

Brain functional connectivity in sensory perception: fNIRS study

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Abstract—This study uses functional near-infrared spectroscopy (fNIRS) to investigate brain functional connectivity dynamics during sensory perception tasks. Thirty-three participants performed the Necker cube task (evaluating rapid perceptual processing) and the Raven's Progressive Matrices task (evaluating sustained logical reasoning). We reconstructed functional networks from changes in oxygenated hemoglobin concentration using Network-Based Statistic (NBS) analysis. For the Necker cube task, functional connectivity in parietal regions decreases between the start and end of the task, accompanied by improved behavioral performance. This suggests an adaptation toward efficient processing strategies. In the Raven's Matrices task, the global clustering coefficient increases significantly with task complexity. Interregional analysis reveals strengthened occipital-parietal and parietal-frontal connectivity with increasing complexity while frontal-temporal connections are weakened. These results demonstrate adaptive functional network reconfiguration in response to cognitive demands, reflecting enhanced integration between bottom-up sensory and top-down executive control mechanisms as processing complexity increases.

Index Terms—functional connectivity, fNIRS, Necker cube, Raven's Progressive Matrices, cognitive load, hemodynamic response, sensory perception

I. INTRODUCTION

Sensory perception and decision-making based on it require coordinated activity across multiple brain regions that form functional networks [1]. When processing information of varying complexity, the brain must adapt its functional architecture, balancing processing efficiency against perceptual accuracy [2]. This adaptation manifests as dynamic changes in functional connectivity — the coordinated activity of spatially distributed cortical areas.

As sensory information varies in complexity, the brain exhibits distinct patterns of functional organization [3]. Processing elementary visual stimuli, such as the Necker cube, primarily engages regions responsible for basic perceptual operations. In contrast, solving complex cognitive tasks, such as Raven's Progressive Matrices, requires integrating multiple systems, including regions associated with attention, working

memory, and executive control [4], [5]. These additional processes involved may explain why the processing of simple versus complex sensory information is accompanied by different patterns of functional connectivity [6].

Investigating the mechanisms of functional network reconfiguration under changing cognitive load is important from both a fundamental and practical perspectives. For example, it can facilitate the development of systems for monitoring cognitive state and optimizing cognitive performance [7].

In this study, we analyze brain functional connectivity of participants performing sensory perception tasks of varying complexity, ranging from interpreting the Necker cube to solving Raven's Progressive Matrices. We use functional near-infrared spectroscopy (fNIRS) to examine changes in the hemodynamic response and to compare functional connectivity patterns across different levels of cognitive load.

II. METHODS

A. Participants and Experimental Design

Thirty-three healthy participants (age 20 ± 2 years) were recruited from Immanuel Kant Baltic Federal University for this study. They were instructed to maintain a healthy lifestyle for 48 hours prior to the experiment, which included getting eight hours of sleep, engaging in moderate physical activity, abstaining from alcohol, and limiting caffeine consumption. The experimental session took place in a quiet room with minimal distractions. Participants sat comfortably at a table facing a monitor. The total experimental duration averaged 90 minutes, including setup of the equipment, instructions for the task, and data collection.

B. Experimental Tasks

The study employed two distinct paradigms designed to examine sensory information processing at different levels of cognitive complexity.

The Necker cube task presented a classic bistable visual stimulus, which creates perceptual ambiguity at the level of visual processing. This paradigm enables the investigation of rapid switching between alternative interpretations. The

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experiment was divided into four blocks of tasks to enable analysis of functional network dynamics over time. In high-error conditions, response times averaged less than 1.5 seconds, reflecting the rapid nature of perceptual processing.

The Raven's Progressive Matrices task consisted of 60 items, divided into five series (A through E), each with 12 items of progressively increasing difficulty. Unlike the Necker cube task, this task's ambiguity emerges not only at the perceptual level, but also during higher-level cognitive analysis of spatial-logical patterns. Participants were required to identify patterns within the matrix configurations and select the correct missing element from multiple options. The total time allotted for the task was 20 minutes, with individual item completion times reaching tens of seconds. This provided sufficient temporal resolution to investigate sustained cognitive processing.

