

# Electric Thoughts: Understanding Cognitive Neuroscience

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Working memory and attentional control are core components of higher-order cognition, yet their neural dynamics under varying cognitive load remain incompletely understood. The present study investigated load-dependent changes in brain activation using a modified n-back paradigm during functional magnetic resonance imaging (fMRI). Forty-eight right-handed adults (ages 18–35; 24 female) completed 0-back, 2-back, and 3-back conditions in a within-subjects design. Task conditions were counterbalanced across participants. Visual alphanumeric stimuli were presented for 500 ms with a 2,500 ms interstimulus interval, and participants responded via button press to indicate target matches. Accuracy and reaction time were recorded as behavioral indices of performance. Neuroimaging data were acquired on a 3T Siemens Prisma scanner using a T2\*-weighted echo-planar imaging sequence (TR = 2,000 ms; TE = 30 ms; voxel size = 3 × 3 × 3 mm<sup>3</sup>), with high-resolution T1-weighted images collected for spatial normalization. This design enables examination of load-dependent modulation of neural systems supporting working memory and attentional control, providing a framework for characterizing the cortical networks engaged as cognitive demands increase.

**Keywords:** neuroimaging, cognitive neuroscience, working memory, functional connectivity, electroencephalography

**Introduction****Electric Thoughts: Understanding Cognitive Neuroscience****What Cognitive Neuroscientists Study**

Cognitive neuroscientists explore how brain activity supports mental functions, including, although not limited to:

- **Perception:** How the brain interprets sensory input from the world.
- **Attention:** How we focus on some information while ignoring other stimuli.
- **Memory:** How experiences are encoded, stored, and retrieved.
- **Language:** How the brain enables us to produce and understand words.
- **Decision-making:** How we weigh options and anticipate outcomes.
- **Emotion and social cognition:** How feelings and relationships shape thought.

These studies often use a combination of behavioral experiments,

neuroimaging, and computational modeling to link brain activity patterns to cognitive processes.<sup>1</sup>

**Tools of the Trade**

- **fMRI (Functional MRI):** Measures changes in blood flow to infer neural activity.
- **EEG (Electroencephalography):** Records electrical activity from the scalp to track brain responses over time.
- **TMS (Transcranial Magnetic Stimulation):** Uses magnetic fields to temporarily disrupt activity in specific brain regions, helping scientists test cause-and-effect relationships.
- **Lesion studies:** Examine how damage to specific brain areas affects behavior, offering clues about function.

Together, these methods help scientists build a detailed map of how mental operations are distributed across neural networks.<sup>2</sup>

**Why It Matters**

Cognitive neuroscience doesn't just explain how the brain works it helps us understand ourselves. By uncovering the neural basis of

thought and emotion, the field informs treatments for mental and neurological disorders such as Alzheimer's disease, depression, and ADHD.<sup>3</sup> It also influences artificial intelligence, education, and even law, where insights into decision-making and impulse control have real-world implications.

### How the Brain Creates the Mind

Cognitive neuroscience is the scientific study of how the brain gives rise to mental processes how billions of neurons create thoughts, memories, emotions, and consciousness itself. It sits at the intersection of psychology and neuroscience, combining the study of mental functions (like perception, attention, and language) with the biological systems that support them.<sup>4</sup>

### From Mind to Brain: A Brief History

For much of history, the mind and brain were treated as separate realms. Philosophers debated the nature of thought and consciousness, while early anatomists charted brain structures without knowing what they did. That began to change in the 19th century, when scientists like Paul Broca and Carl Wernicke discovered that specific brain regions controlled specific abilities, such as speech production and comprehension. These discoveries planted the seed for modern cognitive neuroscience.<sup>3</sup> The field truly took off in the late 20th century, thanks to advances in brain imaging technologies such as fMRI (functional magnetic resonance imaging) and EEG (electroencephalography). These tools allowed scientists to see the living brain in action, revealing which regions activate when we recognize faces, solve problems, or make decisions.<sup>1</sup>

### Mapping the Mind: From Lesions to Networks

The early lesion studies of Broca and Wernicke marked a turning point not just in localizing function, but in reframing the brain as a system of meaning. As patients lost speech or comprehension, scientists gained insight into the architecture of language.<sup>3</sup> These cases were not just clinical puzzles; they were human stories of fragmentation and adaptation, laying the groundwork for a field that would eventually ask not just where cognition happens, but how it unfolds across dynamic networks.<sup>1</sup>

