Exploring the Neural Basis of Cognitive Control using fMRI: A Data Analysis Report

CONTENTS

ABSTRACT

This report presents the results of an analysis conducted on the Flanker Dataset to investigate the differences in the BOLD signal between Congruent and Incongruent Flanker trials. The study utilized functional magnetic resonance imaging (fMRI) to explore cognitive processes related to attention and response inhibition. Significant differences in the BOLD signal were observed between the two conditions through cognitive control, quality control, preprocessing, statistical analysis, and post-analysis using the FSL software. These findings contribute valuable insights into the neural mechanisms underlying cognitive control and response inhibition.

INTRODUCTION

Cognitive processes related to attention and response inhibition have been extensively studied using neuroimaging techniques, particularly functional magnetic resonance imaging (fMRI). In this study, we conducted a task-based experiment using the Flanker Dataset to investigate the differences in the BOLD signal between Congruent and Incongruent Flanker trials. The Flanker task is a well-established paradigm for investigating cognitive control, attention, and response inhibition. During the task, the subject is presented with a fixation cross followed by a Congruent or Incongruent Flanker trial, and they are required to press either the left or right button. Our analysis involved cognitive control, quality control, preprocessing, stats, and post-stats using the FSL software. Our goal was to estimate the magnitude of the BOLD signal to each condition and determine if they are significantly different from each other. Our findings provide important insights into the underlying neural mechanisms involved in cognitive control and response inhibition.

ANALYSIS

In this study, we aimed to investigate the brain regions associated with cognitive control during a visual task using fMRI data. Our study included a total of 26 adult participants who performed the task while their brain activity was recorded.

COGNITIVE CONTROL

To ensure the reliability of our experiment, cognitive control was carried out first, as the noisy nature of fMRI data can make it difficult to draw meaningful conclusions. Our results indicated a robust and reliable difference in reaction times between congruent and incongruent stimuli, providing confidence that our fMRI data would also show a noticeable difference in the BOLD signal.

QUALITY CONTROL

Quality control was carried out on all participants' fMRI anatomy and functional images, with some subjects (sub-03, sub-11, sub-12, sub-16, sub-19, sub-20, sub-25, and sub-26) showing motion artifacts in their functional images. These were accounted for in our analysis.

PREPROCESSING

Preprocessing of the images was carried out using a bash script that applied brain extraction to anatomical images, temporal high-pass filtering, and motion correction to functional images. Slice timing correction was not necessarily due to our short repetition time, and all images were registered over the MNI152 template.

The BET tool was utilized to perform brain extraction on anatomical images, using a fractional intensity of 0.3. Various threshold values were tested, as shown in Figure 1, where it was observed that higher threshold values resulted in the elimination of significant brain parts, while lower threshold values led to the addition of unnecessary information or noise to the task.

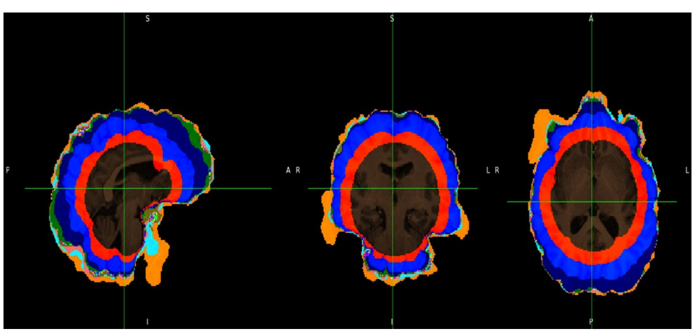

Figure 2, Each color maps to a fractional intensity value.

