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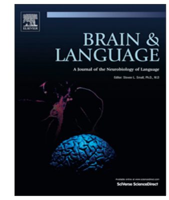

Visuospatial complexity modulates reading in the brain

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ABSTRACT

Neurocognitive processing of orthographic visuospatial complexity was examined through fMRI-based overt naming ($n = 16$) of phonologically transparent, high and low frequency Hindi/Devanagari words that were visually simple (पालक, चातक) or complex (पुलिस, चकली). Participants' overt behavior was modestly influenced by visuospatial complexity (accuracy: main effect $p = .01$, complexity × frequency interaction $p < .07$), while neuroimaging data revealed a robust effect of complexity (main effect FWE $p < 10^{-4}$, complexity × frequency interaction FWE $p < 7 \times 10^{-8}$). Interaction-based RoIs showed higher BOLD response in the VWFA to complex and left posterior temporal cortex to simple words, with greater right lingual de-activation to complex than simple words. Subtractions confirmed additional recruitment of VWFA, right frontal, inferior orbitofrontal, mid-temporal pole and left cerebellum by visuospatially complex over simple words. Finally, low frequency words activated bilateral occipital and putamen areas, left IPL, SPL, IFG and VWFA, suggesting that effortful phonological processing in alphasyllabic Hindi/Devanagari requires neural resources specialized for both visuospatially simple and complex orthographies.

1. Introduction

Although writing systems of the world differ obviously in their *visuospatial complexity*, that is, in the number and spatial configuration of their visual features, research on reading has largely bypassed a direct examination of this dimension. In contrast with writing systems based on the Roman alphabet like English, French and German, alphabets of Semitic origin like Arabic, Hebrew, Persian and Urdu, as well as non-alphabetic systems like Chinese, Japanese and Korean have a noticeably greater visuospatial complexity.

The scant literature available suggests that visuospatial complexity does influence both cognitive processing and its neural correlates. An early study by Shimron and Sivan (1994) demonstrated that Hebrew–English bilingual readers took significantly longer to read passages in the visuospatially complex Hebrew orthography as compared to their translation equivalents in English, despite being more comfortable with Hebrew than with English. A more recent study showed that Arabic–Hebrew bilinguals were slower at processing Arabic compared to Hebrew in a visual trail-making test (in which participants find and connect successive letters and/or numbers), a difference which the authors attributed to the greater visual complexity of Arabic orthography compared to Hebrew (Ibrahim, Eviatar, & Aharon-Peretz, 2002).

Other studies have found readers to be faster and more accurate at processing visually simple compared to complex orthographies. For example, Feldman and Turvey (1980) observed that Japanese readers were slower at naming colours written using complex Kanji characters compared to the same words written in visually simple Kana, despite the Kanji forms being the orthographically legal spelling of these words. Simpson and Kang (1994) reported longer naming latencies for Korean words written using complex Hanja compared to simple Hangul. Rao, Vaid, Srinivasan, and Chen (2011) found that Urdu–Hindi biscriptal readers were slower and more error-prone in reading words written in their native, visuospatially complex Urdu than in the simpler Hindi script.

However, the visuospatially complex orthographies targeted by these studies were also characterized by a lack of *phonological transparency*, that is, by spelling systems which made phonology (word sound) relatively difficult to recover from their written or orthographic representation. Investigators therefore attributed the greater cost of processing the complex orthographies in the above studies to their relatively opaque orthography-to-phonology mapping, rather than to their complex visuospatial layout.

Comparisons in neuroimaging experiments have also adduced evidence to show that visuospatially complex orthographies impose an extra neurocognitive load during reading (Kuo et al., 2001; Lee, 2004; Nakamura, Dehaene, Jobert, Le Bihan, & Kouider,

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2005). Nevertheless, the complex orthographies investigated by neuroimaging studies have also been characterized by a lack of phonological transparency, resulting in varied interpretations of the results.

1.1. Visuospatial complexity in the VWFA

With respect to the neural processing of orthographic visuospatial complexity, the middle section of the left fusiform gyrus (abbreviated *FG*) and widely termed the *visual word form area* or VWFA would appear to be an ideal candidate as a processing center for complex orthographic features. The role of this region has been intensely debated, with one approach holding that the area is specialized for reading-related orthographic processing (Dehaene & Cohen, 2011), while a competing view maintains that the FG/VWFA integrates visuospatial input with previously acquired information from other modalities, thus making it an ideal node for orthographic processing (Price & Devlin, 2011).

Evidence supporting the former view shows the FG/VWFA to be sensitive to *wordlikeness*, that is, to exhibit heightened responses to stimuli approximating real words (Binder, Medler, Westbury, Liebenthal, & Buchanan, 2006; Cohen et al., 2002; Price, Wise, & Frackowiak, 1996). The idea that the area is specialized for reading is further reinforced by reports that damage to the FG/VWFA results in *pure alexia*, that is, in an inability to read despite normal vision (Binder & Mohr, 1992; Damasio & Damasio, 1983). On the other hand, the theory that the FG/VWFA carries out multisensory integration is strengthened by finding picture – word priming in this region (Kherif, Josse, & Price, 2011). Perhaps more convincingly, this view is bolstered by recent evidence that pure alexics exhibit not only impaired reading, but also perform poorly on other tasks requiring finer visuospatial discrimination (Roberts et al., 2013).