C. fNIRS Data Acquisition and Analysis

We recorded hemodynamic responses using fNIRS because it is a reliable tool for investigating task-related brain activity [5], [8], [9]. Changes in oxygenated hemoglobin (HbO) concentration were used as the primary measure to reconstruct functional connectivity due to its strong correlation with blood oxygen level-dependent (BOLD) signals from functional magnetic resonance imaging (fMRI) studies [10], [11].

We assessed functional connectivity between brain regions by calculating Spearman correlation coefficients between time series from all fNIRS channel pairs. The statistical significance of the correlations was evaluated for each channel pair individually, and only the significant connections ($p < 0.05$) were retained in the functional connectivity matrices for subsequent analysis.

For the Necker cube task, functional networks were reconstructed using five-second time windows starting from stimulus presentation. Networks were computed separately for each of the four experimental blocks to track the temporal dynamics of functional organization throughout the session.

For Raven's Matrices, connectivity matrices were calculated for each item from stimulus onset to response confirmation. These were then averaged within each complexity level for each participant, resulting in three functional networks per participant representing brain activity in low-, medium-, and high-complexity conditions.

D. Network-Based Statistical Analysis

The Network-Based Statistic (NBS) method [12] was employed to identify statistically significant differences in functional connectivity patterns between experimental conditions. This approach controls for multiple comparisons while maintaining sensitivity to detect network-level changes.

For each fNIRS channel pair, t -statistics were computed to quantify connectivity differences between conditions. A threshold was applied to these t -values to identify connected network components (clusters) showing the strongest differences. Statistical significance of identified clusters was determined using permutation testing with 1000 iterations,

providing robust control of Type I error rates across multiple comparisons [13].

E. Regional Analysis and Integration Measures

To enhance interpretability and reduce inter-individual anatomical variability effects, functional connectivity was aggregated at the level of major anatomical regions: frontal, parietal, occipital, and temporal cortices. This approach aligns with established neuroscientific frameworks of large-scale brain organization.

An integrated connectivity metric was developed to quantify inter- and intra-regional connections. This metric combined the proportion of significantly altered connections (ratio of significant connections to total possible connections) with their mean strength, providing a comprehensive measure that captures both the extent and magnitude of connectivity changes within the network structure.

F. Complexity Classification

Task complexity levels for Raven's Matrices were empirically determined through behavioral data analysis. Repeated measures ANOVA revealed significant differences in both accuracy and reaction time through series A – E. Based on post-hoc comparisons with Holm correction for multiple comparisons, series were categorized into three complexity levels: low (series A – B), medium (series C – D), and high (series E).

G. Statistical Analysis

Group-level functional networks were constructed by averaging connectivity matrices across participants within each experimental condition. For network metrics, including the global clustering coefficient, repeated measures ANOVA was performed to assess differences across difficulty levels, with post-hoc pairwise comparisons using Holm correction.

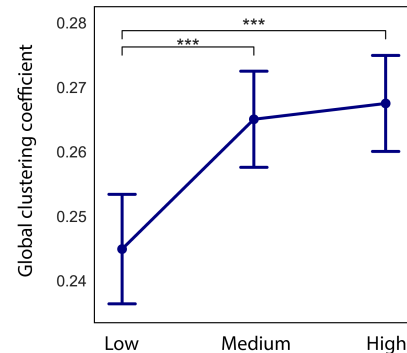


Fig. 1. Mean values of the global clustering coefficient of the brain functional network reconstructed using NBS in low, medium, and high task complexity. “***” indicate statistically significant differences between conditions, identified using repeated-measures ANOVA followed by post hoc pairwise comparisons with Holm correction for multiple testing.