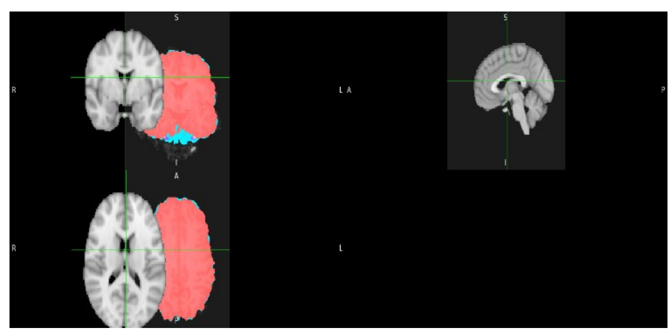

Figure 1, Fractional Intensity (0.3 ~ Red Color) vs MNI152

The functional images underwent several preprocessing steps. First, the temporal high-pass filter cutoff value was set to 100 seconds to remove low-frequency noise. Motion correction was performed using the MCFLIRT Algorithm to correct for subject motion during scanning. The BET tool was then used to remove the skull from the images. Since the experiment had a low TR (Repetition Time), slice timing correction was skipped. Instead, a further temporal derivative step was employed to achieve a similar effect in the analysis.

To enhance registration efficiency and improve the signal quality, a smoothing kernel of 7mm was applied. This smoothing helped to increase the robustness of the registration process and was particularly useful since the task did not aim to detect brain activation in small areas.

Additionally, the anatomical image for each subject was registered to the functional image. This registration step aimed to improve the normalization efficiency. Finally, all images were normalized to MNI152 space using a T1 1mm template image, ensuring spatial alignment across subjects for subsequent group-level analyses.

STATS & POST-STATS

First-Level Analysis

The first-level analysis was conducted on all subjects using a bash script. The script extracted congruent and incongruent timestamps. FILM prewhitening was applied to improve the statistical analysis. The GLM (General Linear Model) was used for statistical modeling, employing two regressors (Congruent and Incongruent) and three COPEs (contrast of parameter estimates). The three contrasts (COPEs) were defined to enhance our experiment, focusing on active congruent pixels only, active incongruent pixels only, and the difference between active pixels in the incongruent condition minus the congruent condition.

Following the statistical modeling, a t-test was performed in the post-statistics phase to assess significance. A Z threshold of 3.1 and a P threshold of 0.05 were used for determining significant activations. This analysis was initially performed on a single subject, resulting in the creation of a "design.fsf" file. Subsequently, another bash script was utilized to apply this file and conduct the first-level analysis on all subjects. As a result, 52 FEAT files were generated, corresponding to the 26 subjects with two runs each.

First -Level Analysis Results

By employing a bash script to extract cluster masks for each contrast and projecting these masks onto the MNI template, the following observations were made:

CONTRAST1: ACTIVE CONGRUENT PIXELS ONLY

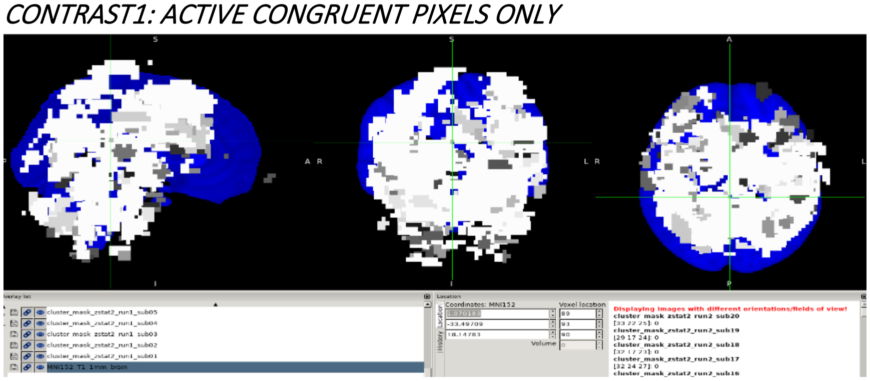

Figure 3, Contrast 1 - Noise

As depicted in Figure 3, the projection of active congruent pixels from the post-stats analysis shows activation throughout the entire brain. This activation pattern does not provide clear information specific to our task-based experiment.