Notwithstanding differences in their theoretical bent, studies across multiple languages have highlighted the VWFA as a component of the visual word recognition network (Bolger, Perfetti, & Schneider, 2005; Jobard, Crivello, & Tzourio-Mazoyer, 2003; McCandliss, Cohen, & Dehaene, 2003; Tan, Laird, Li, & Fox, 2005). The critical importance of the VWFA to orthographic processing has been further underlined by research tracing the development of FG/VWFA sensitivity to word-like stimuli in young children (Ben-Shachar, Dougherty, Deutsch, & Wandell, 2011; Brem et al., 2010) and in illiterate adults learning to read (Dehaene et al., 2010).

Indeed, research in several alphabetic languages points to a role for the FG/VWFA in orthography-to-phonology conversion (Fiez, Balota, Raichle, & Petersen, 1999; Kronbichler et al., 2004; Mechelli et al., 2005; Paulesu et al., 2000). Early experiments demonstrated a clear *word frequency effect* in the VWFA of readers of alphabetic orthographies like English, German and Italian (Fiez et al., 1999; Kronbichler et al., 2004; Paulesu et al., 2000). The word frequency effect is a universally prevalent phenomenon per which readers are slower and less accurate at identifying less familiar or low frequency compared to commonly encountered or high frequency words (Seidenberg, Waters, Barnes, & Tanenhaus, 1984), and is thought to arise because of the greater effort required to retrieve or assemble the phonology of a seldom encountered or novel word. As such, the word frequency effect has been widely exploited to evaluate the behavioral and neural mechanisms of phonological processing.

The connection between the VWFA and phonological retrieval was reinforced when Dehaene et al. (2004) showed that even visually dissimilar prime-target pairs that were phonologically identical (e.g., RADIO – <radio>) produced a significant *repetition suppression effect*, or a reduced response to repeated stimulation in this area. Mechelli et al. (2005) further demonstrated increased functional connectivity during low frequency word reading between the FG/VWFA and the left inferior frontal gyrus, pars opercularis region (LIFG/pO), a known center of phonological processing. Recent evidence suggests that the VWFA is sensitive to low frequency words even in visually complex orthographies like Japanese Kana and Kanji (Twomey et al., 2013).

The role of the FG/VWFA in extracting phonological information from orthographic input may easily be accounted for by both theories of VWFA function outlined above (Dehaene & Cohen, 2011; Price & Devlin, 2011). Of greater relevance to the present research, nevertheless, is the fact that the two approaches give rise to divergent predictions with respect to orthographic visuospatial complexity.

If the VWFA specializes in reading-related orthographic processing, its activation should be driven by the degree of difficulty in retrieving linguistic information from the orthographic features of a stimulus. For example, the frequency of lexical and sub-lexical units, orthographic neighborhood size and density, and spelling-sound transparency should affect VWFA response. At the same time, the strength of VWFA activation should be independent of orthographic features that do not vary systematically in their level of linguistic difficulty, as in the case of the visuospatially complex features of Hindi/Devanagari. By contrast, the theory that the FG/VWFA integrates visuospatial with abstract multimodal information would predict that VWFA activation should correspond to the effort of processing orthographic features, whether or not they covary with linguistic difficulty. Indeed, the latter view would encourage the prediction that FG/VWFA response should reflect the combined influence of linguistic and non-linguistic orthographic difficulty of a given stimulus.

Results of a few studies have suggested that the FG/VWFA is affected by orthographic visuospatial complexity. These studies reported heightened neural activity in the FG/VWFA – BA37 in comparisons of visually complex against simple orthographies, including Kanji versus Kana in Japanese (Ha Duy Thuy et al., 2004; Ino, Nakai, Azuma, Kimura, & Fukuyama, 2009; Nakamura, Dehaene, et al., 2005; Twomey et al., 2013) and Hanja versus Hangul in Korean (Lee, 2004). In their meta-analytical review of the word recognition literature on Chinese and Western alphabetic orthographies, Tan et al. (2005) similarly found additional FG/VWFA response in a contrast of Chinese against alphabetic word recognition.

Nevertheless, two of the above studies specifically refuted the notion that VWFA activity is correlated with the neural effort of processing visually complex characters (Lee, 2004; Twomey et al., 2013). Lee (2004) claimed that an unpublished Hanja versus Hangul (visually complex versus simple) contrast which scrambled the same characters revealed no additional FG activation by Hanja. And although Twomey et al. (2013) reported additional FG/VWFA activation by Kanji compared to Hiragana, they found that adding the number of strokes per character as an index of visual complexity in their analysis did not account for this additional activation.

Evidently, despite the recognized importance of the FG/VWFA in word recognition, its exact role in processing visuospatially complex orthographies remains to be delineated. FG/VWFA involvement in phonological processing also requires further verification, especially in non-alphabetic, visually complex orthographies.

1.2. Visuospatial complexity versus phonological processing

Apart from the FG/VWFA, several studies have implicated certain regions of the brain in processing orthographic visuospatial complexity, including the left middle frontal gyrus (LMFG) – BA9/6, the superior parietal lobule (SPL) – BA7, and parts of the bilateral occipitotemporal cortex or OTC (Ha Duy Thuy et al.,