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Resting-state functional connectivity and reading abilities in first and second languages

Mingxia Zhang [a,b], Jin Li [a], Chuansheng Chen [b,*], Gui Xue [a], Zhonglin Lu [d], Leilei Mei [b], Hongli Xue [a], Feng Xue [c], Qinghua He [c], Chunhui Chen [b], Miao Wei [c], Qi Dong [a,**]

[a] National Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing 100875, China
[b] Department of Psychology and Social Behavior, University of California, Irvine, CA 92697, USA
[c] Department of Psychology, University of Southern California, Los Angeles, CA 90089, USA
[d] Center for Cognitive and Behavioral Brain Imaging, Department of Psychology, Ohio State University, Columbus, OH 43210, USA

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ABSTRACT

An intriguing discovery in recent years is that resting-state functional connectivity (RSFC) is associated with cognitive performance. The current study investigated whether RSFC within the reading network was correlated with Chinese adults' reading abilities in their native language (L1, Chinese) and second language (L2, English). Results showed that RSFC within the reading network was positively correlated to reading abilities in L1 and L2, and RSFC between reading areas and the default network was negatively correlated to reading abilities in L1 and L2. Further conjunction and contrast analyses revealed that L1 and L2 shared similar RSFC correlates including connectivities between the areas for visual analysis (e.g., bilateral posterior fusiform gyrus, lateral occipital cortices, and right superior parietal lobules) and those for phonological processing (e.g., bilateral precentral gyri and postcentral gyrus, Wernicke's area). These results indicate that RSFC is a potential neural marker for reading abilities in both L1 and L2, with important theoretical implications for reading in L1 and L2.

Introduction

Although reading a familiar word takes less than 1 s and is a seemingly simple task for a typical adult, the brain has to integrate signals from many regions specialized for cognitive processing including visual, phonological, semantic, and other linguistic processing (Turkeltaub et al., 2002; Vigneau et al., 2006). Conventional functional MRI studies have mapped out several "critical reading areas" in the left hemisphere because of their consistent involvement in reading across different languages (both first and second languages [L1] and [L2], both alphabetic and logographic writings) (Bolger et al., 2005; Tan et al., 2005; Xue et al., 2006b). This reading network includes the left inferior frontal gyrus (IFG, including Broca's area) (Bokde et al., 2001; Costafreda et al., 2006; Gough et al., 2005; Roskies et al., 2001), the left superior temporal gyrus (STG, including Wernicke's area) (Chang et al., 2010; Geschwind, 1970; Simos et al., 2000), the left temporo-occipital cortex (e.g., the left posterior fusiform gyrus [FFG], including the so-called "visual word form area" [VWFA]) (Cohen and Dehaene, 2004; Cohen et al., 2002; Dehaene et al., 2005), as well as some other regions around the left sylvian fissure (Bolger et al., 2005; Price, 2000; Tan et al., 2005).

Because reading takes coordination of the different areas in the reading network, brain imaging data have been further analyzed to examine functional connectivity (FC) between these areas. Previous studies have examined FC in the reading network with various reading tasks (e.g., reading aloud and semantic judgment) (Hampson et al., 2006; Seghier and Price, 2010; Wu et al., 2009), reading materials (e.g., words and pseudowords) (Mechelli et al., 2002), and types of brain data (e.g., fMRI and EEG) (Ligges et al., 2010; Schinkel et al., 2011). FC during reading has generally been found to be associated with reading (dis)ability. For example, Hampson et al. (2006) found that good readers showed stronger FC between BA39 (the left angular gyrus and part of the middle temporal gyrus) and Wernicke's area than did poor readers. Some studies found that readers with dyslexia showed decreased FC between left BA39 and other reading-related areas (Horwitz et al., 1998; Pugh et al., 2000). One recent study also revealed a disruption of FC between the VWFA and reading regions in children with dyslexia (van der Mark et al., 2011).

In addition to FC during reading, studies have also evaluated task-independent FC in the reading network at resting state. The low-frequency spontaneous BOLD fluctuations ($\approx$0.01–0.1 Hz), which used to be treated as noise in conventional analysis, have been suggested to reflect neuronal function (Biswal et al., 1995, 1997; Damoiseaux et al., 2006; Fox and Raichle, 2007). These signals can be captured quickly with brief (5–10 min) fMRI scans. Temporal correlations of the signals between one region (the seed region) and other parts of the brain are calculated to index resting state functional connectivity (RSFC). This technique has been utilized to characterize motor (Biswal et al., 1995), visual (Nir et al., 2006), and attention (Fox et al., 2006) systems as well

* Corresponding author. Fax: +1 949 824 3002.
** Corresponding author. Fax: +86 10 58807615.
E-mail addresses: cschen@uci.edu (C. Chen), dongqi@bnu.edu.cn (Q. Dong).

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as the reading network (Koyama et al., 2010). It provides us with a new way to evaluate functional connectivity within the brain.

Using this approach, Hampson et al. (2002) first demonstrated RSFC between two classical reading areas, Broca's and Wernicke's areas. Their work was extended to more seed regions in subsequent studies. The topographical functional connectivity pattern in the left middle frontal, parietal, and temporal areas was revealed for the three subregions of Broca's area (Xiang et al., 2010). Other reading areas also showed functional connectivity at resting state, for example, between the left FFG and left IFG and between the left STG and left IFG (Koyama et al., 2010; Turken and Dronkers, 2011). More recently, RSFC within the reading network (e.g., Wernicke's and Broca's areas) was observed in a large sample (970 subjects) from various countries (Tomasi and Volkow, 2012). Further research revealed that RSFC also existed between the reading area (VWFA) and the attention network (Vogel et al., 2012).

