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The Distinct Roles of Dorsal and Ventral Visual Systems in Naming of Chinese Characters

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Abstract—We aimed to investigate the role of dorsal and ventral visual systems in rapid naming of simple Chinese characters. Twenty college students (10 female; M_{age} = 22.5 years) were required to covertly read a character- and a cross-matrix during an fMRI experiment. A basic prosaccade and a prosaccade-naming task was also performed to confirm the functional significance of the findings. The results of whole brain analysis showed that both dorsal and ventral visual systems were activated in the character-matrix reading. The cross-matrix scanning elicited weaker activation in the left middle frontal gyrus, superior temporal gyrus, and ventral occipitotemporal cortex. Next, whereas both top-down and bottom-up effective connectivities (ECs) were found between these two systems in the character-matrix reading, only top-down ECs were observed in the cross-matrix scanning. Moreover, in the character-matrix reading, we found a negative correlation between the reaction time of naming in the prosaccade-naming task and the EC strength from visual word form area to superior temporal gyrus and a positive correlation between the reaction time in the basic prosaccade task and the EC strength from middle frontal gyrus to intraparietal sulcus. The cross-matrix scanning did not show any brain-behavior relationship. These results suggest that while the dorsal visual system is mainly engaged in eye-movement control, the ventral system is associated more with orthographic processing and orthography-phonology mapping.

Key words: dorsal visual regions, ventral visual regions, effective connectivity, character reading, rapid automatized naming, Chinese.

INTRODUCTION

To date, functional magnetic resonance imaging (fMRI) research of naturalistic reading is scarce (see Choi et al., 2014; Henderson et al., 2015; Hillen et al., 2013; Schuster, et al., 2016, for a few exceptions), and the few studies in the field have used short words or phrases to make up for sentences or paragraphs (e.g., Breznitz, 2005; Pallier et al., 2011). An implication of this methodological constraint is that the role of the ventral visual system in reading, which is thought to tap visual word identification, has been overemphasized over that of the dorsal visual system, which is thought to tap eye-movement control and visual attention processes (Cohen et al., 2008; Vogel et al., 2012; Zhou and Shu, 2017). In the current study, we tried to understand the role of the dorsal and ventral visual systems in reading using a rapid naming task that allows researchers to investigate the roles of these two systems simultaneously.

Previous neuroimaging studies have most often used a discrete word or character reading task, wherein the role of eye movements was minimized, to investigate the activity of ventral visual regions during reading (see Price, 2012, for a review). Researchers have reported that there is hierarchical coding of visual words in ventral regions from the inferior occipital cortex (IOC) to the visual word form area (VWFA) (Dehaene and Cohen, 2011; Vinckier et al., 2007). In turn, previous eye-movement experiments in fMRI studies have most often used simple eye-movement or attentional paradigms, wherein linguistic materials are seldom presented, to investigate the function of the dorsal visual system. For instance, participants were required to make prosaccades from a central fixation to a peripherally presented target (e.g., Hallett 1978; Hutton, 2010). These studies have shown that dorsal visual regions such as the middle fron-

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Abbreviations: ECs, effective connectivities; fMRI, functional magnetic resonance imaging; GCA, Granger causality analysis; IOC, inferior occipital cortex; IPS, intraparietal sulcus; medFC, medial frontal cortex; MFG, middle frontal gyrus; preFC, prefrontal regions; RAN, rapid automatized naming; VWFA, visual word form area.

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tal gyrus (MFG) and the intraparietal sulcus (IPS) were involved in the prosaccade processing (see Jamadar et al., 2013, for a review). Although the neural mechanisms of isolated word reading and eye movements have been studied separately for decades, there is clearly a need to marry these two fields. This will enhance our understanding of the neural mechanism involved in natural reading (see Zhou and Shu, 2017, for a review).

Emerging studies in the field have tried to design fMRI experiments on story reading, in which full-line sentences were presented one at a time to participants (Altmann et al., 2014; Hsu et al., 2015; Wang et al., 2015). However, most of these studies concentrated on high-level processing such as semantic integration, while the role of eye-movement processes situated in dorsal visual regions remains neglected. Only recently, studies have begun to report the involvement of dorsal visual regions in natural reading (e.g., Choi et al., 2014; Henderson et al., 2015; Hillen et al., 2013; Schuster et al., 2016). However, it remains unclear how the dorsal and ventral visual systems interact with each other during this process. In order to address this gap, Zhou et al. (2016) asked participants to covertly read the story that was presented as sentence by sentence. Unfortunately, their participants were required to read a text and thus comprehension processes could not be switched off along with the absence of an index of low-level eye-movement processes, which confounded their results regarding the role of the dorsal visual system. To bypass these problems, we employed in this study a rapid automatized naming (RAN) task with simple characters and crosses (see below for more information).

