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Visual dorsal stream is associated with Chinese reading skills: A resting-state fMRI study

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ABSTRACT

The present study explored the relationship between visual dorsal stream and Chinese reading by resting-state fMRI technique. We collected the resting-state brain activities and reading skills of Chinese-speaking adult readers. The results showed that the values of amplitude of low frequency fluctuation (ALFF) in right posterior parietal cortex (PPC) and left visual middle temporal area (MT) (two regions of dorsal stream) were significantly correlated with rapid naming (RAN) speed, and the ALFF values of right PPC were correlated with orthographic awareness (OA). Further resting-state functional connectivity (RSFC) analysis revealed that RAN speed was related to RSFCs between dorsal stream areas and reading areas (e.g., left fusiform gyrus, bilateral middle occipital gyrus). OA was correlated with RSFCs between right PPC and left middle occipital gyrus. It suggested that spontaneous activities of visual dorsal stream, as well as connection between it and reading-related areas, were highly associated with Chinese reading skills.

1. Introduction

The visual dorsal stream, also known as the "where" stream, connects V1 to the posterior parietal cortex (PPC), including middle temporal area (MT/V5) (Goodale & Milner, 1992; Merigan & Maunsell, 1993). Then, information from MT projects to prefrontal cortex, especially, the frontal eye field (FEF). Therefore, FEF is also regarded as a part of dorsal pathway (Barbas, 2000). This stream is involved in many types of visual-spatial processing, such as object localization, motion perception, initiation of goal-directed movements (Goodale & Westwood, 2004), and selective visual attention (Posner, 1995). Meanwhile, dorsal stream is reported to be involved in some higher cognitive functions, such as reading (Boden & Giaschi, 2007; Stein, 2001).

In alphabetic languages, some behavioral studies showed that reading skills were correlated with coherent motion sensitivity, which effectively reflected dorsal stream function (Boden & Giaschi, 2007). Coherent motion sensitivity was significantly correlated with several reading skills, including orthographic awareness, phonological awareness, rapid naming and reading rate (Benassi, Simonelli, Giovagnoli, & Bolzani, 2010; Boets, Vandermosten, Cornelissen, Wouters, & Ghesquière, 2011; Chase, Dougherty, Ray, Fowler, & Stein, 2007; Demb, Boynton, & Heeger, 1998; Hansen, Stein, Orde, Winter, & Talcott, 2001; Hulslander et al., 2004; Kevan & Pammer, 2008; Kinsey, Hansen, & Chase, 2006; Levy, Walsh, & Lavidor, 2010; Talcott et al., 2000, 2002). Functional magnetic resonance imaging (fMRI) studies found that stronger activation in MT was correlated with superior phonological awareness in normal children (Ben-Shachar, Dougherty, Deutsch, & Wandell, 2007). Compared with age-matched normal readers, dyslexics showed a reduction or absence of brain activity in MT+ (Demb et al., 1998; Eden et al., 1996; Heim et al., 2010; Olulade, Napoliello, & Eden, 2013). These studies consistently manifested the association between visual dorsal stream and reading skills.

Reading is complex process that involves neural networks that mediate orthography, phonology, semantics, eye movements and attention (Roux et al., 2004; Schlaggar & McCandliss, 2007). Numerous fMRI studies in alphabetic languages show that some brain regions are responsible for specific reading processing. Although there remains controversy (Price & Devlin, 2003; Vogel, Miezin, Petersen, & Schlaggar, 2011), some researchers indicate that "visual word form area" (VWFA) may be responsible for

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orthographic processing. It is located in left occipito-temporal cortex, especially posterior region of the left midfusiform gyrus, and may preferentially respond to visual forms of written words relative to other categories such as line drawings (e.g., Cohen & Dehaene, 2004; Cohen et al., 2002; Dehaene & Cohen, 2011; McCandliss, Cohen, & Dehaene, 2003). Phonological and/ or semantic processing may be occurring in temporo-parietal regions (e.g., Jobard, Crivello, & Tzourio-Mazoyer, 2003; Palmer, Brown, Petersen, & Schlaggar, 2004). Superior temporal gyrus and supramarginal gyrus may be activated in phonological tasks, while inferior/ middle temporal gyrus and angular gyrus may be associated with semantic processing (Binder, Desai, Graves, & Conant, 2009; Boukrina & Graves, 2013; Mechelli, Josephs, Ralph, McClelland, & Price, 2007; Price, Moore, Humphreys, & Wise, 1997). Additionally, inferior frontal gyrus is involved in phonological and semantic processing, the anterior part is related to semantic processing while the posterior part is for phonological processing (McDermott, Petersen, Watson, & Ojemann, 2003; Vigneau et al., 2006). Then, we hypothesize that as certain regions of the brain are related to specific reading processes, there will be relationships between dorsal stream and some specific reading regions but not others.

