Large-Scale Analysis of Canonical Cortical Network Dynamics Across Five Visual Target Detection Tasks

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Abstract— **We quantify effects of experimental events in five RSVP tasks on measures of functional integration and information flow within four canonical cortical networks and compare these results to event-related potential and event-related spectral perturbation measures at the channel and source level.**

I. Introduction

Target detection tasks have been widely used in the past to understand cognitive responses to visual and other stimuli [1]. Furthermore, detection of visual and other sensory targets using electroencephalography (EEG) has comprised the basis for a number of Brain-Machine Interface (BMI) system designs [2] - [4]. It has been commonly shown that a transient neural response, known as the P300 event-related potential (ERP), is elicited in EEG recordings around 300 ms after the onset of target detection [1]. While many brain areas have been associated with the P300 response, it is not well understood what cortical networks are involved and how they are modulated within different frequency bands.

Some studies have combined EEG with functional magnetic resonance imaging (fMRI) in order to determine which brain networks are active during visual target detection paradigms [5]. However, these studies only identify the functional networks associated with stimuli responses and do not examine the temporal dynamics of the information flow in such networks.

Characterizing cortical network responses to visual target detection tasks is difficult because most studies rely on small sample sizes (< 20) and use many different types of stimuli (e.g. letters, numbers, pictures of faces, animals, etc.) in each paradigm [6] that make it challenging to generalize significant findings. In recent work [7, 10] we demonstrated the feasibility of performing a large-scale multi-study EEG analysis using a pipeline that includes annotating experiment-specific event codes using a common Hierarchical Event Descriptor (HED) ontology, facilitating the isolation and analysis of brain activity related to cognitive aspects (i.e. groups of events that share common properties). We mitigated confounding effects of temporally adjacent events on neural responses using Temporal Hierarchical Overlap Regression (THOR), and modeled the effects of subject, paradigm, and cognitive aspect factors, on event-related responses using a hierarchical regression approach we denoted as General Regression of Aspects and Details (GRAND).

Here we analyze event-related functional brain network measures in five Rapid Serial Visual Presentation (RSVP) studies. We quantify effects of three cognitive aspects common to all studies (related to target, non-target and involuntary blink events) on measures of information exchange within four canonical cortical networks: (visual) attention, salience, default mode, and cognitive control. We evaluate similarities in neural responses to each cognitive aspect both qualitatively and quantitatively by projecting event-related connectivity responses onto a 3D manifold using t-distributed stochastic neighbor embedding (t-SNE), and applying support vector machine (SVM) classification and Mahalanobis distance metrics between classes of responses to quantify separability in the 3D t-SNE projected space. We compare these results to THOR-regressed event-related potentials (rERP) and event-related spectral perturbation (rERSP) measures for channels and cortical sources.

II. Methods

We analyzed 64-channel EEG data from 80 subjects (225 recordings) from five RSVP datasets described in [7]. Data curation and pre-processing were performed as described in [7]. For each continuous recording, cortical current source density (CSD) was estimated using sLORETA and averaged within each of a set of 20 regions of interest (ROIs) constructed from the Destrieux cortical atlas and comprising the nodes of four canonical cortical networks adapted from [8]. We computed the time-varying Direct Directed Transfer Function (dDTF), a frequency-domain measure of multivariate Granger causality, using a 500ms sliding window applied to continuous ROI CSD time-series. For each canonical network, we averaged the dDTF within delta (1-3Hz), theta (4-7Hz), alpha (8-15Hz), beta (16-30Hz), and gamma (30-50Hz) frequency bands. For each band we computed graph theoretic measures of information exchange efficiency within a network, including mean flow and normalized and non-normalized Local and Global Efficiency (GE) [9]. Here we focus results on the non-normalized Global Efficiency measure, called event related connectivity (ERC).

We selected a set of cognitive aspects common to all studies and modeled event-related responses of the time-

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varying network to each cognitive aspect using THOR. Each THOR pattern was smoothed using a 10-point moving average, followed by subtraction of the mean over a 750ms baseline preceding event onset. We modeled the study-level effects of each cognitive aspect on these regressed network measures using a second-level regression model (GRAND). We applied 3D t-SNE to the combined THOR-regressed GE measures for all networks and frequency bands and visualized separability of each cognitive aspect. We quantified separability using the Mahalanobis distance. Details on the methods and parameters used for THOR, GRAND, and t-SNE are described in [10].

For comparison we applied the same 3D t-SNE metric to channel and source rERP and rERSP measures. For each of these we concatenated all features for the given measure (e.g. all ROIs, or all channels, or all networks + bands) into a single measurement vector prior to applying t-SNE. We quantified classification accuracy using a support vector machine (SVM) with 10-fold cross validation. We compared separability metrics for rERCs to channel and source rERPs and rERSPs. A one-way ANOVA was used to determine if classification performance was significantly different across the three types of measures.

III. Results

Canonical network rERC results showed that target presentations were associated with significantly increased GE in delta and theta bands for the Attention and Default Mode networks and decreased alpha, beta, and gamma GE in all networks (Figure 1). Significant peaks were typically present around 300-500 ms after stimulus onset. Non-target events failed to elicit significant responses for any frequency band across all canonical networks.

