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Deciding where to attend: Large-scale network mechanisms underlying attention and intention revealed by graph-theoretic analysis

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ABSTRACT

The neural mechanisms by which intentions are transformed into actions remain poorly understood. We investigated the network mechanisms underlying spontaneous voluntary decisions about where to focus visual-spatial attention (willed attention). Graph-theoretic analysis of two independent datasets revealed that regions activated during willed attention form a set of functionally-distinct networks corresponding to the frontoparietal network, the cingulo-opercular network, and the dorsal attention network. Contrasting willed attention with instructed attention (where attention is directed by external cues), we observed that the dorsal anterior cingulate cortex was allied with the dorsal attention network in instructed attention, but shifted connectivity during willed attention to interact with the cingulo-opercular network, which then mediated communications between the frontoparietal network and the dorsal attention network. Behaviorally, greater connectivity in network hubs, including the dorsolateral prefrontal cortex, the dorsal anterior cingulate cortex, and the inferior parietal lobule, was associated with faster reaction times. These results, shown to be consistent across the two independent datasets, uncover the dynamic organization of functionally-distinct networks engaged to support intentional acts.

Introduction

Volitional control over our actions is a hallmark of human behavior. Dysfunctions of volitional control are characteristic of numerous brain disorders. Recent neuroscience studies have begun to investigate the neural substrates of human volition. Converging evidence from functional neuroimaging (Lau et al., 2004; Soon et al., 2013, 2008), electrophysiological recordings (Fried et al., 2011; Libet et al., 1983; Pesaran et al., 2008), cortical stimulation (Fried et al., 1991), and focal brain lesions (Sirigu et al., 2004; Thaler et al., 1995) has implicated areas in the medial and lateral frontal cortex as well as the posterior parietal cortex as key structures underlying the generation and representation of volitional acts. Specifically, studies have repeatedly shown heightened activity within the pre-supplementary motor area (preSMA), dorsal anterior cingulate cortex (dACC), bilateral dorsolateral prefrontal cortex (DLPFC), and inferior parietal lobule (IPL), when actions that are internally generated were compared with those elicited by external events (for a review, see Haggard (2008)). Damage in the aforementioned brain areas has also been shown to disrupt self-initiated actions in both macaques (Thaler et al., 1995) and humans (Assal et al., 2007; Sirigu et al., 2004).

Despite these advances, the processes, especially at the level of functional connectivity, through which internally-generated intentions are transformed into volitional actions are still largely unknown. This lack of understanding is partly attributable to the univariate approaches employed in prior neuroimaging and electrophysiological studies, which are primarily suitable for identifying activity within circumscribed brain regions, whereas volitional acts are known to require the cooperation of distributed brain regions. One specific unanswered research question is whether the brain regions activated by volitional acts form a unitary network, or alternatively, a collection of functionally segregated subnetworks, with each carrying out a distinct aspect of volition. Recent theoretical work posits that human volitional acts consist of a cascade of cognitive processes that transform

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goals and intentions into actions and behavior (Haggard, 2005). The successful implementation of volitional acts might therefore require that each of the specific cognitive processes in the cascade be represented within functionally specialized, but cooperating subnetworks. Our first goal is to address this hypothesis by investigating the existence of functionally specialized subnetworks among regions activated during volitional acts, and to learn how they interact.

Recent studies of large-scale brain networks suggest that network hubs, characterized by their high connectivity to other regions in the network, play a central role in the process of functional integration (van den Heuvel and Sporns, 2013). Network hubs integrate neural information from distributed regions and route communications to other network constituents through their connections, and hence, might serve as the backbone for efficient local and global communications between different cognitive components during human volition. Our second goal is to examine the potential hub regions in the activated network and how they help integrate the various processes underlying volitional acts.