CONTRAST2: ACTIVE INCONGRUENT PIXELS ONLY

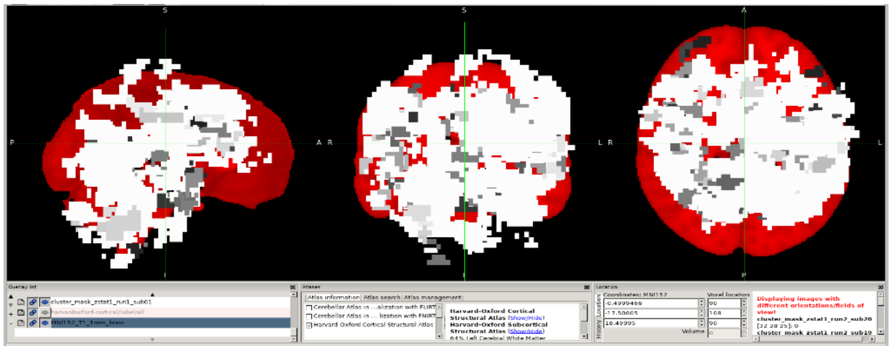

Figure 4, Contrast 2 – Noise

Figure 4 illustrates the projection of active incongruent pixels from the post-stats analysis, revealing activation throughout the entire brain. This pattern does not convey clear information relevant to our task-based experiment.

CONTRAST3: ACTIVE INCONGRUENT MINUS CONGRUENT PIXELS ONLY

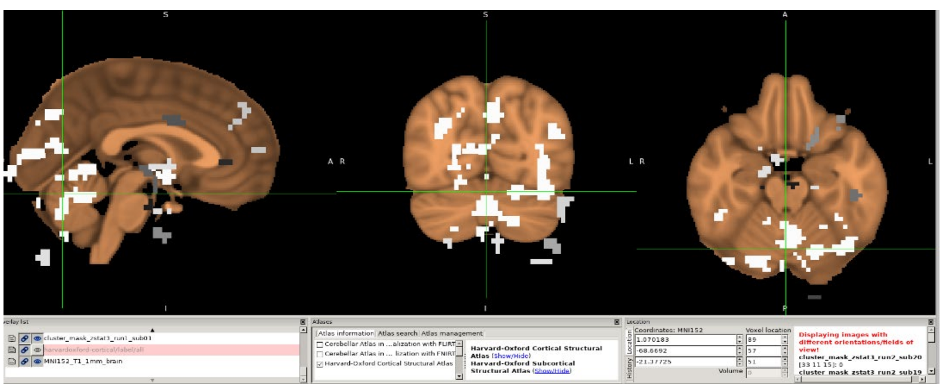

Figure 5, Contrast 3 – Very Clear

Figure 5 displays the projection of active incongruent minus congruent pixels from the post-stats analysis. In this case, only a specific region of the brain shows activation. This finding aligns with our task-based experiment and provides clear information.

However, to determine if the activated voxels are true positives for our task, further analysis is needed. We will proceed with the group analysis, combining activated voxels from all subjects, and draw conclusions regarding the sufficiency of the first-level analysis for our task-based experiment.

Second-Level Analysis

The second-level analysis was performed on the 52 FEAT files, resulting in the generation of 26 files corresponding to the 26 subjects. The analysis involved applying a measure of central tendency using different algorithms. Since each subject had two runs, it was necessary to segment each subject's data before conducting the group analysis. The second-level analysis was performed on each subject using three algorithms: Fixed, Flame 1, and Simple OLS. This step aimed to determine which algorithm would be more effective for the group analysis.

Third-Level Analysis

Exploratory group analysis was conducted using Flame 1 on the results obtained from the second-level analysis algorithms. The purpose was to assess the effectiveness of the different algorithms in the second-level analysis.

Cluster browser
thresh_zstat1
Z statistics for COPE1 (group mean) | Add Z statistics | Add cluster mask

Cluster index	Size (voxels)	P	-log10(P)	Z Max	Z Max location	COG location	COPE Max
6.0	1827.0	2.38e-07	6.62	4.41	[66.0 20.0 33.0] →	[57.45 26.35 25.2] →	46.6
5.0	1637.0	8.94e-07	6.05	4.52	[33.0 30.0 62.0] →	[28.1 34.95 58.8] →	50.4
4.0	786.0	0.000408	3.39	4.71	[23.0 65.0 49.0] →	[23.65 69.45 45.4] →	41.5
3.0	743.0	0.000584	3.23	4.43	[20.0 31.0 30.0] →	[21.3 28.799999999999997 31.95] →	47.4
2.0	441.0	0.00915	2.04	4.33	[58.0 34.0 62.0] →	[57.15 32.5 61.2] →	41.8
1.0	434.0	0.00981	2.01	4.0	[43.0 71.0 62.0] →	[43.725 70.6 61.25] →	43.5

Figure 6. Flame 1 is based on Fixed Effect.