Blink/Max events preceded significantly decreased theta GE for Attention network and increased alpha, beta, and gamma GE in all networks. Increased delta GE preceding Blink/Max were observed for salience, cognitive control, and attention networks.

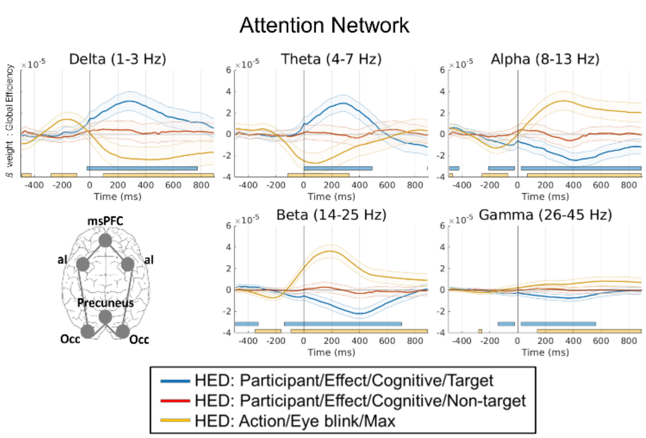

Figure 1. One example network (Attention) rERC responses to 3 cognitive events. Time 0 is event onset. Shaded regions denote 99% conf. intervals, while horizontal bars denote significantly non-zero GE (p<0.01, fdr).

Canonical network rERC 3D t-SNE analysis showed distinct clustering of blink, target, and non-target events (Figure 2). The Mahalanobis distance metrics also showed similar separability for blinks and targets, with reduced separability for non-targets. Figure 3 similarly shows rERSP spectrograms for these 3 cognitive events in different regions of interest (ROIs).

SVM classification of the target, non-target, and blink/max cognitive aspects using rERC, rERP, and rERSP patterns after 3D t-SNE projection. rERC yielded a mean classification accuracy of 84.35% (S.D. = 3.31%), while channel rERP accuracy was 72.25% (S.D. = 3.93%), and source rERP accuracy was 62.49% (S.D. = 3.43%).

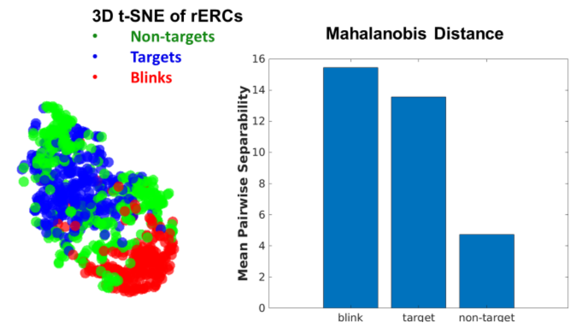

Figure 2. Canonical network rERC 3D t-SNE visualization and Mahalanobis distance for three cognitive aspects.

One-way ANOVA identified a significant effect of type of measure on classification accuracy (F = 70.87, p<0.001) with greater accuracy for network rERCs than both channel (p<0.001) and source rERPs (p<0.001). Channel rERP classification accuracy was significantly greater (p<0.001) than source rERPs. However, we did not find significant differences in classification accuracy between rERC measures and channel rERSP (86.24%, S.D. = 3.93%) or source rERSP (84.13%, S.D. = 3.43%) measures.

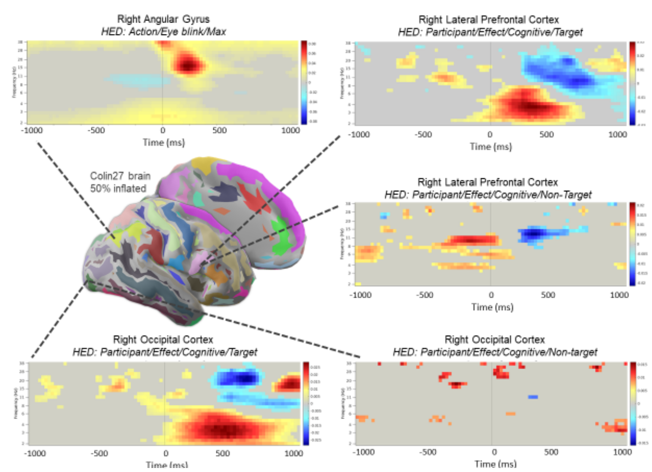

Figure 3. Source rERSP spectrograms for 3 different ROIs showing examples of each of the 3 cognitive aspects. Masked (gray) ERSP values denote non-significant effects ($p \geq 0.05$, fdr-corrected)

IV. Conclusions

We quantified the effects of a set of experimental events common to five RSVP tasks on measures of functional integration and information flow within four canonical cortical networks. We observed significant differential effects on frequency-specific canonical network global efficiency for target, non-target, and spontaneous blink events supporting the utility of the proposed approach for large-scale analysis of canonical network activity across multiple studies and paradigms. Use of event-related connectivity features resulted in similar or greater ability to discriminate between cognitive aspects as for channel or source level event-related potential and spectral power features, as measured by Mahalanobis distance and classification accuracy following 3D t-SNE feature projection. SVM classification using network rERCs resulted in significantly higher classification accuracy than both channel and source rERPs, and comparable classification accuracy as for channel and source rERSPs.

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