To accomplish these goals we recorded functional magnetic resonance imaging (fMRI) data from two cohorts of subjects, at two different sites, who performed the same visual spatial attention task. Graph-theoretic measures were applied to characterize two different forms of voluntary attention, one where subjects were instructed by an external cue where to focus attention between two spatial locations (one in each hemifield), and a second where the cue signaled that the subjects were permitted to spontaneously choose which of the two spatial locations to attend; we refer to the latter as “willed attention” (Bengson et al., 2014). Comparing the properties of the functional networks during willed attention to those obtained with the instructed attention condition, we sought to provide an integrated view of the neural mechanisms of volitional acts in terms of the network organization of the underlying mechanisms. Functional connectivity between brain regions was calculated using the beta series correlation method (Rissman et al., 2004) in which single-trial blood-oxygen-level-dependent (BOLD) activity evoked by the cue was estimated and correlated across different brain regions. To identify functionally specialized subnetworks embedded in the network underlying volitional acts, the graph-theoretic metric of modularity (Newman, 2006; Rubinov and Sporns, 2010) was used to measure the level of functional segregation by partitioning the entire network into clusters of tightly interconnected regions. Node strength and betweenness centrality (Freeman, 1978; Rubinov and Sporns, 2010), which capture a node's influence on information transfer in the network, were calculated for each node to enable the identification of potential hubs within the network. To further assess the functional role of the identified network hubs in terms of intra- versus inter-subnetwork interactions, the connection pattern of each hub region was examined via the graph-theoretic metric of participation coefficient (Guimerà and Nunes Amaral, 2005; van den Heuvel and Sporns, 2013). If hub regions truly impact the integration of the cognitive events underlying volitional acts, an association between the connectivity patterns of hub regions and participants' behavioral performance is also expected. To test this, we examined the association between the node strength, betweenness centrality, and participation coefficient from each hub region with each participant's reaction time. The use of two independently collected datasets provided a powerful opportunity to examine the replicability of the main findings.

Material and methods

Participants and study sites

The study was conducted at two sites, one at the University of Florida (UF dataset) and the other at the University of California, Davis (UCD dataset), using the same instructed versus willed attention task. The two datasets were separately analyzed and then combined, when appropriate, via a meta-analysis. The experimental procedure was approved by the Institutional Review Boards of the University of Florida and the University of California, Davis. Written informed consent was obtained from all participants before the experimental session. The participants were healthy college students with no history of neurological or psychiatric disorders, were right-handed, and had normal or corrected-to-normal vision. They received either course credits or a financial compensation for their participation. For the UF dataset, fMRI data was collected from eighteen (n = 18) participants. Five participants were excluded from further analyses according to the following criteria: 1) failure to follow experimental instructions (1 participant); 2) overall accuracy below 70% (1 participant); and 3) excessive head or body movements (3 participants). The UCD dataset, which contains nineteen (n = 19) participants, has been published before where different methods were used to address a different set of questions (Bengson et al., 2015). One participant was excluded due to unstable performance (accuracy fell to 55% during the latter half of the experiment).

Procedure

Participants viewed the stimulus presentation via a reflective mirror attached to the head-coil. One small white dot marking the eye fixation point was constantly placed at the center of the monitor. Two additional white dots marking the two peripheral spatial locations to attend were placed below the horizontal meridian in the lower left and lower right visual fields. Participants were instructed to maintain constant eye fixation on the central dot during the experiment whenever the dot was displayed on the screen.

The sequence of events within a trial is illustrated in Fig. 1. Three small symmetric symbols were used as cues (cross, diamond, and circle; see Supplementary Materials for visual angles of the stimuli used at each study site). Two of the symbols explicitly instructed the participants to direct their attention covertly either to the left or right hemifield location without moving their eyes (instructed attention), whereas the third symbol prompted them to freely choose one of the two hemifields to attend while maintaining central fixation (willed attention). The three cue conditions occurred with equal probability and the symbols used as cues were counterbalanced as to their meanings across participants, i.e., attend-left, attend-right, and freely-choose. Further, the willed and instructed attention conditions were randomly interleaved across trials in order to discourage stereotypic responses (e.g., always selecting one side to attend or alternating between the left and right side).

At the beginning of each trial, the cue was presented above the fixation dot for 200 ms. Following a cue-target interval randomized between 2000 to 8000 ms, the target stimulus consisting of a square patch containing a black-and-white grating pattern (100% contrast) appeared at one of the two peripheral spatial locations for 100 ms. Targets occurred in the left and right visual fields with equal probability (50% target validity) and were randomly selected to have one of the two possible spatial frequencies (low vs. high) that were highly similar and therefore difficult to discriminate without focused spatial attention (see Supplementary materials for the target spatial frequencies used at each study site). Participants were instructed to discriminate the spatial frequency of the target grating appearing in the attended hemifield and perform a 2-alternative forced choice (2-AFC; low or high) as fast as possible via a button-press (index vs. middle finger button). Targets appearing on the unattended hemifield were to be ignored completely. Compared with the probabilistic cues used in Posner types of paradigms (Posner, 1980), this target response requirement facilitated focused spatial attention and minimized attentional spread.

Following a variable inter-stimulus interval (ISI) randomized between 2000 and 8000 ms after the target stimulus, participants were prompted by the visual cue “?SIDE?” to report the spatial location they attended within that trial via a button-press (index: left; middle: right).