Reading and its neural mechanism have language specificity. For instance, Chinese is a logographic language without grapheme-phoneme correspondence (GPC) (Tan, Laird, Li, & Fox, 2005). Chinese characters are visually compact (Ho, Chan, Lee, Tsang, & Luan, 2004) and look like two-dimension pictures (Zhang, Guo, Ding, & Wang, 2006). So, visual skills are particularly important for reading (Chung et al., 2008; Li, Shu, McBride-Chang, Liu, & Peng, 2012; Yang et al., 2013). Some studies showed the brain regions responsible for Chinese reading were different from that for alphabetic languages. For example, the left ventral occipito-temporal system was important for orthographic processing in alphabetic languages, but bilateral were crucial for Chinese (Tan et al., 2005). Meanwhile, left dorsal lateral frontal region (Brodmann Area (BA) 9) and the left dorsal aspect of the inferior parietal region were specially important for Chinese phonological processing (Tan et al., 2005). Accordingly, it is possible that dorsal stream plays a unique role in Chinese reading.

Behavioral studies showed that Chinese children with developmental dyslexia had deficits in visual dorsal stream (Meng, Cheng-Lai, Zeng, Stein, & Zhou, 2011; Qian & Bi, 2014; Wang, Bi, Gao, & Wydell, 2010). The dorsal stream function was associated with Chinese orthographic processing skills and rapid naming (Meng et al., 2011; Qian & Bi, 2014). Additionally, a recent fMRI study showed that activities in dorsal stream were correlated with orthographic awareness, rapid naming, reading fluency and reading accuracy for Chinese skilled readers (Qian, Deng, Zhao, & Bi, 2015). Since dorsal stream and reading-related areas are both associated with Chinese reading, it is hypothesized that there may be connections between them for Chinese readers.

Based on previous studies, we hypothesize that the connections between dorsal stream and reading-related areas are associated with specific reading skills. Resting-state functional connectivity (RSFC) is an effective method to test this hypothesis. RSFC analysis has recently been applied to investigate the functional relevance of intrinsic brain regions. RSFC is task-independent, and uses correlations in low-frequency (approximately 0.01–0.1 Hz) fluctuations of the blood oxygen level dependent (BOLD) signal present at rest to define functional relationships between regions (Biswal, Zerrin Yetkin, Haughton, & Hyde, 1995). Moreover, correlating the RSFC strength with behavioral performance can provide more evidence about the neural mechanism of certain cognitive skills. A recent study found that RSFCs between the VWFA and regions of the dorsal attention network increased with age and reading skills (Vogel et al., 2011). In the study of Vogel et al. (2011), the dorsal attention network included bilateral frontal eye fields (FEF), intraparietal sulcus (IPS), and MT. The network was close to dorsal stream in the human brain. Therefore, it seemed that VWFA was connected to dorsal stream in the resting state, and the connection strength was associated with English reading abilities. However, whether the connections are responsible for different reading skills, especially Chinese reading skills, is still unsolved.

The current study sought to explore the relationship between Chinese reading skills and visual dorsal stream by resting fMRI. We focused on three reading skills, including phonological awareness, orthographic awareness and rapid naming speed. Phonological awareness is widely considered to be critical for alphabetic reading (Bar-Kochva, 2013; Brunswick, Neil Martin, & Rippon, 2012; Lonigan, Burgess, & Anthony, 2000; Wimmer, Mayringer, & Landerl, 2000), while orthographic awareness is important for Chinese reading (Ho et al., 2004; Yeung et al., 2011). Additionally, rapid naming is associated with reading success in previous studies (Manis, Seidenberg, & Doi, 1999; Savage & Frederickson, 2005). Moreover, researchers indicate that fluent reading and rapid naming share some cognitive processes, from eye saccades to the connecting of orthographic and phonological representations (Norton & Wolf, 2012). Hence, excluding the effect of individual differences in vocabulary, a digit rapid naming task was adopted in the present study to measure readers' basic reading skills.

