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Dissociable intrinsic functional networks support noun-object and verb-action processing

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ABSTRACT

The processing mechanism of verbs-actions and nouns-objects is a central topic of language research, with robust evidence for behavioral dissociation. The neural basis for these two major word and/or conceptual classes, however, remains controversial. Two experiments were conducted to study this question from the network perspective. Experiment 1 found that nodes of the same class, obtained through task-evoked brain imaging meta-analyses, were more strongly connected with each other than nodes of different classes during resting-state, forming segregated network modules. Experiment 2 examined the behavioral relevance of these intrinsic networks using data from 88 brain-damaged patients, finding that across patients the relative strength of functional connectivity of the two networks significantly correlated with the noun-object vs. verb-action relative behavioral performances. In summary, we found that verbs-actions and nouns-objects are supported by separable intrinsic functional networks and that the integrity of such networks accounts for the relative noun-object- and verb-action-selective deficits.

1. Introduction

Nouns and verbs, commonly referring to two major types of concepts of the human mind – objects (entities) and actions (events), are the core components that support syntax for all known human languages (Robins, 1952). While grammatical classes (nouns and verbs) and conceptual classes (objects and actions) could be dissociated - there are nouns and verbs referring to concepts that are beyond objects and actions (e.g., abstract words) - object and action naming and comprehension tasks have been the common proxy for studying noun and verb processing in the literature. Classical neuropsychological studies have long established that brain damage can lead to relatively selective impairment to nouns (objects) or verbs (actions), suggesting that they are supported at least partly by segregated brain systems (Breedin, Saffran, & Schwartz, 1998; Caramazza & Hillis, 1991; Damasio & Tranel, 1993; Daniele, Giustolisi, Silveri, Colosimo, & Gainotti, 1994; Goodglass, Klein, Carey, & Jones, 1966; McCarthy & Warrington, 1985; Miceli, Silveri, Villa, & Caramazza, 1984; Zingeser & Berndt, 1988). The brain basis underlying such behavioral dissociation, however, has been elusive.

From the lesion study perspective, there are tendencies that more severe verb-action processing deficit is associated with the left frontal damage, while more severe noun-object processing deficit with damage of the left temporal cortex (Aggujaro, Crepaldi, Pistarini, Taricco, & Luzzatti, 2006; Bates, Chen, Tzeng, Li, & Opie, 1991; Cappa et al., 1998; Damasio & Tranel, 1993; Daniele et al., 1994; Druks, 2002; Glosser & Donofrio, 2001; Lubrano, Filleron, Démonet, & Roux, 2014). Yet there are cases that do not follow this pattern (De Renzi & Di Pellegrino, 1995; Luzzatti, Aggujaro, & Crepaldi, 2006) and that patients with verb-action impairment are rarely caused by a cerebral lesion limited to the frontal or the parietal lobe (Aggujaro et al., 2006). Neuroimaging studies of healthy populations have reported much more distributed regions for the two word/conceptual classes: Preferential activations by verbs-actions were observed in left inferior frontal gyrus, middle and superior temporal gyrus, precentral area, and right cerebellum, while noun-object preferential activations were found in left fusiform gyrus, inferior parietal lobe, inferior frontal gyrus, and right cerebellum (Crepaldi, Berlingeri, Paulesu, & Luzzatti, 2011; Vigliocco, Vinson, Druks, Barber, & Cappa, 2011).

One hypothesis about verb-action and noun-object processing that readily accommodates the neuropsychological and neuroimaging findings is that noun-object or verb-action processing is not attributable to specific circumscribed regions, but rather are supported by networks of many different regions, and it is the integrity of the whole functional

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systems that are predictive of noun-object or verb-action processing skills. Damage to any component of the network, including the connections among the cortical regions, would affect the functional integration of the system and thus compromise the processing of the corresponding word/conceptual class.

We here test this hypothesis explicitly by asking two questions: (1) Are the regions showing preferential activation to a particular word/conceptual class (nouns-objects or verbs-actions) intrinsically more tightly connected, i.e., forming functional networks? (2) Is the integrity of the functional network, i.e., the strength of the functional connectivity, associated with behavioral performances for the corresponding class? In Experiment 1 we employed graph-based brain network analysis methods (Newman, 2006) to examine the intrinsic organization of verb/action- and noun/object-preference brain regions obtained in previous fMRI studies, using resting-state fMRI data in 146 healthy individuals. Experiment 2 tested whether the network functional connectivity strength (FCS) associates with noun-object- or verb-action- behavioral deficits in 88 brain-damaged patients.

Given that object and action naming and comprehension tasks are commonly used in the literature, the conceptual and grammatical origins of the word class distinction in these tasks is difficult to be teased apart (see Vigliocco et al., 2011 for a review). We use nouns-objects and verbs-actions without committing to either dimension, and use noun- and verb-specific networks when referring to relevant brain networks for the sake of simplicity. Also note that noun-object- and verb-action-dissociations similar to studies with Indo-European language have been demonstrated in Chinese using both neuropsychological and neuroimaging approaches (e.g., Bi, Han, Shu, & Caramazza, 2007; Yu, Bi, Han, Zhu, & Law, 2012; Yu, Law, Han, Zhu, & Bi, 2011), we thus considered previous results of both studies using English and those using Chinese in Experiment 1 and tested Chinese speaking patients in Experiment 2.