RAN, defined as the ability of an individual to name visually presented simple stimuli such as objects, digits and letters, has been described as "a microcosm" of natural text reading (e.g., Norton and Wolf, 2012; Protopapas et al., 2013). As RAN shares many basic processes with natural text reading, such as visual attention, word form recognition, and grapheme-phonology/semantics mapping, an in-depth examination of how RAN develops and reaches an automatic level can provide invaluable information on how natural text reading is achieved (see Altani et al., 2018; Protopapas et al., 2018, for recent evidence).[1] Several studies have shown that RAN is a significant predictor of reading across languages (e.g., Araújo et al., 2014; de Jong and van der Leij, 1999; Georgiou et al., 2016; Landerl and Wimmer, 2008; Liao et al., 2008) and a core deficit in dyslexia (e.g., de Jong and van der Leij, 2003; Ho and Lai 1999a; Wolf and Bowers, 1999).

An obvious similarity among natural text reading, RAN, and cross-matrix scanning is that all tasks include eye movements from left to right and top to bottom. The difference in the eye-movement aspect between text reading and RAN is that, eye-movement control in text reading is primarily driven by high-level factors such as syntactic and semantic processes (Radach et al., 2008), whereas the time and location to move eyes during RAN rely on relative low-level factors such as letter/digit processing and spacing between items (Yan et al., 2013). This difference between RAN and text reading is more obvious when reading Chinese. Without spaces between words in Chinese text, readers abstract high-level lexical information in parafovea for saccade-targeting rather than using the information of low-level spatial frequency as in spaced alphabetic text (Yan et al., 2010). In turn, the difference in eye-movement control between cross-matrix scanning and RAN is that cross-matrix scanning does not involve character reading processes. Moreover, compared to cross-matrix scanning, the orthography-to-phonology mapping in RAN is highlighted and is an important skill in read acquisition (Norton and Wolf, 2012; Pan et al., 2013). On these grounds, the use of RAN Characters offers a good opportunity for researchers to identify the cognitive and neural mechanism(s) underlying single character reading, eye-movement processes, and the relation between them. For instance, recent behavioral eye-movements studies on RAN have shown that orthography-to-phonology mapping could influence parafoveal processing, perceptual span and eye-voice span as indicated by eye-movement patterns (e.g., Pan et al., 2013; Yan et al., 2013).

Accordingly, a comparison of cognitive mechanisms between natural text reading, RAN Characters, and cross-matrix scanning, could further confirm that the dorsal visual system is engaged in all of these tasks, and answer the question whether the involvement of the ventral system and the interaction between the dorsal and ventral visual systems is different among tasks. While the "top-down" effect derives from selective visual attention situated in dorsal visual regions, the automatic "bottom-up" capture of attention is driven by the properties of the stimuli situated in ventral visual regions (Buschman and Miller, 2007; Schurz et al., 2014). Zhou et al. (2016) found that there were effective connections from the left MFG to both dorsal visual region (i.e., left IPS) and ventral visual region (i.e., the VWFA) and from IPS to VWFA during natural text reading, indicating primarily "top-down" modulation from dorsal to ventral visual system. As the RAN of Characters is also driven by conspicuous stimuli processing, we would expect an existence of "bottom-up" brain connections in this task. As cross-matrix scanning lacks complex visual input, there would be less involvement of ventral visual regions and less "bottom-up" brain connections. In the last few years, some studies have examined the neural substrates of RAN using fMRI (Al Dahhan et al., 2017; Christodoulou, 2010; Cummine et al., 2014, 2015; Misra et al., 2004). Although these studies have revealed the involvements of both ventral and dorsal visual regions in RAN, it is still unknown how the dorsal and ventral visual systems interact with each other during this task.

Taken together, although previous studies have reserved a significant role for both ventral visual and dorsal visual regions in word reading and eye movements separately, there is still lack of focus on the dorsal visual system and its interaction with the ventral visual system in natural reading, which, importantly,

[1] Notice that in some psychometric batteries (e.g., The Process Assessment of The Learner; Berninger, 2007), RAN is assessed with rapid word naming.