Cluster browser
thresh_zstat1
Z statistics for COPE1 (group mean) | Add Z statistics | Add cluster mask

Cluster index	Size (voxels)	P	-log10(P)	Z Max	Z Max location	COG location	COPE Ma:
6.0	1373.0	5.36e-06	5.27	4.43	[32.0 29.0 61.0] →	[28.6 33.9 58.5] →	49.6
5.0	839.0	0.000276	3.56	4.41	[66.0 20.0 33.0] →	[66.45 25.75 30.95] →	46.6
4.0	750.0	0.000572	3.24	4.24	[49.0 23.0 22.0] →	[46.64 26.9 19.4] →	42.2
3.0	698.0	0.000887	3.05	4.29	[23.0 32.0 33.0] →	[21.3 28.799999999999997 32.005] →	47.1
2.0	624.0	0.00169	2.77	4.71	[23.0 65.0 49.0] →	[22.95 68.35 47.4] →	41.7
1.0	405.0	0.0135	1.87	4.29	[59.0 34.0 63.0] →	[57.3 32.6 61.35] →	41.9

Figure 7. Flame 1 is based on Flame 1.

Cluster browser
thresh_zstat1
Z statistics for COPE1 (group mean) | Add Z statistics | Add cluster mask

Cluster index	Size (voxels)	P	-log10(P)	Z Max	Z Max location	COG location	COPE Ma:
6.0	1065.0	7.47e-05	4.13	4.16	[33.0 30.0 63.0] →	[30.2 32.5 57.9] →	53.3
5.0	783.0	0.000614	3.21	4.49	[67.0 29.0 34.0] →	[66.5 25.450000000000003 32.385] →	46.2
4.0	718.0	0.00103	2.99	4.32	[23.0 31.0 32.0] →	[22.45 26.549999999999997 33.48] →	45.1
3.0	636.0	0.00203	2.69	4.08	[55.0 33.0 60.0] →	[57.05 31.85 58.75] →	41.6
2.0	635.0	0.00205	2.69	4.68	[22.0 66.0 50.0] →	[22.85 68.5 46.7] →	49.9
1.0	312.0	0.0419	1.38	3.98	[45.0 34.0 18.0] →	[45.1555 31.4 18.55] →	36.5

Figure 8. Flame 1 is based on Simple OLS.

Based on Figures 6, 7, and 8, it can be inferred that the P-values obtained from Flame 1 based on the Fixed Effect algorithm were the most favorable among the three categories. This finding is reasonable since the Fixed Effect algorithm computes the average of the two runs, which is crucial as the two runs come from the same subject in a similar environment. Therefore, we will rely on the results obtained from this algorithm.

To address the issue of false positives in fMRI, Eklund et al. (2016) suggested accepting only P-values below 0.001 to increase the significance of the results. Accordingly, we will consider clusters with indices 3, 4, 5, and 6, corresponding to MNI 152 coordinates [50, -64, -12], [44, 4, 26], [24, -66, 52], and [-42, -86, -6], respectively, to decrease false positives.

