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Language experience shapes fusiform activation when processing a logographic artificial language: An fMRI training study

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The significant role of the left midfusiform cortex in reading found in recent neuroimaging studies has led to the visual word form area (VWFA) hypothesis. This hypothesis suggests that years of experience reading native language change the visual expertise of this region to be especially sensitive to the visual form of native language. The present study aimed at testing this hypothesis by exploring the role of language experience in shaping the fusiform activation. We designed a logographic artificial language (LAL) using the visual form and pronunciation of Korean Hangul characters (but their correspondence was shuffled) and assigning arbitrary meanings to these characters. Twelve native Chinese Mandarin speakers (6 male and 6 female, 18 to 21 years old) with no prior knowledge of Korean language were trained in the visual form of these characters for 2 weeks, followed by 2 weeks each of phonological and semantic training. Behavioral data indicated that training was effective in increasing the efficiency of visual form processing and establishing the connections among visual form, sounds, and meanings. Imaging data indicated that at the pre-training stage, subjects showed stronger activation in the fusiform regions for LAL than for Chinese across both one-back visual matching task and the passive viewing task. Visual form training significantly decreased the activation of bilateral fusiform cortex and the left inferior occipital cortex, whereas phonological training increased activation in these regions, and the right fusiform remained more active after semantic training. Increased activations after phonological and semantic training were also evident in other regions involved in language processing. These findings thus do not seem to be consistent with the visual-expertise-induced-sensitivity hypothesis about fusiform regions. Instead, our results suggest that visual familiarity, phonological processing, and semantic processing all make significant but different contributions to shaping the fusiform activation.

Keywords: Chinese language; fMRI; Fusiform; Language learning; Logographic artificial language; Phonology; Semantics; Visual form; VWFA

Introduction

Benefited from the development of neural imaging techniques, one striking advance in our understanding of language representation in the brain is the discovery of left midfusiform cortex's involvement in reading. The activation of this region has been consistently reported across various kinds of reading tasks, as well as across different language systems (for reviews, see Bolger et al., 2005; Cohen and Dehaene, 2004; Feiz and Petersen, 1998; Jobard et al., 2003; Price, 2000; Xue et al., 2005). With the increase of reading skills, this region becomes more critical in the recognition of printed words (Booth et al., 2001; Shaywitz et al., 2002; Turkeltaub et al., 2003). Children with reading difficulties have abnormal fusiform function compared to their normal counterparts (see Habib, 2000 for a review). These findings have triggered the reevaluation of the neuropsychological data, as well as the revision of the more-than-one-century-old neural model of reading by incorporating the left midfusiform region in the reading network (e.g., Jobard et al., 2003; Price, 2000).

Despite the widespread consensus on the fusiform's involvement in visual language processing, there are also debates on its function and on its being labeled as the visual word form area (VWFA) by Cohen and his colleagues (Cohen et al., 2000, 2002). The debates are carried out on two interconnected fronts. The first is related to the functional computation that is implemented in VWFA. It is suggested that VWFA is responsible for feature-invariant (like location, size, font, color and case), pre-lexical, visual word recognition, i.e., the extraction of abstract visual word form. Others tend to suggest the VWFA might also be involved in lexical, multimodal word processing (Kronbichler et al., 2004; Hillis et al., 2005 for most recent neuropsychological results), or in integrating phonology and visual information during both word and picture processing (Price and Friston, 2005).

Another line of controversy is related to the functional properties of the left midfusiform cortex. By labeling this area as

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visual *word* area, it implies that neurons in this region have some specific functional properties that are especially suitable for visual word processing. Cohen and his colleagues provide two major lines of evidence: word-specific sensitivity and case-invariant computation (see Cohen and Dehaene, 2004 for a review). Several studies have reported word- or letter-sensitive response in the left ventral visual system by contrasting words with false fonts (Petersen et al., 1990), words or pseudowords with consonant strings or false fonts (Cohen et al., 2002; Price et al., 1994, 1996), letters with digits (Polk and Farah, 2002; also see Cohen and Dehaene, 2004 for a review).

However, the link of these findings to the word-specific sensitivity hypothesis in VWFA is less clear. First, existing results do not seem to show a consistent picture of the location of the so-called word-sensitive region, which varied across studies from extrastriate cortex (e.g., Petersen et al., 1990) to the midfusiform cortex (Cohen et al., 2002) and to the occipitotemporal area (Allison et al., 1994). Second, some studies did not reveal a word-sensitive region in the left ventral visual system, by using either passive viewing tasks (e.g., Indefrey et al., 1995, 1997) or one-back matching tasks (Tagamets et al., 2000). These results also suggest that task difficulty is an important factor that needs to be further explored when examining the word sensitivity hypothesis. Third, Cohen and his colleagues proposed that portion of the fusiform might be tuned to be sensitive to the whole words (e.g., Cohen and Dehaene, 2004; Dehaene et al., 2005), which is not consistent with the stronger activation in the midfusiform area for pseudowords than for words (see Mechelli et al., 2003 for a review). Finally, because a wide neural network of the classical language areas was activated even in simple implicit reading tasks, the difference between words and pseudowords in fusiform activation might reflect the modulation of semantics and phonology (Price et al., 1996). For the same reason, it is hard to attribute the different activation between words/pseudowords and consonant strings to the orthographic constraints per se because they differ in semantics and phonology as well as in orthography.

