Ecological Neuroscience Reveals Surprise and Adaptation in the Human Brain

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Abstract: Movies and stories inspire innovation in basic neuroscience and clinical applications. This ecological approach has influenced memory research, timescales representations, and the function of large-scale networks. Here we present a neuro-ecological approach combined with machine learning to uncover neural representations of surprise and adaptation in the human brain.

Keywords: Surprise, Adaptation, Prediction-Error, Ecological, Movies, Neuroimaging

Introduction

Recent neuroimaging research indicates that the Default Mode Network (DMN) is crucial not only for self-directed activities but also, intriguingly, for the long-term processing of naturalistic, real-life events [1]. This highlights its central role in understanding how the brain processes information in everyday contexts. However, a key challenge lies in pinpointing the cognitive processes reflected by DMN activity during naturalistic stimulation, particularly in connecting dynamic cognitive states to DMN responses.

To address this, we developed a novel neuro-ecological approach called State-Fluctuation Pattern Analysis (SFPA), which directly links cognitive states to DMN activity[2]. Specifically, we modeled cognitive states along the time-course of a movie stimulus using a technique we term Retrospective Behavioral Sampling [3](see Methods). We then compared these cognitive measures to the temporal patterns of neural responses evoked by the same movie. Critically, we built on our previous discovery that task-driven DMN coactivation can be revealed using Inter-Subject Functional Correlation (ISFC)[1]. By applying SFPA to systematically link ISFC to behavior, we found that the cognitive measure most strongly associated with DMN coactivation dynamics is the level of surprise induced by movie events. Furthermore, we demonstrated surprise-dependent DMN coactivation with subcortical regions implicated in predictive processing.

This study reveals a surprising role of DMN as a central hub in the representation of prediction errors during ongoing real-life events [2]. This process is akin to the evaluation of a cost function in deep neural networks (DNNs) during training, where the mismatch between predictions and true observations (i.e., surprise) guides the adjustment of network weights via backpropagation. This brain-machine convergence [4] underscores the importance of the DMN in processing real-life events, serving as a hub for prediction-error representation and the temporal integration of incoming information with memory-stored representations.

More recently, in our ongoing work, we aim to study a complementary aspect of the naturalistic sensory stream- namely the consequences of persistent high activations. To achieve that aim we examined movie endings of 14 movie clips followed by 20-second resting-state periods. In contrast to the *narrative surprise* that coactivated DMN regiones, our preliminary results point to traces of activation changes following periods of high, persistent activations. Focusing on the resting-state window following the movie-clips, free from stimulus-induced activity, we had a unique opportunity to study how such persistent activations may impact long term sensitivity of neuronal regions under naturalistic conditions. Our results hint at a wide-spread renormalization effect following naturalistic stimulation in the human brain which we currently explore.

Methods

Neurocognitive approach to study neural and cognitive dynamics: State-Fluctuation Pattern Analysis (SFPA)

Cognitive dynamics were modeled from behavioral responses of 45 participants to the first episode of Sherlock (BBC series, 2010), sampling 49 events of the movie on measures of surprise, vividness of memory, emotional intensity and valence, perceived importance, episodic memory and theory of mind. Neural dynamics of coactivation (i.e. activity correlations across brain regions), were modeled from functional magnetic resonance imaging (fMRI) responses of 35 participants to the same movie , in regions of the DMN and hippocampus, as well as the dorsal attention network (DAN) and visual-processing areas (Vis). Since the DMN manifests spontaneous fluctuations both at rest and at task , we used ISFC to eliminate these spontaneous signals and extract the shared component of stimulus-induced coactivation across brain regions and across individuals [1]. Our approach was thus optimized for matching across temporal response patterns of brain and behavior to a dynamic naturalistic input.

Machine Learning for the adaptation study - Our work was based on 7T-fMRI data from the Human Connectome Project, where 170 subjects watched 14 movie clips with 20-second resting intervals in between clips. We used SVM classification accuracy of 14 movie-clips across 17 groups of subjects, for the entire set of 300 cortical regions. Both for end-of-clips classifications, and end-of-resting states classification that were followed by the clips.