In the present study, in order to improve the pertinence of RSFC analysis, we firstly explored the correlation between the amplitude of the low frequency fluctuations (ALFF) in the brain regions of dorsal stream (i.e., MT, PPC and FEF) and these reading skills. As demonstrated by prior studies (Li et al., 2013; Yang et al., 2007; Zang et al., 2007), ALFF of resting-state fMRI signals reflects the magnitude of spontaneous brain activities in a resting- state functional network. Thus, the correlation analysis between ALFF of dorsal stream and reading skills might indicate which regions whose spontaneous activities were correlated with specific reading skills. Secondly, we tried to find the association between reading skills and the RSFCs between reading regions and dorsal stream (whose ALFF values were correlated with reading skills).

2. Material and methods

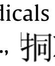
2.1. Participants

Twenty college students took part in the experiment (11 females and 9 males; age range 20–24 years; mean age ± standard deviation = 22.5 ± 1.59). All participants were native Chinese speakers, and had normal or corrected-to-normal vision, without previous history of neurological impairment, psychiatric disorder, or severe reading disability. Each participant provided written, informed consent in accordance with procedures and protocols approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences.

2.2. Reading tests

Prior to the fMRI scan, all participants underwent reading skill tests. Three reading-related tests were used to evaluate orthographic awareness, phonological awareness and rapid naming, respectively, which have been used in the previous fMRI study (Qian et al., 2015). The sequence of tests was counterbalanced across participants. The tests were described below.

2.2.1. Orthographic awareness test (OA)

This task consisted of 40 real characters, 20 pseudo-characters, and 20 non-characters. Pseudo-characters and non-characters did not exist in fact, and the configuration of radicals followed the orthographic rules for pseudo-characters (e.g., ) but not for non-characters (e.g., 䜣). The radicals of pseudo-characters were in legal positions, while the radicals of non-characters were not. Therefore, the performance difference between them might reflect readers' awareness of positional regularity of radicals, which was an important component of orthographic awareness (Ho, Ng, & Ng, 2003). The task was computerized, and each item was presented in isolation in the center of the computer screen. Participants were asked to judge whether or not a presented item was a real character. The response accuracy of each type of stimuli was recorded.

2.2.2. Phonological awareness test (PA)

An oddball paradigm (Bradley & Bryant, 1978) was adopted. Within a trial, three characters were presented orally by the experimenter, and participants were asked to pick out a phonologically odd item from them. There were three types of oddity: onset, rime, and lexical tone. For example, for the three items "tan4", "tong3", and "ji1", "tan4" and "tong3" had the same onset "t" except for "ji1". Meanwhile, the three items were completely different in rime and lexical tone. A total of ten trials for each type of oddity were presented. The response accuracy was recorded.

2.2.3. Rapid naming (RAN)

Five digits (2, 4, 6, 7, and 9) were used for this task. Digits were repeatedly presented visually in random order on a six row × five column grid. Participants were asked to name each digit in sequence as quickly as possible. Each participant completed the test twice, and the total time (s) taken to name all digits was collected, averaged and converted to a per-second score.

2.3. MRI data acquisition

Data were collected on a Siemens Trio 3.0 T scanner with a custom-built volume head coil at the Beijing MRI Center for Brain Research. For resting-state functional imaging, scans lasted about eight minutes and were composed of 240 continuous echo-planar imaging (EPI) whole-brain functional volumes (TR = 2000 ms, TE = 30 ms, flip angle = 90°, FOV = 200 mm, matrix = 64 × 64, slice thickness = 3.99 mm, and voxel size = 3 × 3 × 3.99 mm). During the scan, participants were instructed to relax with their eyes open and try not to think about anything systematically or fall asleep. None of them fell asleep according to a simple questionnaire after the scan. For spatial normalization and localization, a T1-weighted anatomical image was obtained using a magnetization-prepared rapid gradient echo (MPRAGE) sequence (TR = 2530 ms, TE = 3.37 ms, flip = 7°, FOV = 256 mm, matrix = 256 × 256, slice thickness = 1.33 mm, and voxel size = 0.5 × 0.5 × 1.33 mm).

2.4. Data preprocessing

Resting-state MRI data preprocessing was carried out using Data Processing Assistant for Resting-State fMRI (DPARSF) (Yan & Zang, 2010) in the following steps: (1) discarding the first 10 volumes for signal equilibrium; (2) slice timing correction; (3) head motion correction; no participant exhibited head motion of 2 mm maximum translation or 2° rotation throughout the course of scans. (4) spatial normalization to the MNI space using T1 image unified segmentation; the resampling voxel size was 3 × 3 × 3 mm^3; (5) spatial smoothing with 4 mm FWHM Gaussian kernel; (6) removal of linear trends; (7) band-pass temporal filtering (0.01–0.08 Hz).

