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Effects of visual complexity and sublexical information in the occipitotemporal cortex in the reading of Chinese phonograms: A single-trial analysis with MEG

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ABSTRACT

We employ a linear mixed-effects model to estimate the effects of visual form and the linguistic properties of Chinese characters on M100 and M170 MEG responses from single-trial data of Chinese and English speakers in a Chinese lexical decision task. Cortically constrained minimum-norm estimation is used to compute the activation of M100 and M170 responses in functionally defined regions of interest. Both Chinese and English participants' M100 responses tend to increase in response to characters with a high numbers of strokes. English participants' M170 responses show a posterior distribution and only reflect the effect of the visual complexity of characters. On the other hand, the Chinese participants' left hemisphere M170 is increased when reading characters with high number of strokes, and their right hemisphere M170 is increased when reading characters with small combinability of semantic radicals. Our results suggest that expertise with words and the decomposition of word forms underlies processing in the left and right occipitotemporal regions in the reading of Chinese characters by Chinese speakers.

1. Introduction

Skilled readers show remarkable efficiency in visual word recognition. There has been a growing body of research concerning the manner in which readers extract visual features, word forms, and lexical and meaning-related information during the early stages of visual word recognition. With excellent temporal resolution, electrophysiological methods have proved most appropriate for addressing this kind of question. For example, in studies using event-related potentials (ERPs), Sereno, Rayner, and Posner (1998) have reported lexicality and frequency effects in the N1 ERP component. Hauk et al. (2006) have reported a lexicality effect around 200 ms and an earlier interaction between lexicality and the orthographic typicality around 160 ms. Similar inferences have been drawn from magnetoencephalography (MEG) studies that have demonstrated differentiated early MEG components reflecting processes at the form level or orthographic level in visual word recognition (Solomyak & Marantz, 2009; Tarkiainen, Cornelissen, & Salmelin, 2002; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). Tarkiainen and colleagues have demonstrated that the Type I activity, also called the M100 response, is found around 100 ms in or near the primary visual cortex (V1) and is sensitive to the low-level analysis of visual features. The differentiation between letter and symbol strings was picked up by a later component, Type II activity, around 150 ms (greater for letter than symbol strings) in the inferior-temporal cortex, reflecting object-level processing (Tarkiainen et al., 1999, 2002). In other work, a robust difference between orthographic and non-orthographic stimuli has been reported in the M170 or the N170 responses (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Solomyak & Marantz, 2009; Tarkiainen et al., 1999; Zweig & Pylkkänen, 2009). Studies have suggested that this response originates from the left occipitotemporal region, the so-called visual word form area (VWFA), and that its function is specific to processing orthographic stimuli (Cohen et al., 2000; McCandliss, Cohen, & Dehaene, 2003).

Although a pattern seems to be emerging from these studies, indicating that the earliest electrophysiological response to visual word recognition in the brain peaks around 100 ms after stimulus onset and reflects the analysis of the surface feature of a visual word, and a subsequent component at around 150–200 ms reflects lexicality or the identification of word forms, the findings are still inconsistent across studies. Controversy still surrounds the nature of the representations accessed during the early processing of a word. This inconsistency could be attributable to the fact that most studies only look at one or two linguistic properties, such as lexicality, lexical frequency, or word length, in a factorial design,

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in order to determine the effect of a particular variable on brain responses. However, most psycholinguistic variables, such as frequency or word length, are continuous in nature, and many co-vary in complicated ways. By dichotomizing the continuous variables into categories (e.g., high versus low frequency) and trying to match other variables (e.g., word length), factorial designs may result in substantial loss of statistical power and require selection of atypical stimuli (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004). Moreover, high correlation between the confounding and manipulated variables can be problematic to their interpretation.

One possible way to overcome these problems is to use regression analysis in order to find the best-fit relationship between brain activities and a set of predicting variables. This approach has only very recently been applied to the field of human electrophysiology (Dambacher, Kliegl, Hofmann, & Jacobs, 2006; Hauk, Davis, Ford, Pulvermuller, & Marslen-Wilson, 2006; Hauk et al., 2006; Solomyak & Marantz, 2009, 2010). For example, Hauk et al. (2006) applied it to examine how 10 psycholinguistic features of 300 stimulus words modulate the processing of visual word recognition in different time courses at distinct brain regions. They found that variables associated with the surface structure of a word (such as word length and orthographic typicality) showed effects on the left inferior-temporal cortex within the first 100 ms after stimulus onset, and that lexical frequency showed its effect slightly later at 110 ms, with a semantic variable modulating a widely distributed cortical network shortly after 160 ms, simultaneously with lexicality.

A series of studies conducted by Solomyak and Marantz (2009, 2010) also employed single-trail correlational analysis, this time with MEG in the source space, to investigate whether lexical access occurs within 200 ms after perceiving a word. They first found that M170 is sensitive to form properties (such as bigram, trigram, and lexical frequency), but not to a targeted lexical property (heteronym frequency ratio: relative frequency of the different meanings of a heteronyms) and concluded that true lexical properties did not affect the processing until after 300 ms, while earlier activation of M170 is primarily modulated by orthographic form. Their later study showed that the orthographic form features exert an effect on earlier stages in processing around 130 ms, and then the M170 is sensitive to the conditional probability between affixes and stems of morphologically complex words (Solomyak & Marantz, 2009), which reflects morphological decomposition in earlier stages of reading based on the visual word forms of stems and affixes.