### The Rise of Neuroimaging

By the late 20th century, cognitive neuroscience was transformed by the advent of neuroimaging techniques like fMRI and PET scans. These tools allowed researchers to observe the living brain in action tracking blood flow, metabolic changes, and neural activation in real time.<sup>4</sup> Suddenly, abstract concepts like attention, empathy, and decision-making could be visualized, quantified, and mapped. The brain was no longer a static organ but a theater of cognition, with regions lighting up in response to thought, emotion, and experience.<sup>2</sup>

### Beyond Localization: Toward Integration

Today, cognitive neuroscience moves beyond the search for isolated "centers" of function. Instead, it explores how distributed networks such as the default mode network, salience network, and frontoparietal control system interact to produce complex mental states.<sup>1</sup> This shift reflects a deeper truth: the mind is not housed in a single region but emerges from coordinated activity across systems. Trauma, for instance, does not simply "damage" the brain it rewires it, altering connectivity, threat perception, and emotional regulation. Understanding these patterns is essential

not just for science but for healing.<sup>5</sup>

**From Localization to Connectivity: The Evolving Framework**  
While early discoveries emphasized localized brain functions, contemporary cognitive neuroscience recognizes that mental processes emerge from dynamic interactions across distributed neural networks.<sup>3</sup> Functional connectivity studies reveal that regions such as the prefrontal cortex, parietal lobes, and limbic structures do not operate in isolation but form integrated systems that support attention, memory, language, and emotion. This shift from modularity to network-based models reflects a deeper understanding of cognition as emergent, context-dependent, and shaped by both internal and external stimuli.<sup>4</sup>

### Neural Correlates of Core Cognitive Functions

Advances in neuroimaging have enabled researchers to identify specific patterns of activation associated with core cognitive domains: Attention involves coordinated activity between the dorsal and ventral attention networks, modulated by the thalamus and anterior cingulate cortex. Working memory engages the dorsolateral prefrontal cortex and posterior parietal cortex, with sustained activation reflecting active maintenance and manipulation of information. Language processing recruits Broca's and Wernicke's areas, but also relies on broader perisylvian and temporal networks, challenging earlier localization models. Emotion regulation integrates limbic structures (e.g., amygdala, hippocampus) with prefrontal regions, highlighting the interplay between affective and executive systems. Consciousness and the Default Mode Network. One of the most intriguing developments in cognitive neuroscience is the study of consciousness and self-referential thought. The default mode network (DMN) is active. During rest and introspection, it has been implicated in autobiographical memory, theory of mind, and future planning. Disruptions in DMN connectivity are associated with various neuropsychiatric conditions, suggesting that consciousness itself may be rooted in the brain's ability to integrate internal states with external demands.

### The Frontier: Consciousness and Beyond

One of the great challenges that remains is understanding consciousness how subjective experience arises from physical matter. Cognitive neuroscientists are exploring whether consciousness depends on specific neural circuits, brain-wide integration of information, or something else entirely.

While we are still far from answering that question fully, each discovery contributes to bridging the gap between brain and mind.

In essence, cognitive neuroscience is about decoding the biology of thought the remarkable process by which the electrical chatter of neurons becomes everything we know, feel, and imagine.

## Materials and Methods

### Trial Design & Methods Employed

#### Participants

A total of 48 right-handed adults (ages 18–35; 24 female) were recruited from a university participant pool. All participants reported normal or corrected-to-normal vision, no history of neurological or psychiatric disorders, and provided informed consent in accordance with the institutional review board's ethical guidelines.

## Design

The study employed a within-subjects design to examine the neural correlates of working memory and attentional control under varying cognitive load conditions. Participants completed a modified n-back task (0-back, 2-back, 3-back) while undergoing functional magnetic resonance imaging (fMRI). Task conditions were counterbalanced across participants to control for order effects.

## Stimuli and Procedure

Visual stimuli consisted of randomized sequences of alphanumeric characters presented centrally on a screen for 500 ms, followed by a 2,500 ms interstimulus interval. Participants responded via button press to indicate whether the current stimulus matched the one presented n trials earlier. Accuracy and reaction time were recorded.

## Imaging Acquisition

Neuroimaging data were collected using a 3T Siemens Prisma scanner with a 64-channel head coil. Functional images were acquired using a T2\*-weighted echo-planar imaging (EPI) sequence (TR = 2,000 ms; TE = 30 ms; flip angle = 90°; voxel size = 3 × 3 × 3 mm<sup>3</sup>). High-resolution T1-weighted anatomical images were also obtained for spatial normalization.