2.5. Seed regions of interest (ROI) of visual dorsal stream

We selected 6 regions in the dorsal stream, including bilateral MT, bilateral PPC and bilateral FEF. The coordinates of these regions were defined from a meta-analysis of 4 published studies (Carter et al., 2010). They were also used in the study of Vogel et al. (2011) and were similar to those reported in previous studies (e.g., Ciaramelli, Grady, & Moscovitch, 2008; Olulade et al., 2013; Qian et al., 2015; Wilms et al., 2005). Table 1 showed the coordinates of 6 ROIs in dorsal stream. We created spherical ROIs centering on the MNI coordinates with a radius of 6 mm.

2.6. Correlation analyses between visual dorsal stream and reading skills: Amplitude of low frequency fluctuation (ALFF) and resting-state functional connectivity (RSFC) analysis

The correlation analyses were divided into two steps. In order to investigate the relationship between spontaneous activities of ROIs and reading skills, the first step was ALFF analysis, including ALFF computation and conducting correlations between ALFF and reading skills. The second step was voxel-wise RSFC computation and RSFC-reading correlation analysis.

2.6.1. Amplitude of low frequency fluctuation (ALFF) computation and correlation analysis between ALFF and reading skills

The ALFF analysis was carried out using Resting-State fMRI Data Analysis Toolkit (REST) (Song et al., 2011). The calculation procedure was the same as that reported in the previous studies (Yang et al., 2007; Zang et al., 2007). The fMRI time series were transformed to frequency domain using fast Fourier transform (FFT) (parameters: taper percent = 0, FFT length = shortest) and the power spectrum was obtained. Since the power of a given frequency is proportional to the square of the amplitude of this frequency component in the original time series in time domain, the power spectrum obtained by FFT was square rooted and then averaged across 0.01–0.08 Hz at each voxel. This averaged square root was taken as the ALFF. For standardization, the ALFF of each voxel was further divided by the global mean of ALFF values. Then, the mean ALFF values of each ROI were extracted, which was further made correlation analysis with reading skills after controlling head motion effect. Here, head motion was measured by mean frame-by-frame displacement (FD) derived with Jenkinson's relative root mean square (RMS) algorithm (Jenkinson, Bannister, Brady, & Smith, 2002; Yan, Craddock, He, & Milham, 2013). A p value of 0.1 was used to designate statistical significance of correlations, and the Bonferroni correction was used for multiple comparisons (set at $p < 0.017$).

2.6.2. RSFC computation and correlation analysis between RSFCs and reading skills

According to the ALFF results, we selected the dorsal stream areas which were correlated with reading as the ROIs in the RSFC analysis. Further, we made correlation analysis between RSFCs

Table 1
MNI coordinates of ROIs in dorsal stream.

MNI coordinates (X Y Z)	Seed ROIs
−26 −5 50	Left frontal eye fields (FEF.L)
32 −6 39	Right frontal eye fields (FEF.R)
−25 −62 51	Left aIPS (PPC.L)
25 −64 51	Right aIPS (PPC.R)
−45 −71 −1	Left MT (MT.L)
44 −68 −6	Right MT (MT.R)

Note: Regions were obtained from a meta-analysis study of Carter et al. (2010). The abbreviations of these ROIs were shown in parentheses.

Table 2
Correlations between ALFF of dorsal stream ROIs and reading skills.

	Orthographic awareness (OA)	Phonological awareness (PA)	Rapid naming speed (RAN)
FEF.L	−0.35	0.28	−0.15
FEF.R	0.25	0.29	−0.22
PPC.L	0.21	−0.33	0.27
PPC.R	0.43	−0.05	**0.57**+
MT.L	0.12	−0.15	**0.55**+
MT.R	−0.17	−0.10	0.29

Note:
+ $p < 0.1$, Bonferroni corrected.

Table 3
MNI coordinates and correlation coefficients of the significant RSFC-orthographic awareness correlation relationships.

Seed ROIs	Region	Peak (x y z)	Number of voxels	*r*
PPC.R	Middle/Inferior Occipital Gyrus (L)	−51 −66 −12	22	0.78
	Middle Temporal Gyrus (R)	39 −63 12	16	0.69
	Middle Temporal Gyrus (L)	−30 −69 18	17	0.69
	Inferior Parietal Lobule (R)	42 −48 39	127	0.86
	Inferior Parietal Lobule (L)	−36 −51 48	39	0.78
	Precentral Gyrus (L)	−12 −27 69	41	−0.77

and reading skills after controlling FD. Only the reading skills significantly correlated with ALFF of dorsal stream were adopted.