2. Materials and methods

2.1. Experiment 1: Characterizing the intrinsic functional network organization of verb- and noun-preferential regions in healthy subjects

In this experiment, we examined whether the brain regions previously shown to be preferentially activated by verbs or nouns are intrinsically organized into dissociable functional networks by testing the resting-state functional connectivity (RSFC) pattern using resting-state fMRI data of 146 healthy subjects. First, activation likelihood estimation (ALE) meta-analyses were applied to define verb nodes and noun nodes based on the task-based fMRI activation results. We then examined: (1) Are the within-class (i.e., among the ALE-defined-verb nodes and among the ALE-defined-noun nodes) FCS greater than the between-class (i.e., between ALE-defined-verb nodes and ALE-defined-noun nodes) FCS? (2) Are the nodes, when pulled together, can be partitioned into distinct modules on the basis of the FCS pattern?

2.1.1. Participants

One hundred and forty-six right-handed healthy young participants (76 females; 22.7 ± 2.1 years old; range, 19–30 years old) were recruited from Beijing Normal University for this experiment. Fifty-seven members of this group took part in another scanning session with identical scanning parameters about 6 weeks later, the data of which were used in our validation analyses as the retest dataset. All subjects were from the same cohort reported in our earlier study (Xu, Lin, Han, He, & Bi, 2016). They were native Mandarin speakers with no history of neurological or psychiatric disorders. Each gave written informed consent and the research was approved by the Institutional Review Board of the National Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University.

2.1.2. Image acquisition and preprocessing

Structural and functional imaging data were acquired using a Siemens TrioTim 3-Tesla scanner at the Beijing Normal University Imaging Center for Brain Research. During resting-state fMRI scanning, participants were asked to stay relaxed and to rest with their eyes closed and not fall asleep. T1-weighted three-dimensional magnetization-prepared rapid gradient echo (3D MPRAGE) images were obtained with the following parameters: repetition time (TR) = 2530 ms, echo time (TE) = 3.39 ms, flip angle = 7°, slice thickness = 1.3 mm, slice gap = 0.65 mm, slice in-place resolution = 1.3 × 1.0 mm^2, field of view (FOV) = 256 × 256 mm^2, slice number = 144. Functional images were acquired using an echo planar imaging (EPI) sequence (TR = 2000 ms, TE = 30 ms, flip angle = 90°, slice thickness = 3.5 mm, slice gap = 0.7 mm, slice in-place resolution = 3.1 × 3.1 mm^2, FOV = 200 × 200 mm^2, slice number = 33, volume number = 200).

Functional imaging data preprocessing was performed using Data Processing Assistant for Resting-State fMRI (DPARSF, available at http://rfmri.org/DPARSF, Chao-Gan & Yu-Feng, 2010). The first 10 volumes of the functional images were discarded before slice timing and head motion correction. In the main dataset, two participants exhibited head motion of >2 mm maximum translation or 2° rotation and were excluded from the analyses, resulting in 144 remaining subjects (75 females; 22.7 ± 2.3 years old; range, 19–30 years old). Next, each participant's structural images were co-registered to their mean functional images and were subsequently segmented. The functional images were normalized to the Montreal Neurological Institute (MNI) space (resampling voxel size was 3 × 3 × 3 mm^3) using the parameters obtained during segmentation. Next, linear trend removal, band-pass filtering (0.01–0.1 Hz) and spatial smoothing (6 mm FWHM Gaussian kernel) were applied to the functional images. Finally, some nuisance covariates were regressed out, including rigid-body 6 head motion parameters, white matter signal, and cerebrospinal fluid signal. The residual time series were used in the subsequent network analysis.

2.1.3. Node definition

ALE meta-analyses were used to identify regions showing consistent preferential activation to nouns or verbs across studies as the following procedures.

Literature selection. An influential and comprehensive review written by Vigliocco et al. (2011) summarized the verb- and noun-activation preference results from 26 imaging studies. We selected 20 studies from this summary, with six studies excluded for the following reasons: one reported only the ROI analysis results (Palti, Ben-Shachar, Hendler, & Hadar, 2007); one did not report the number of subjects (Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995); two did not find any positive results contrasting verbs and nouns (Fujimaki et al., 1999; Vigliocco et al., 2006); and two did not report the coordinates of the activation differences (Kable, Lease-Spellmeyer, & Chatterjee, 2002; Li, Jin, & Tan, 2004). Two studies that compared noun and verb processing using Chinese language (Yu et al., 2011, 2012) that were published after the review were additionally included for completeness and for having the same language speakers with our current study. As a result, 22 articles (containing 16 fMRI and 6 PET studies) were designated suitable for the meta-analyses. Twenty of them were used for verb-preference ALE meta-analysis, while 11 were involved in a noun-preference ALE meta-analysis (see Table 1). It is important to note that different sets of studies are used in verb > noun and noun > verb activation meta-analysis because many studies do not find both types of activations with many cases finding verb > noun activity with no noun > verb activity. The inconsistency between studies may be related to the complex nature of the noun/verb dissociations (see Section 4).

Types of contrast. We focused on the verbs versus nouns direct comparison in the meta-analyses. Simple effects of verbs or nouns versus baseline were not considered for the following two reasons: (1) The baselines used in each study were quite different, ranging from "resting" to "face picture identification"; (2) The activations observed for the simple effect might be dominated by the cognitive components