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Ichi, Ni, 3, 4: Neural representation of kana, kanji, and Arabic numbers in native Japanese speakers

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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.

1. Introduction

Behavioral evidence from previous studies with both humans and animals has supported the idea of a central area of number processing in the brain (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Verguts & Fias, 2004) and has generated theories of an internal analog magnitude representation, similar to a 'mental number line' (Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Verguts & Fias, 2004). 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*) (Dehaene et al., 1998; Libertus, Woldorff, & Brannon, 2007; Moyer & Landauer, 1967; Verguts & Fias, 2004). It has been suggested that the internal representation of numerical magnitude is coded in a notation-independent representation, and 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 analog 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 analog 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 et al., 2005; Dehaene, Piazza, Pinel, & Cohen, 2003; Göbel, Johansen-Berg, Behrens, & Rushworth, 2004). 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 (Ansari 2008; Fias et al., 2003). 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;

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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. 452) 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 (Bolger, Perfetti, & Schneider, 2005; Siok, Perfetti, Jin, & Tan, 2004; Tan, Laird, Li, & Fox, 2005a; Tan, Spinks, Eden, Perfetti, & Siok, 2005b; Tan et al., 2003), whereas alphabetic writing systems activate a left temporoparietal system, including the superior temporal gyrus and the inferior parietal cortex (Bolger et al., 2005; Tan et al., 2005a). 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 (Coderre, Filippi, Newhouse, & Dumas, 2008; Nakamura, Dehaene, Jobert, Bihan, & Kouider, 2005; Sakurai et al., 1993; Sakurai et al., 2000; Thuy et al., 2004; Ischebeck et al., 2004) whereas kanji, like logographic writing systems, activate the temporal cortex, particularly the fusiform gyrus (Coderre et al., 2008; Nakamura et al., 2005; Sakurai et al., 2000; Thuy et al., 2004). 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 Fig. 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

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

Fig. 1. Japanese kana, Japanese kanji, and Arabic numbers 1–5 with pronunciation.