The voxel-wise RSFC analysis was performed using REST after removing of several nuisance covariates by regression to control for the effects of physiological processes and head motion (six head motion parameters, the white matter signal, the cerebrospinal fluid signal and the global signal). For each participant, a whole-brain analysis was conducted to correlate the time courses of the seed ROIs with the time courses of all the other voxels in the brain in order to obtain RSFC map of each participant. These maps were converted to Z-value maps using Fisher's r-to-z transformation for further group-level analysis. Then, we correlated these Z-maps with reading skills after controlling FD ($p < 0.01$, AlphaSim corrected, cluster size ⩾ 16).

3. Results

3.1. Reading skills

The mean accuracy of each type of characters in the orthographic awareness (OA) test was as follows, real characters: 0.98 (SD: 0.03); pseudo-characters: 0.73 (SD: 0.26); non-characters: 0.97 (SD: 0.04). As mentioned, the accuracy difference between pseudo-characters and non-characters reflected radical position knowledge of OA (Ho et al., 2003). So, the accuracy difference between pseudo-characters and non-characters (mean: 0.24; SD: 0.24; median: 0.15; range: 0.80) was regarded as OA in the present study. For phonological awareness, the mean accurate rate was 0.85 (SD: 0.14; median: 0.90; range: 0.57). The average rapid naming (RAN) speed was 4.53 numbers per second (SD: 0.67).

3.2. The correlation between ALFF of dorsal stream and reading skills

The correlations between ALFF of dorsal ROIs and reading skills were shown in Table 2 and Fig. 1. Phonological awareness was not significantly correlated with ALFF of any dorsal stream ROIs. RAN was correlated with ALFF of right PPC ($r = 0.57$, $p = 0.06$, Bonferroni corrected) and left MT ($r = 0.55$, $p = 0.09$, Bonferroni corrected). ALFF of right PPC was positively correlated with OA ($r = 0.43$, $p = 0.07$, uncorrected), but was not significant after Bonferroni correction. Nonetheless, OA was still adopted as a reading skill in the further analysis to explore the subtle relationship between dorsal stream and orthographic processing, because orthographic processing was particularly important for Chinese reading development (Ho et al., 2004; Yeung et al., 2011).

3.3. The correlation between RSFCs and reading skills

In the ALFF analysis, right PPC was associated with both OA and RAN while left MT was associated with RAN. So, we correlated voxel-wise RSFC maps of right PPC with OA and RAN, and correlated RSFC maps of left MT with RAN. The results showed that RSFCs between ROIs in dorsal stream and several reading-related areas were correlated with OA and RAN, which were shown in Tables 3 and 4 and Fig. 2. According to previous studies (Bolger, Perfetti, & Schneider, 2005; Wang, Han, He, Liu, & Bi, 2012), the following areas were closely associated with Chinese reading: Left inferior occipital gyrus, right inferior occipital gyrus, left fusiform gyrus, right fusiform gyrus, and left inferior temporal gyrus, left superior temporal gyrus, and left inferior frontal gyrus. So, we picked the above areas in the Tables 3 and 4 when the RSFCs between them and dorsal stream areas were significantly correlated with OA and RAN.

As shown in Fig. 2a, OA was significantly correlated with the RSFC between left middle occipital gyrus and right PPC. RAN speed was positively correlated to the RSFC between reading–related areas (i.e., left FFG, bilateral middle occipital gyrus, and left inferior frontal gyrus) and left MT, which were shown in Fig. 2b. In order to verify whether the RSFCs themselves were significant, we conducted one-sample *t* test in the mask of the significant correlation. The result showed that the RSFC between right PPC and left middle occipital gyrus was significant ($t = 6.25$, $p < 0.05$). The RSFCs