Results

Using SFPA we revealed that narrative surprise elicited DMN coactivation, both within cortical DMN regions and between DMN and hippocampus, fluctuated proportionally to the magnitude of surprise, but not other behavioral measures. Particularly, SFPA revealed significant correlations (via permutation test; $p < 0.05$, corrected) between surprise ratings and ISFC among DMN region pairs. The overall correlation between surprise ratings and ISFC mean across all DMN region pairs was $r(47) = 0.44$ ($p = 0.001$, 95% CI [0.18, 0.64]). In addition, surprise ratings were significantly correlated with ISFC between DMN regions and hippocampus (perm. $p < 0.05$, corrected). By contrast, surprise ratings did not correlate with pairwise ISFC in DAN and Vis (perm. $p > 0.05$, corrected). The overall correlation between surprise ratings and ISFC mean across all regions in DAN was $r(47) = 0.03$ ($p = 0.859$, 95% CI [-0.25, 0.31]) and in Vis was $r(47) = -0.08$ ($p = 0.589$, 95% CI [-0.35, 0.21]). Results revealed coactivations of DMN regions, hippocampus and NAcc, which fluctuate as a function of surprise during naturalistic movie viewing. DMN was further shown to be selectively coactivated during peak surprise, in contrast to other cognitive states. This was found exclusively in DMN, as compared with DAN and Vis, suggesting that surprise ratings are unlikely to reflect low-level attentional or perceptual processing typical to DAN and Vis 23.

In our current study we found that successful SVM classification of resting-state periods followed by the movie-clips led to the discovery of widespread renormalization process revealed across 100 cortical regions, as the brain transitions from movie viewing to post-movie rest. Specifically, we found that most of the voxels that were highly activated at the end of movie clips displayed a pronounced inactivation that persisted throughout the 20-sec rest period following those movies. By contrast, voxels that were suppressed by the movie showed a rebound activation above the resting state baseline.

Discussion

Ecological Neuroscience offers promising avenues for investigating brain function across the rich, realistic spectrum of human experiences. However, the complex, uncontrolled nature of such stimuli — and the resulting mixture of neuronal and physiological responses embedded within fMRI signals — present significant challenges for data analysis and interpretation.

In this work, we explored two complimentary dynamics that are ubiquitous in naturalistic conditions- surprise and adaptation. Narrative surprise revealed coactivations of key brain regions, including the Default Mode Network (DMN), hippocampus, and nucleus accumbens (NAcc), which fluctuate as a function of surprise during naturalistic movie viewing. Notably, the DMN was shown to be selectively coactivated during peak moments of surprise, distinguishing it from other cognitive states [2].

By contrast, preliminary analysis of high intensity persistent activation appears to reveal an adaptation effect, characterized by the renormalization of neural responses across a wide range of cortical regions involved in movie processing. This adaptation effect was consistent across subjects, suggesting a robust, stimulus-driven recalibration of neural activity.

These two complementary processes can be likened to mechanisms in artificial neural networks: adaptation-related adjustments of neuronal weights are reminiscence of batch normalization, which facilitates learning and minimizes internal covariate shifts. While surprise effect may be comparable to error- detection training procedures. This brain-machine convergence evolution [4] strengthens our findings and highlights the functional relevance of the neural representations observed during surprising events and adaptation effects.

Conclusions

This work reveals the rich and deep insights that can be gained by moving from controlled laboratory conditions to more ecological stimuli and their unique dynamics. Specifically, we demonstrate that Narrative surprise could uncover naturalistic memory-related mechanisms of encoding and recollection, as reflected by fluctuations in connectivity between the hippocampus and the DMN. By contrast, adaptation effects may reveal homeostasis-related mechanisms, demonstrated by the renormalization of neural activity following abrupt and prolonged changes in external stimuli. These insights could have significant clinical implications, particularly in the early diagnosis of memory impairments. Given that neurodegenerative diseases are often linked to disruptions in brain homeostasis, understanding these mechanisms could pave the way for novel diagnostic and therapeutic approaches.

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References

[1] E. Simony *et al.*, "Dynamic reconfiguration of the default mode network during narrative comprehension," *Nature Communications,* vol. 7, Jul 2016, Art no. 12141, doi: 10.1038/ncomms12141.

[2] T. Brandman, R. Malach, and E. Simony., "The Surprising Role of the Default Mode Network," *Communication biology,* In Press p. 2020.05.18.101758, 2020, doi: 10.1101/2020.05.18.101758.

[3] T. Brandman, R. Malach, and E. Simony, "Retrospective behavioral sampling (RBS): A method to effectively track the cognitive fluctuations driven by naturalistic stimulation," (in English), *Frontiers in Human Neuroscience,* Methods vol. 16, 2022-November-09 2022, doi: 10.3389/fnhum.2022.956708.

[4] E. Simony, S. Grossman, and R. Malach, "Brain–machine convergent evolution: Why finding parallels between brain and artificial systems is informative," *Proceedings of the National Academy of Sciences,* vol. 121, no. 41, p. e2319709121, 2024, doi: doi:10.1073/pnas.2319709121.