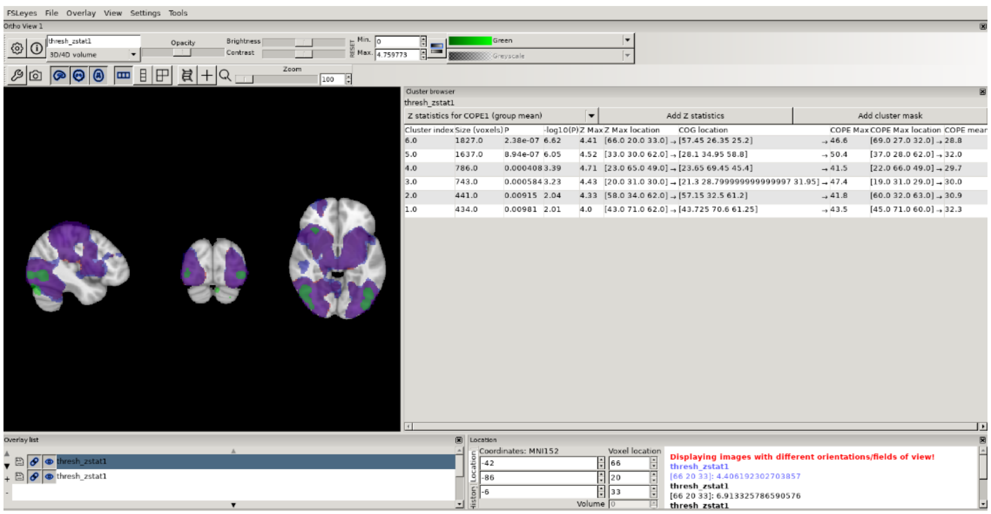

Figure 9. Incongruent minus congruent clusters.

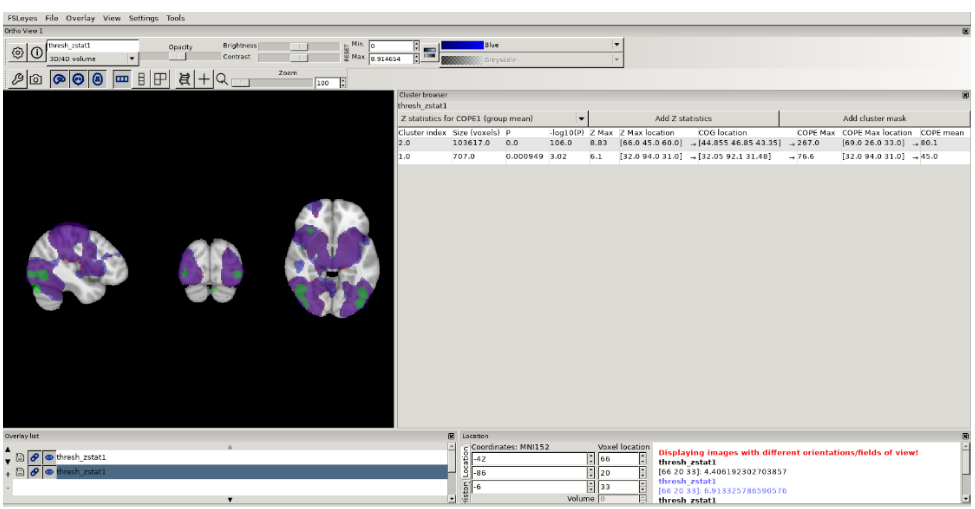

Figure 10. Incongruent clusters.

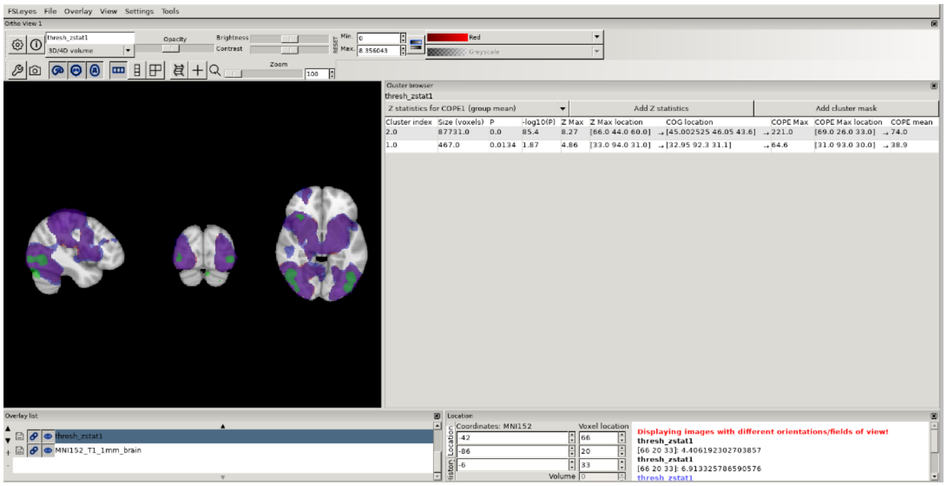

Figure 11. Congruent Clusters

By examining Figures 9, 10, and 11, it can be concluded that there is complete overlap between the clusters in the Congruent, Incongruent, and Incongruent minus Congruent Contrasts. Therefore, we will focus on the base clusters present in all contrasts, specifically Cluster numbers 3, 4, 5, and 6 in the Incongruent minus Congruent contrast.