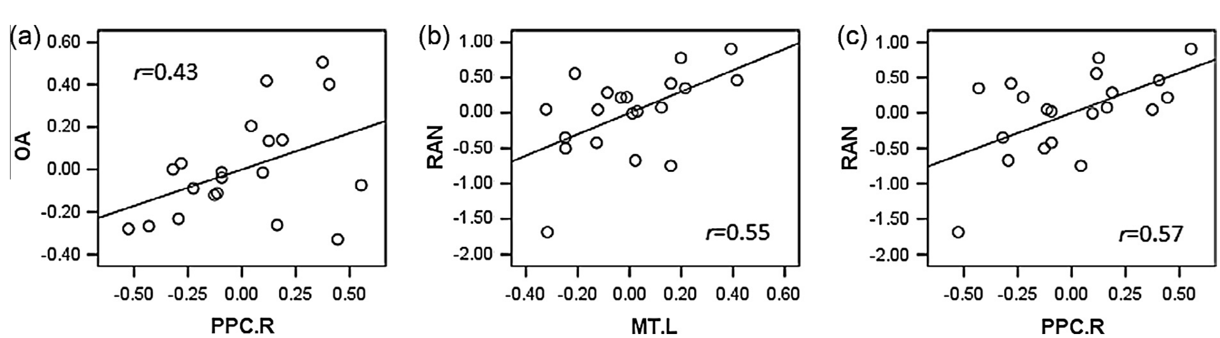


Fig. 1. The partial regression plots between ALFF and reading skills after controlling head motion. (a) ALFF of right PPC was correlated with the accuracy of orthographic awareness (OA) test ($r = 0.43$, $p = 0.07$, uncorrected); (b) the speed in rapid naming (RAN) test was correlated with ALFF of left MT ($r = 0.55$, $p = 0.09$, Bonferroni corrected); (c) RAN was correlated with ALFF of right PPC ($r = 0.57$, $p = 0.06$, Bonferroni corrected).

Table 4
MNI coordinates and correlation coefficients of the significant RSFC-rapid naming correlation relationships.

Seed ROIs	Region	Peak (x y z)	Number of voxels	r
PPC.R	Cerebellum Posterior Lobe (L)	−30 −54 −15	19	0.72
	Inferior Frontal Gyrus (L)	−51 30 −3	20	−0.75
	Superior Temporal Gyrus (R)	60 −48 9	28	0.72
	Middle Temporal Gyrus (L)	−30 −78 15	33	0.74
	Cingulate Gyrus	0 −36 27	18	−0.65
	Supramarginal Gyrus(L)	−54 −63 30	36	−0.72
	Superior Frontal Gyrus (L)	−15 24 60	16	−0.70
MT.L	Middle Temporal Gyrus (L)	−54 −69 21	16	−0.72
	Middle Occipital Gyrus (L)	−48 −69 −12	54	0.76
	Middle Occipital Gyrus(R)	42 −72 −12	37	0.81
	Fusiform Gyrus (L)	−42 −54 −15	43	0.74
	Anterior Cingulate (L)	−9 45 0	394	−0.88
	Cingulate Gyrus (L)	−3 −24 36	1212	−0.85
	Superior Frontal Gyrus (L)	−18 60 12	25	−0.67
	Superior Frontal Gyrus (R)	30 21 54	250	0.85
	Inferior Parietal Lobule(R)	45 −60 45	157	−0.75
	Angular Gyrus(L)	−42 −69 33	16	−0.73
	Angular Gyrus(R)	54 −63 30	71	−0.69
	Inferior Frontal Gyrus (R)	51 18 18	103	0.79
	Inferior Frontal Gyrus (L)	−51 12 12	71	0.78
	Medial Frontal Gyrus (L)	−12 63 −3	17	−0.77
	Precuneus (R)	27 −54 51	24	0.73
	Precuneus (L)	−27 −57 51	39	0.72