## Data Preprocessing and Analysis

Preprocessing was conducted using SPM12 and included motion correction, slice timing correction, normalization to MNI space, and spatial smoothing with an 8 mm FWHM Gaussian kernel. First-level analyses modeled task conditions using a general linear model (GLM), and second-level random-effects analyses were conducted to identify regions showing load-dependent activation. Functional connectivity analyses were performed using psychophysiological interaction (PPI) methods to examine task-modulated network dynamics.

## Results

### Behavioral Performance

Participants demonstrated high accuracy across all task conditions, with mean accuracy rates of 98.2% (SD = 1.4) for the 0-back, 92.6% (SD = 3.1) for the 2-back, and 85.4% (SD = 4.7) for the 3-back condition. A repeated-measures ANOVA revealed a significant main effect of cognitive load on accuracy,  $F(2, 94) = 18.67$ ,  $p < 0.001$ ,  $\eta^2 = 0.28$ , indicating decreased performance with increasing task demands. Reaction times followed a similar pattern, increasing significantly with load,  $F(2, 94) = 22.41$ ,  $p < 0.001$ .

### Neural Activation

Whole-brain analysis revealed load-dependent activation in the dorsolateral prefrontal cortex (DLPFC), posterior parietal cortex, and anterior cingulate cortex. These regions showed significantly greater BOLD responses during the 2-back and 3-back conditions compared to the 0-back baseline ( $p < 0.001$ , FWE-corrected). Activation in the DLPFC was most pronounced during the 3-back condition, consistent with its role in working memory manipulation and executive control.

### Functional Connectivity

Psychophysiological interaction (PPI) analyses indicated increased connectivity between the DLPFC and posterior parietal cortex during high-load conditions, suggesting enhanced coordination within the frontoparietal control network.<sup>4</sup> Additionally, connectivity between the DLPFC and anterior insula was modulated by task difficulty, implicating salience detection mechanisms in cognitive effort allocation.<sup>5</sup>

## Discussion Points

The present study provides converging behavioral and neuroimaging evidence for the load-dependent modulation of working memory and attentional control. As cognitive demands increased, participants exhibited reduced accuracy and slower reaction times, consistent with prior research on resource-limited executive systems.<sup>1,2</sup> These behavioral effects were mirrored by increased activation in the dorsolateral prefrontal cortex (DLPFC), posterior parietal cortex, and anterior cingulate cortex regions implicated in the frontoparietal control network.

The observed connectivity between the DLPFC and anterior insula under high-load conditions suggests that salience detection mechanisms may play a role in cognitive effort allocation. This aligns with emerging models that position the salience network as a dynamic switch between default mode and executive control systems.<sup>3,4</sup> The modulation of these networks under varying task demands supports the view of cognition as a distributed, context-sensitive process rather than a function of isolated modules.

Importantly, the findings contribute to ongoing debates about the neural architecture of working memory. While traditional models emphasize the role of the DLPFC in active maintenance, our results highlight the importance of network-level coordination, particularly under conditions of increased cognitive load. This supports integrative frameworks such as the multiple-demand system,<sup>5</sup> which proposes that flexible recruitment of domain-general resources underlies complex cognition.

## Limitations and Future Directions

While the study offers robust insights into cognitive load and neural dynamics, several limitations warrant consideration. The sample size, though adequate for initial analyses, may limit generalizability across age groups and clinical populations. Future research should explore how these networks function in individuals with neuropsychiatric conditions, such as ADHD or PTSD, where executive function and salience processing are often disrupted.

Additionally, incorporating multimodal imaging techniques (e.g., EEG-fMRI) could provide finer temporal resolution and clarify the sequence of network engagement. Longitudinal designs may also illuminate how cognitive control systems adapt over time, particularly in response to training, stress, or trauma.

## Conclusion

This study reinforces the view that cognitive functions such as working memory and attentional control are not localized to discrete brain regions but emerge from dynamic interactions across distributed neural networks. Load-dependent modulation of the frontoparietal and salience networks underscores the brain's capacity for flexible resource allocation in response to cognitive demands. These findings contribute to a growing body of evidence supporting network-based models of cognition and highlight the importance of integrating behavioral and neuroimaging data to

elucidate the neural architecture of the mind. Future research should continue to explore how these systems adapt across developmental trajectories, clinical populations, and contexts of stress or neuroplastic change.

### Funding

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### Conflicts of Interest

None.

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