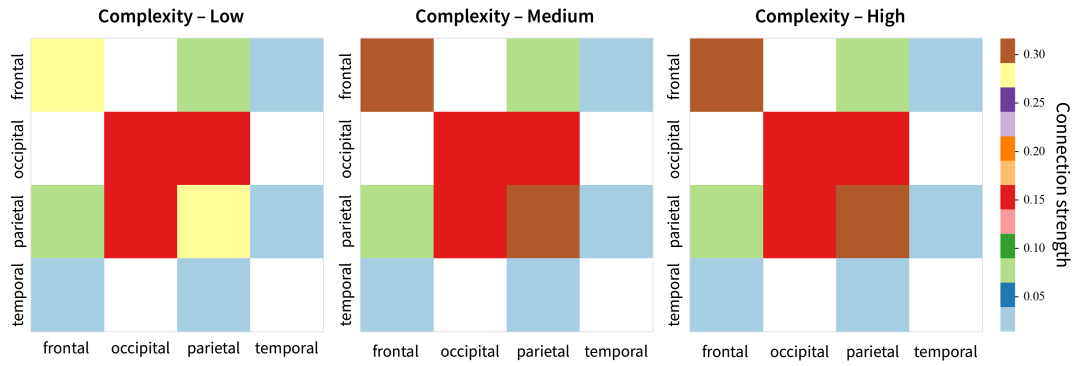


Fig. 2. Average functional connectivity matrices between major brain regions (frontal, parietal, temporal, occipital) in low, medium, and high task complexity. The color scale represents the mean connectivity value between regions.

III. RESULTS

During the Necker cube task, NBS analysis that compared functional networks reconstructed for the beginning and the end of the experimental session identified a statistically significant cluster of connections, indicating stable changes in the organization of brain activity. The cluster's connections are localized within parietal regions involved in the regulation of directed attention, integration of sensory information, and the spatial organization of perception. An analysis of change directionality revealed a decrease in the strength of functional connectivity in these regions toward the end of the experiment, which is well-aligned with our previous findings [14]. The observed reduction in parietal functional connectivity may reflect a diminished allocation of neural resources during task performance.

A reduction in connectivity may indicate a shift toward a more selective and efficient strategy for processing sensory information, helping to maintain a stable level of cognitive functioning during prolonged task performance. This dynamics were accompanied by improvements in behavioral performance — higher response accuracy and shorter reaction times, which suggests a shift toward a more efficient information-processing strategy.

In the Raven's Progressive Matrices task, we identified a network with its structure depending on the task complexity. The global clustering coefficient of the functional network demonstrated a statistically significant increase with increasing task complexity (Figure 1).

Analysis of inter-regional interactions revealed a reconfiguration of functional connections with changes in cognitive load. Figure 2 presents the average functional connectivity matrices between major brain regions for the three levels of task complexity.

The analysis of inter-regional connections showed that the strongest functional connectivity was observed between the occipital and parietal cortices, as well as between the parietal and frontal cortices. Contrarily, connections between the frontal and temporal cortices, and between the temporal and parietal cortices, were less pronounced. As task complexity increased, we observed divergent dynamics: connectivity between the

frontal and temporal cortices weakened, whereas interactions between the other cortical regions strengthened.

These results indicate a functional redistribution of connectivity under rising cognitive load [15], [16]. The attenuation of fronto-temporal interactions may reflect reduced engagement of mechanisms of semantic integration or speech representation, whereas the strengthening of links between occipital, parietal, and frontal areas reflects the activation of neural networks associated with directed attention and visuospatial processing required for more demanding tasks.

CONCLUSION

This study shows that brain functional connectivity, measured with fNIRS, adaptively reorganizes in response to changing sensory and cognitive demands. During the Necker cube task, NBS revealed a significant parietal cluster with reduced connectivity from the beginning to the end of the session, paralleling improvements in behavioral performance and suggesting a shift toward more efficient processing. In Raven's Progressive Matrices, increasing task complexity was accompanied by a significant rise in the global clustering coefficient and a redistribution of inter-regional interactions — strengthened occipito-parietal and parieto-frontal connectivity alongside weakened fronto-temporal coupling. This is consistent with enhanced integration of bottom-up sensory input and top-down control. Together, these findings highlight fNIRS-derived connectivity metrics as promising noninvasive markers of cognitive load and performance.

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