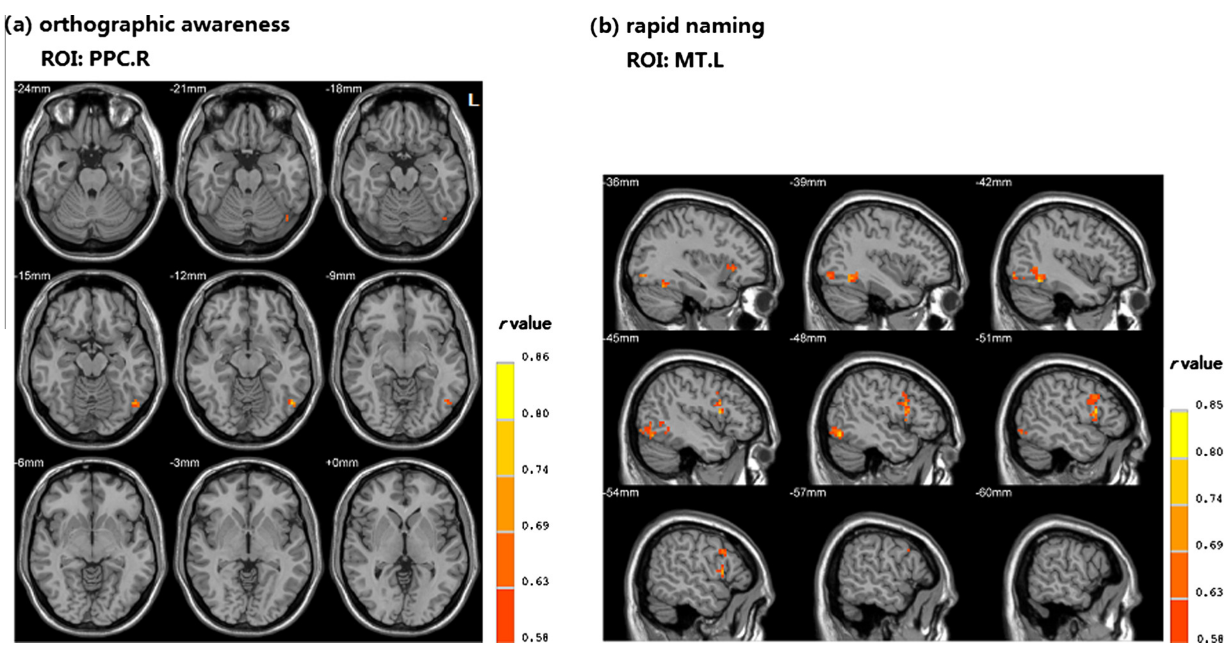


Fig. 2. The significant correlation between RSFC-reading in voxel-wise analysis. (a) The RSFC between left middle occipital gyrus and right PPC was correlated with orthographic awareness; (b) the RSFCs between reading areas (i.e., left fusiform gyrus and bilateral middle occipital gyrus) and left MT were correlated with rapid naming speed.

between left MT and left fusiform gyrus ($t = 6.89$), bilateral middle occipital gyrus ($t(L) = 13.5$, $t(R) = 8.65$) were also significant ($ps < 0.05$). However, the RSFC between left MT and left inferior frontal gyrus was not significant.

4. Discussion

In the present study, the results showed that ALFF of right PPC and left MT was correlated with rapid naming. It suggested that higher intensity of spontaneous activities of right PPC and left MT was associated with faster rapid naming. Voxel-wise RSFC results showed that rapid naming speed was related with the connectivity strength between dorsal stream areas (right PPC and left MT) and visual form areas (i.e., left fusiform gyrus and bilateral middle occipital gyrus). Orthographic awareness was correlated with RSFCs between right PPC and left middle occipital gyrus. These results manifested the association between Chinese reading and dorsal stream.

4.1. The relationship between rapid naming (RAN) and dorsal stream

RAN tasks required speeded naming of serially presented stimuli and shared key characteristics with reading, and activated visual dorsal stream (e.g., FEF and SPL) (Misra, Katzir, Wolf, & Poldrack, 2004). Previous studies showed that the activation of dorsal pathway (MT and PPC) was positively correlated with RAN speed and reading fluency (Demb et al., 1998; Qian et al., 2015). Consistent with previous studies, the present study showed that RAN speed was positively correlated with the ALFF values of right PPC and left MT, suggesting that the spontaneous activity of dorsal stream even in the resting state was associated with RAN performance. Meanwhile, RAN was correlated with the RSFCs between visual dorsal stream (especially, left MT) and reading areas, including left FFG and bilateral MOG. RAN involved rapid sequential processing of individual symbols (Kail, Hall, & Caskey, 1999) and required rapid integration of many lower- and higher-level visual and linguistic processes (Bowers & Wolf, 1993; Manis et al., 1999; Wolf & Bowers, 1999). It was pointed out that the MT might be involved in building an initial global image of stimuli and rapidly triggering attention to salient exogenous stimuli (Laycock & Crewther, 2008; Laycock, Crewther, Fitzgerald, & Crewther, 2009). Meanwhile, PPC might modulate attentional processing (Laycock & Crewther, 2008). The strong connection between dorsal stream and reading areas might ensure the fast visual processing of character form via rapid visual processing and attention modulation, so the stronger connection was associated with faster naming.