ROI Analysis

After extracting the four ROIs from the exploratory test, a confirmation test called ROI Analysis was performed. The four key points identified in the previous analysis were used to create four spheres with a radius of 10 mm, with each sphere centered at its respective key point.

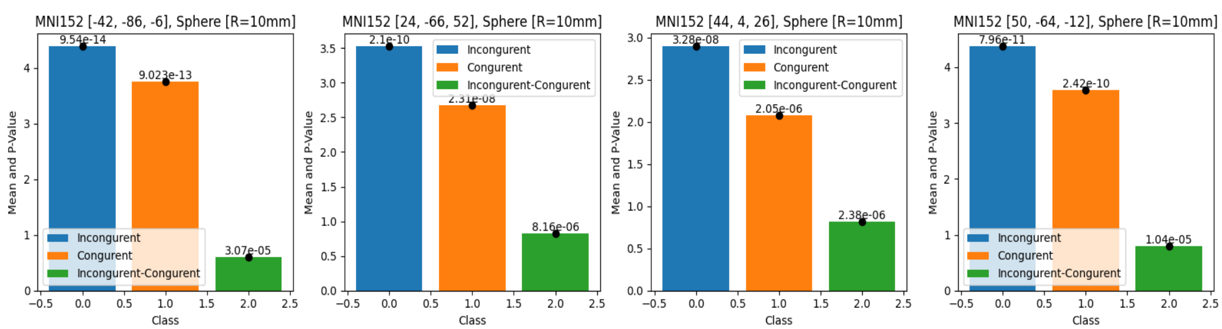

Figure 12. Contrast type dominance on each key point.

Figure 12 shows that each key sphere has a P-value <<< 0.001 for every contrast, indicating that these four key spheres are statistically significant. Additionally, due to complete overlap, we can observe the ratio of each contrast within the four key point spheres. Python code scripts were employed to calculate the mean, conduct one-sample t-tests, and generate the above figures.

Group Analysis vs Individual Analysis.

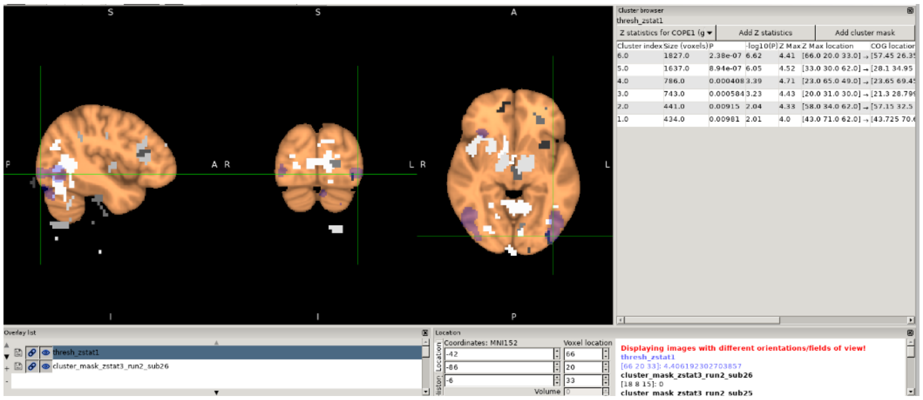

Figure 13. Cluster 6 (magenta) vs Activated Pixels from all subjects (1st Level Analysis)