Although the above studies demonstrated the existence of RSFC within the reading network, only one study thus far has examined the relationship between RSFC and reading ability (Koyama et al., 2011). In their study of 25 children and 25 adults who were native English speakers, Koyama et al. found that English reading ability was positively correlated with RSFC among motor regions (the left precentral gyrus [PCG] and postcentral gyrus) and that between speech regions (Broca's and Wernicke's areas) in both children and adults. They further found that, for adults only, reading ability was negatively correlated with RSFC between the left FFG and the default network (Koyama et al., 2011).

The current study examined how RSFC within the reading network was associated with L1 (Chinese) and L2 (English) reading abilities in a group of native Chinese speakers. Researchers have long been interested in how the brain represents L1 and L2. A fundamental question is whether the neural substrates are shared or segregated for L1 and L2. Previous studies found both dissociated (Dehaene et al., 1997; Kim et al., 1997) and shared neural basis for L1 and L2 (Nakada et al., 2001; Perani and Abutalebi, 2005; Tan et al., 2003). The notions of “assimilation” and “accommodation” (Nelson et al., 2009) have recently been proposed to explain L1 and L2 processing, especially when they belong to different language systems. Assimilation means that the brain uses the L1 network to support L2 (thus, a shared neural basis) (Liu et al., 2007a) and accommodation means that the brain's reading network adapts to the features of L2 (e.g., a new writing system that could not be assimilated because it is based on a distinct neural mechanism) (Nelson et al., 2009). In this study, we examined both shared and divergent RSFC correlates of reading abilities in Chinese (L1) and English (L2).

Method

Subjects

Forty three Chinese students (age range: 19–24 years, mean age = 21, SD = 1.4, 23 female and 20 male) from Beijing Normal University participated in our experiment. All were native Chinese speakers, learning English as their L2 (since elementary school) and passed the college entrance examination of Chinese and English. They had normal or corrected-to-normal vision, with no previous history of neurological or psychiatric diseases and were strongly right-handed as judged by Snyder and Harris's handedness inventory (Snyder and Harris, 1993). Informed written consent was obtained from the subjects before the experiment. This study was approved by the IRB of the National Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University.

Behavioral assessment

English reading ability was assessed using the Sight Word Efficiency subtest in the Test of Word Reading Efficiency (TOWRE-SWE), a nationally normed measure of word reading accuracy and fluency in the U.S. for individuals from 6 to 24 years of age (Torgesen et al., 1999). Reading score was indexed by the number of printed words that were accurately read within 45 s. Test items were arranged in order of difficulty from easy to more difficult items. There are two equivalent forms (A and B) in the test, each with 104 items. Both forms were administered in the current study and their scores were averaged.

Chinese character reading was measured by the Chinese Character Reading Efficiency Test (CCRET). This test was developed in the format of TOWRE-SWE. There were also 104 items in the CCRET selected from the Chinese character psycholinguistic norms (Liu et al., 2007b) with word frequency ranging from 4 to 5636 (mean = 196), number of strokes ranging from 2 to 14 (mean = 7.3), and number of units ranging from 1 to 5 (mean = 2.4). Reading score was indexed by the number of printed Chinese characters that were accurately read in 45 s. Test items were arranged in order of difficulty from easy to more difficult items. Both tests (TOWRE-SWE and CCRET) have been used in our previous study that examined the structure of the left FFG and L1 and L2 reading in Chinese subjects (Zhang et al., 2013). The correlation between reading scores of L1 and L2 was significant ($r = .50$, $p < .001$).

A non-verbal reasoning (or intelligence) test, Raven's Advanced Progressive Matrices (RAPM), was also used in the current study to test whether RSFC in the reading-related ROIs was specifically related to reading skills or rather generally related to basic cognitive abilities. RAPM has been widely used in previous studies (see Zhu et al., 2010, for a detailed description of this test as used in the current study). Table 1 shows subjects' basic demographic information and cognitive scores.

MRI data acquisition

Data were acquired with a 3.0 T Siemens MRI scanner in the MRI Center of Beijing Normal University. A single-shot T2*-weighted gradient-echo EPI sequence was used for a brief scan (8 min) which comprised 240 continuous echo planar imaging functional volumes with the following parameters: TR/TE/θ = 2000 ms/25 ms/90°, FOV = 192 × 192 mm, matrix = 64 × 64, and slice thickness = 3 mm. During the scan, subjects laid supine on the scanner bed. Foam pads were used to minimize head motion. Subjects were instructed to close their eyes, keep their head still, think about nothing in particular, and just relax. All subjects reported having their eyes closed and being awake during the scan. Anatomical MRI was acquired using a T1-weighted, three-dimensional, gradient-echo pulse-sequence (MPRAGE) with TR/TE/θ =2530 ms/3.09 ms/10°, FOV = 256 × 256 mm, matrix = 256 × 256, and slice thickness = 1 mm. Two hundred and eight sagittal slices were acquired to provide high-resolution structural images of the whole brain.

Data preprocessing

Image preprocessing was carried out using tools from the FMRIB's software library (http://www.fmrib.ox.ac.uk/fsl) version 4.1.8. The first five volumes in each time series were automatically discarded by the scanner to allow for T1 equilibrium effects. The remaining images

Table 1
Characteristics of the subjects.

Characteristics	Mean (SD)	Range
Age (years)	21 (1.4)	19–24
Gender (F/M)	22/20	
Handedness	All right-handed	
Raven' Progressive Matrices		
Score	27.9 (3.8)	20–35
Time (min)	31.4 (7.6)	13–40
Reading score of L1	85.5 (13.0)	51–104
Reading score of L2	72.6 (9.2)	54–93

Note: Standard deviations are shown in parentheses.