4.2. The relationship between orthographic awareness (OA) and dorsal stream

OA was important for reading acquisition (Badian, 2001; Ho et al., 2004; Sprenger-Charolles, Siegel, Béchennec, & Serniclaes, 2003; Yeung et al., 2011). Previous behavioral studies indicated that visual dorsal stream function was associated with OA (Boets et al., 2011; Levy et al., 2010; Qian & Bi, 2014; Talcott et al., 2000). An fMRI study also showed that the activation of right PPC was correlated with Chinese OA (Qian et al., 2015). In fact, some evidence pointed out that superior parietal lobule (SPL), a part of PPC, was specially related with Chinese character recognition (Siok, Spinks, Jin, & Tan, 2009; Sun, Yang, Desroches, Liu, & Peng, 2011; Tan et al., 2001; Wu, Ho, & Chen, 2012). Because of the visual complexity of Chinese characters, Chinese orthographic processing might need more help from visual-spatial analysis and attention, which were the function of PPC (Wu et al., 2012). Such role might be more closely associated with right PPC rather than left PPC, which was consistent with the opinion of lateralization of visuospatial attention network. Right hemisphere was dominant for visual-spatial attention, and the degree of anatomical lateralization was correlated with the performance on visual-spatial tasks (De Schotten et al., 2011). ALFF of right PPC tended to be correlated with OA in the present study, suggesting that the stronger magnitude of spontaneous brain activities was in right PPC, the better performance was in the OA test.

Furthermore, voxel-wise analysis showed the RSFC between PPC and left MOG was correlated with OA, suggesting that the connections between dorsal stream (particularly, right PPC) and visual form processing areas were associated with orthographic processing. This finding was consistent with the results of Vogel et al. (2011), which showed that dorsal attention network (left and right aIPS, MT+, and FEF regions) had RSFCs with VWFA, and the connection between the VWFA and bilateral aIPS increased with reading skills. Likewise, a resting-state fMRI study also found that Chinese reading performance was positively correlated with RSFCs between OT regions (including left IOG and right FFG) and SPL (Wang et al., 2012). Ventral OT cortex (including MOG, FFG and IOG, etc.), especially, VWFA might be engaged in visual word form processing (Cohen et al., 2002; Dehaene & Cohen, 2011; McCandliss et al., 2003; Wu et al., 2012). PPC was responsible for visual-spatial attention (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Gitelman, Parrish, Friston, & Mesulam, 2002; Silver, Ress, & Heeger, 2005; Thompson, Biscoe, & Sato, 2005), and exerted top-down modulatory influence on visual occipital cortex in relation to visual attention (Bressler, Tang, Sylvester, Shulman, & Corbetta, 2008). Therefore, the connection between PPC and MOG here might reflect that the modulation of visual-spatial attention to word form processing, which further influenced the orthographic awareness. Strong RSFCs between PPC and MOG could ensure the top-down attentional modulation to successful word form processing.

4.3. The relationship between phonological awareness (PA) and dorsal stream

However, there were no significant correlations between ALFF of dorsal stream areas and PA. It suggested that dorsal stream was not associated with Chinese PA. However, Ben-Shachar et al. (2007) found that dorsal stream activities were correlated with English PA, but they did not investigate the correlation between dorsal stream and OA. The weak relationship between phonology and dorsal stream in Chinese might be related to language specificity. Owing to the specific GPC rules, it was difficult to separate orthography and phonology, and OA is tightly correlated with PA in alphabetic languages. Therefore, it was hard to explore the relationship between dorsal stream and OA or PA independently in alphabetic languages. However, it was proper to examine the relationship in Chinese, given that OA and PA are relatively separate. Additionally, PA might play a less important role in Chinese reading than in alphabetic languages (Yeung et al., 2011), so the association between dorsal stream and Chinese reading skills might not be reflected in PA. The last but not least, the oddball paradigm test for PA was not very discriminating for adults (here, mean accuracy was 0.85), which might lead to insignificant correlation. Therefore, future studies were required to measure adults' PA by more effective tests.

5. Limitations

While the present study provided insight into the relationship between visual dorsal stream and Chinese reading, it had several limitations. Firstly, the IQ scores of the participants were not collected, and the potential confound of IQ could not be excluded. Secondly, the sample size was relatively small. Although the effect sizes were generally decent with medium to high Pearson R values, some of the statistical results were borderline significant only and thus further studies with larger samples are desired.

6. Conclusion

The current study found that the spontaneous activities of visual dorsal stream in resting-state, as well as the resting-state connection between dorsal stream and reading-related areas (e.g., bilateral middle occipital gyrus, left fusiform gyrus), were correlated with Chinese reading skills, especially rapid naming skills. Dorsal stream might influence Chinese reading via the mechanism of rapid processing and visual-spatial attention modulation.

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