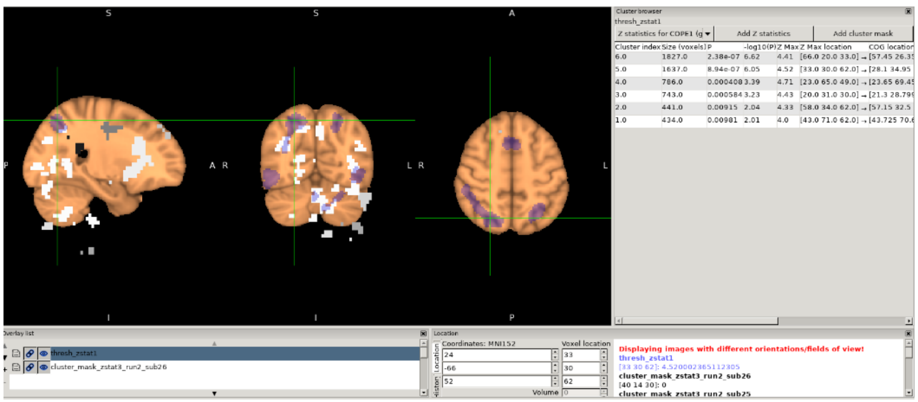

Figure 14. Cluster 5 (magenta) vs Activated Pixels from all subjects (1st Level Analysis)

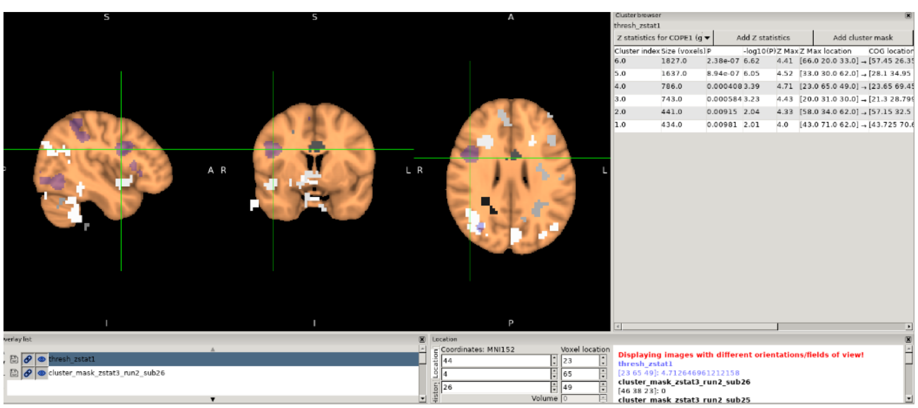

Figure 15. Cluster 4 (magenta) vs Activated Pixels from all subjects (1st Level Analysis).

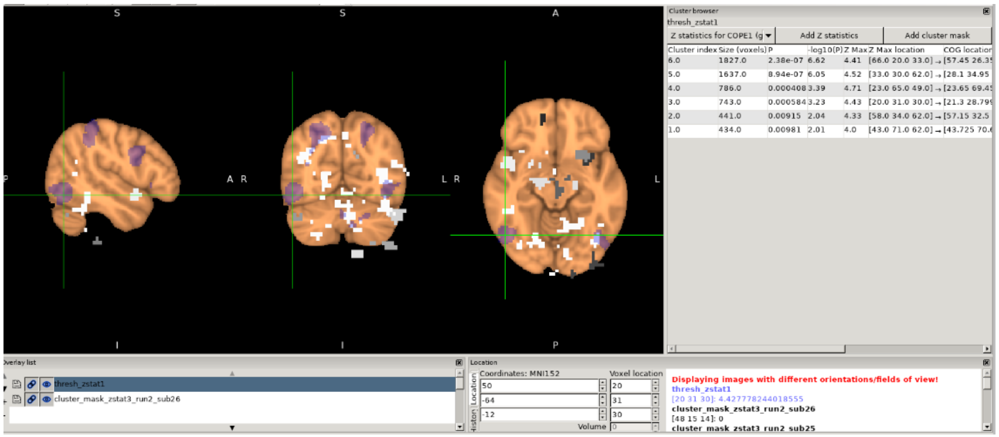

Figure 16. Cluster 3 (magenta) vs Activated Pixels from all subjects (1st Level Analysis).

By examining Figures 13, 14, 15, and 16, it is evident that there is very weak overlap between the confirmed cluster (magenta) and the white activated voxels behind it. In some areas, there is no overlap at all.

