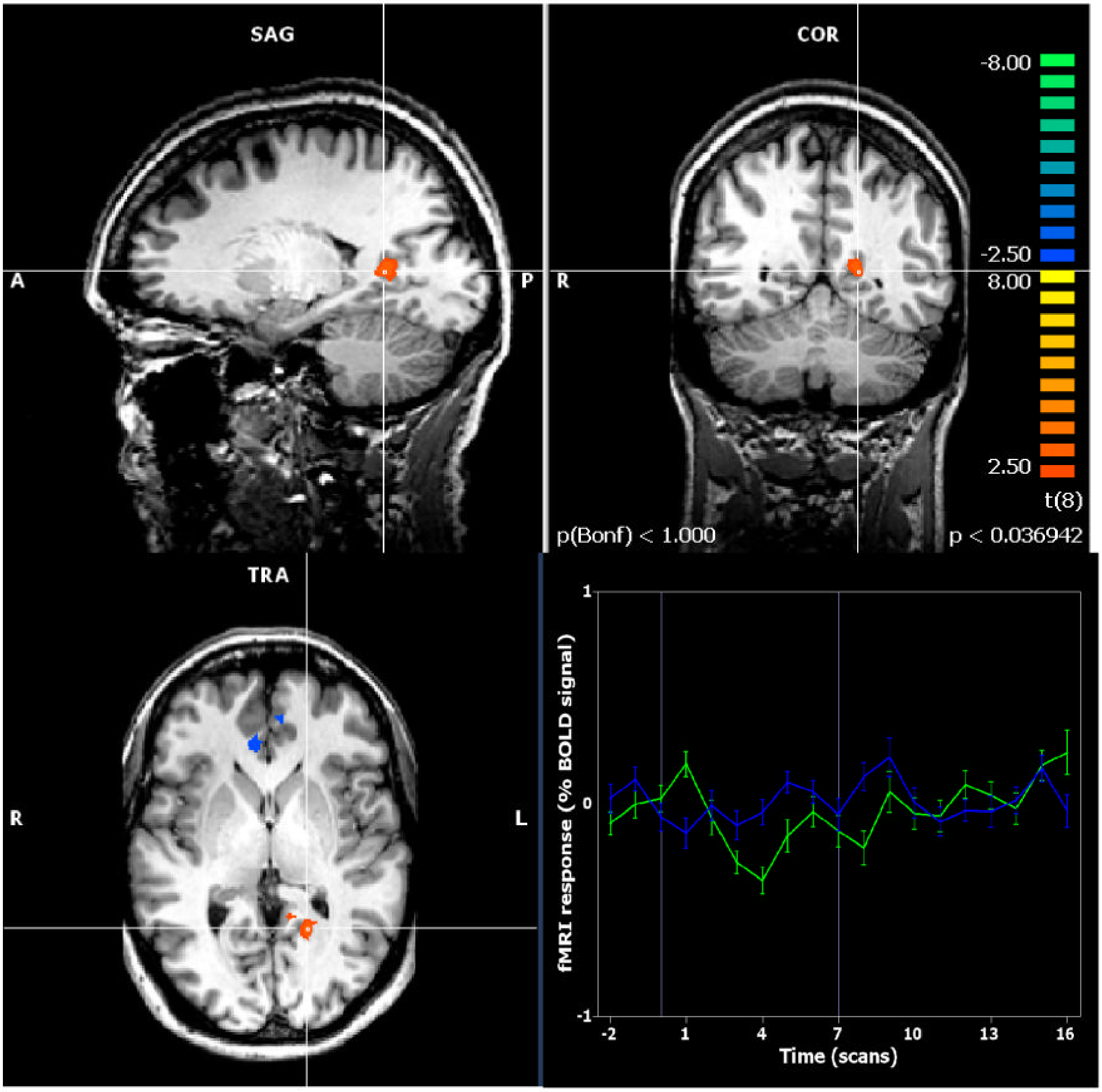

Figure 3.

Kana minus kanji subtraction, showing activation of the left posterior cingulate displayed with the cluster level correction of $p < 0.05$. The line graph represents the percent BOLD signal change in this left posterior cingulate ROI over time (kana in blue, kanji in green).