Regarding the case-insensitive processing in VWFA, Cohen and Dehaene (2004) showed: (1) the VWFA responses were equally robust to words in upper-case (“TABLE”), lower-case (“table”) or even in mixed case (“tAbLe”) format; and (2) the VWFA showed repetition priming regardless whether the two words were printed in the same or in different case (e.g., “table” followed by “TABLE”) (Dehaene et al., 2001). This functional property is certainly beyond the generic principle of invariant-view in the ventral visual cortex (Riesenhuber and Poggio, 1999), which leads Cohen and his colleagues to argue that the cross-case priming likely reflects the cultural constraint and the effect of language experience.

But it is not conclusive what may contribute to the cross-case repetition priming effect. Because the two words share the same phonology and semantic identity, it is possible that the priming effect occurs at the phonological and/or semantic level, but not at the pre-lexical abstract visual word level. Consistent with this view, previous research also showed cross-language (Chee et al., 2003) and cross-script (Nakamura et al., 2005) priming effect in the fusiform region, but as well as in several other language areas. Thus, the exact mechanisms for how language experiences modulate the priming effect in fusiform cortex need to be elucidated.

To summarize, existing evidence raises questions about the VWFA hypothesis’ claim on how language experiences shape the midfusiform activation in visual word processing. Particularly, two major questions need to be further explored. First, though the word-sensitivity hypothesis has been tested under certain conditions (e.g., compared with nonwords or false fonts, using passive-viewing tasks with brief stimulus exposure such as 100 ms), it is not clear whether this can be extended to other experimental conditions (e.g., different visual matches, longer stimulus exposure, and using comparison tasks). Second, pertaining to the idea of visual-expertise-induced sensitivity to words in the VWFA hypothesis, it is important to disentangle the role of visual familiarity, phonology and semantics in shaping the VWFA activation. Previous results from word–nonword comparisons or the priming paradigm most likely reflect a combined effect of those factors. The present study aimed at addressing these questions with two major methodological considerations.

The first consideration is to find an ideal visual match for one’s native language in testing the language-sensitivity hypothesis. Existing literature with alphabetic languages generally used word/pseudoword vs. nonword comparisons (e.g., Cohen et al., 2002; Petersen et al., 1990; Price et al., 1994, 1996). In the case of Chinese language, however, this strategy seems to be less effective. The orthographic regularity of Chinese characters largely depends on the positional regularity of the lexical radicals, and a common way to construct Chinese nonwords is to put the radicals in illegitimate positions (Chen et al., 1996). There are several limitations. First, the radicals in the nonwords are still familiar units for subjects, which will affect the pattern of visual processing (Chen et al., 1996). Second, most radicals in Chinese characters convey semantic (semantic radicals) or phonological (phonological radicals) information, which may be activated during the processing of nonwords. Third, each Chinese character is a well-designed figure, and the change of positional regularity may destruct the harmony and integrity of the character, which may also influence the cognitive and neural process. The last point might also apply to alphabetic scripts. Consequently, we decided to use Korean Hangul characters, and compared them to Chinese characters. Korean Hangul characters are logographic, formed hierarchically with strokes and units (Fig. 1). The high extent of similarity in spatial patterns between Hangul characters and Chinese characters enables a strict match in terms of the visual integrity and visual complexity (i.e., number of strokes, units and spatial organization).

Another consideration is how to disentangle the role of visual familiarity, phonology and semantics, which are mixed in the comparisons between native language characters and foreign characters. Unlike the natural reading acquisition, in which visual form, phonology and semantics are usually taught all at once, this study adopted an artificial language training paradigm: We first trained subjects with the visual form then added in the phonology and semantics. We hoped this would help to partly disentangle these effects on visual word processing and midfusiform activation.

Following previous studies, a passive viewing task was administered across the training stages, but the duration of presentation was extended to 750 ms to enable full processing of these characters (Indefrey et al., 1995, 1997). The same paradigm with Chinese characters was included in the same scan session as a control task to account for the possible instability of the MRI measurement across times/sessions (Poldrack, 2000). At the pre-training stage, we also used a one-back visual matching paradigm to explore the effect of task difficulty. With this design, the