Chinese is characterized as an ideographic writing system that presents the highest contrast to alphabetic systems such as that used for English. The character forms the basic unit of the Chinese writing system. Each character is composed of basic strokes, and these strokes are then combined to form components called radicals. Approximately 80% of the Chinese characters are phonograms that consist of a semantic radical (usually on the left) and a phonetic radical (usually on the right). The semantic radical is related to the meaning of a given character, while the phonetic radical is related to its pronunciation. In addition, the phonetic radicals are usually stand-alone characters with their own pronunciations and meanings, which do not contribute to the meaning of the character. There is increasing evidence indicating that reading a complex character involves the processing of its radicals (Ding, Peng, & Taft, 2004; Feldman & Siok, 1997, 1999; Hsu, Tsai, Lee, & Tzeng, 2009; Lee, Tsai, Huang, Hung, & Tzeng, 2006; Lee, Tsai, Su, Tzeng, & Hung, 2005; Lee et al., 2007). Lee et al. (2006) conducted a priming experiment and found a reduced N400 activation at 50 ms and 100 ms stimulus onset asynchronies (SOA) when a target (e.g., 雨/yu3/, rain) was semantically related to the phonetic radical (e.g., 風/feng1/, wind) embedded in the prime (e.g., 楓/feng1/, maple). Furthermore, such a priming effect was absent at 500 ms SOA. Since the reduction in the N400 amplitude indexes the associative semantic relation in prime-target pairs (Kutas & Federmeier, 2000), the result suggests that phonograms are decomposed at the earlier stage of visual word recognition, and that the semantic value of the phonetic radical is temporarily accessed. The evidence for automatic sublexical semantic activation of Chinese phonetic radicals supports the hypothesis that sublexical decomposition is purely structural and arises in the early stage of visual word recognition (Ding et al., 2004; Perfetti, Liu, & Tan, 2005).

However, it remains unclear what kind of properties of the characters contribute to their decomposition into radicals. The hypothesis of a VWFA suggests that this region is sensitive to informative sublexical units (Dehaene, Cohen, Sigman, & Vinckier, 2005), e.g., open-bigrams in English. For Chinese characters, Feldman and Siok (1997) have introduced the variable "combinability of radicals," defined as the number of phonograms that share the same phonetic or semantic radical, as the appropriate measurement for the component frequency of phonograms. Several studies have demonstrated faster response latency in reading characters with large combinability compared with reading characters with small combinability in a lexical decision task and a semantic judgment task (Chen & Weekes, 2004; Feldman & Siok, 1997, 1999; Hsiao, Shillcock, & Lavidor, 2006, 2007). In fact, studies have demonstrated that a variety of sublexical properties can be found to modulate the early stages of lexical processing. Hsu et al. (2009) have demonstrated that large phonetic combinability characters elicited greater negativity at N170 than small phonetic combinability characters. Furthermore, this effect was further modulated by phonetic consistency, which indicates whether the pronunciation of a phonogram agrees with phonograms containing the same phonetic radical. The combinability effect on the N170 was only found in the reading of high-consistency characters (Hsu et al., 2009). Meanwhile, reading high-consistency characters produced greater negativity of the N170 than reading low-consistency characters in the bilateral occipitotemporal electrodes. Several fMRI studies on reading Chinese have also demonstrated effects of frequency, consistency, and lexicality in the bilateral occipitotemporal area (Kuo et al., 2003; Lee, Huang, Kuo, & Tzeng, 2010; Lee et al., 2004). All this evidence suggests that the N170 originating in bilateral occipitotemporal region may index early decomposition processing in reading Chinese characters.

It is noteworthy that most studies of alphabetic writing systems suggest that the left lateralized occipitotemporal regions play important roles in earlier processes of visual word recognition, compared to a bilateral activation for Chinese characters and Japanese Kanji (Bolger, Perfetti, & Schneider, 2005; Nakamura, Dehaene, Jobert, Bihan, & Kouider, 2005; Tan, Laird, Li, & Fox, 2005). Nakamura et al.'s (2005) study found increased activation in the anterior and posterior fusiform gyrus regions in both hemispheres of Japanese participants as they read Kanji and Kana, respectively. A study involving Koreans who were educated in both Chinese and written English reported a left-lateralized N170 effect for both English and Korean words but a bilateral N170 effect for Chinese characters and pictures (Kim, Yoon, & Park, 2004). Such cross-linguistic differences provide support for the phonological mapping hypothesis of the left-lateralized N170 effect (Maurer & McCandliss, 2007). That is, the left lateralization of the reading-related N170 effect may reflect the spelling-to-sound mapping consistency of alphabetic writing systems.

In addition, an fMRI study has showed that after training with Chinese characters' pronunciations and meaning, native English speakers' fusiform activation is stronger in the right hemisphere than in the left hemisphere in response to Chinese characters (Liu, Dunlap, Fiez, & Perfetti, 2007). Furthermore, native English