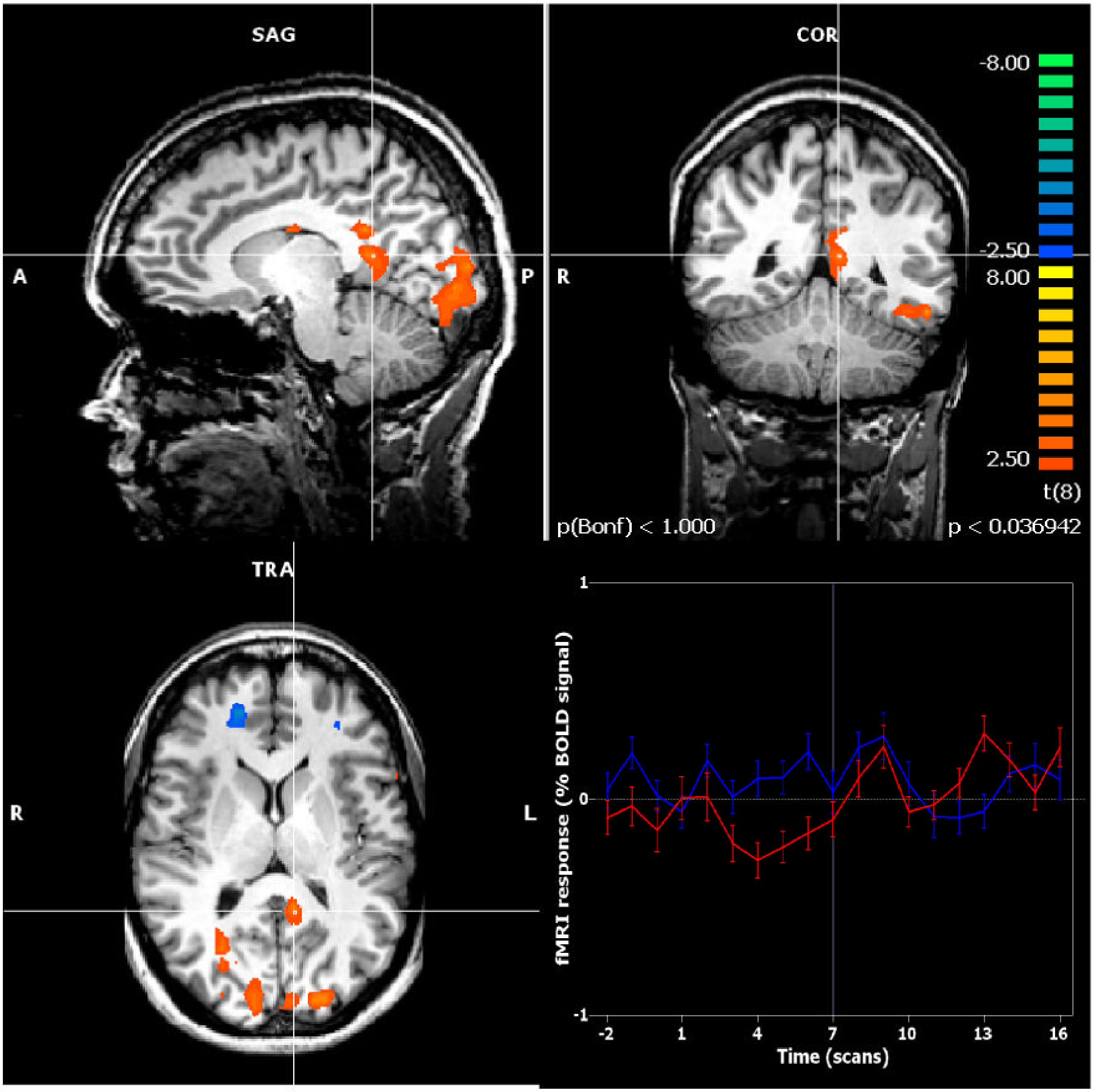

Figure 4.

Kana minus Arabic subtraction, showing activation of the left posterior cingulate displayed with the cluster level correction of $p < 0.05$. The line graph represents the percent BOLD signal change in this ROI over time (kana in blue, Arabic in red).

Figure 5.

Conjunction analysis of (kana > kanji) & (kana > Arabic). This analysis combines significant activation from each individual comparison in order to identify areas specific to kana number processing. Activation of the left posterior cingulate is shown under the cross-hatches. The cluster level correction is $p < 0.05$.

Table 1

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

Contrast	**Coordinates**			**Cluster Extent**	**Region Description**	***t* value**	***p* value**
	x	**y**	**z**				
Kana > kanji	-18	-55	7	335	Left posterior cingulate (BA 30)	3.841	0.00494
	-3	35	10	79	Left anterior cingulate (BA 32)	-3.786	0.005344
	-42	-13	-5	344	Left insula (BA 13)	5.461	0.000601
Kana > Arabic	12	-91	4	2093	Right cuneus (BA 17)	5.763	0.000423
	-9	-46	10	232	Left posterior cingulate (BA 29)	4.430	0.002196
	-27	35	28	526	Left middle frontal gyrus (BA 9)	-6.312	0.00023
	18	47	7	284	Right medial frontal gyrus (BA 10)	-4.981	0.001079
Arabic > kanji	57	-34	34	667	Right inferior parietal lobe (BA 40)	6.307	0.000231
	-27	-67	-8	3333	Left fusiform gyrus (BA 19)	-10.08	0.000008
	-24	-85	10	734	Left middle occipital gyrus (BA 19)	-5.631	0.000492
	-12	-91	-11	4194	Left inferior occipital gyrus (BA 17)	-13.76	7.5e-7

Table 2

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

Contrast	**Coordinates**			**Cluster Extent**	**Region Description**	***t* value**	***p* value**
	x	**y**	**z**				
(Kana > kanji) & (Kana > Arabic)	-9	-46	7	208	Left posterior cingulate (BA 29)	3.284	0.01112
	12	-85	-2	129	Right lingual gyrus (BA 18)	3.171	0.013173
	9	-88	19	108	Right cuneus (BA 18)	2.992	0.017269
(Arabic > kana) & (Arabic > kanji)	42	-31	28	195	Right inferior parietal lobe (BA 40)	5.876	0.000371
	15	-82	-5	1130	Right lingual gyrus (BA 18)	-4.246	0.002815
	-12	-88	-5	1876	Left inferior occipital gyrus (BA 17)	-4.759	0.00143