Depending solely on the activated voxels from all subjects and all runs during the first-level analysis would result in numerous false positives and false negatives, rendering the results statistically insignificant. Therefore, group analysis and confirmation analysis were conducted to address these issues. The focus will be on the four clusters identified in our analysis.

FINAL RESULTS

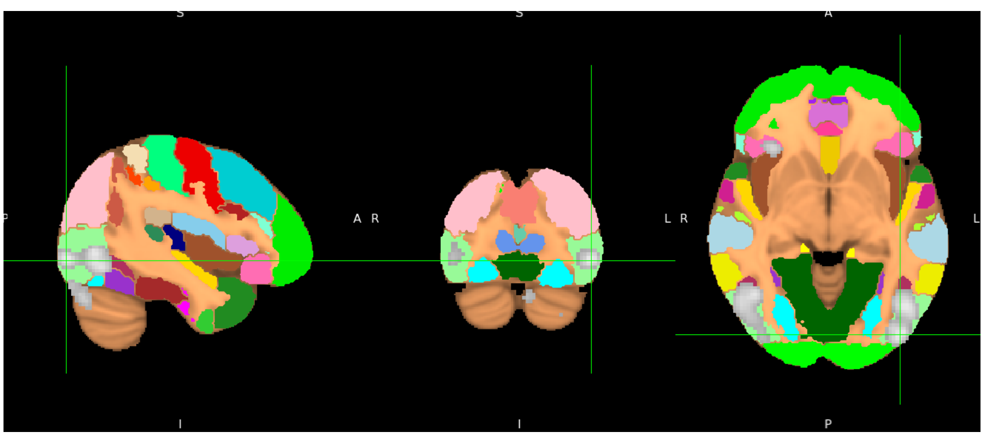

Figure 17. Cluster 3, 6 (Lateral Occipital Cortex, Inferior division) [Silver Color].

From Figure 17, it is evident that the relationship between the flanker task and the "Lateral Occipital Cortex, Inferior division" is not direct. This region is primarily associated with visual processing, object recognition, and scene perception. The flanker task, on the other hand, focuses more on cognitive control and response inhibition. However, during the flanker task, participants still need to process visual stimuli, and this processing may involve early visual areas, including the lateral occipital cortex. Therefore, while the lateral occipital cortex, inferior division, may not be directly implicated in the specific cognitive demands of the flanker task, it likely contributes to the initial visual processing of the flanker stimuli.

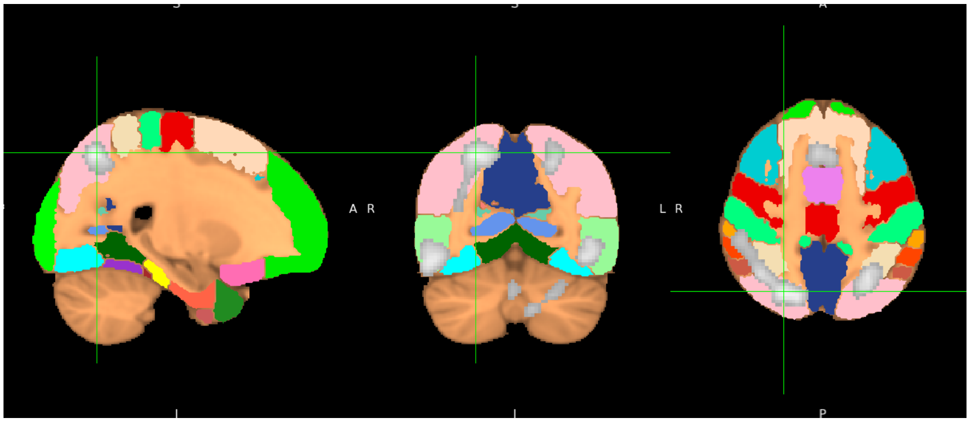

Figure 18. Cluster 5 (Lateral Occipital Cortex, Superior division) [Silver Color].

Figure 18 shows that the relationship between the flanker task and the "Lateral Occipital Cortex, Superior division" is also not direct. This region is primarily involved in the processing of visual motion information. The flanker task, however, primarily engages cognitive control processes and response inhibition rather than motion perception. Nonetheless, it is possible that certain aspects of the flanker task, such as the perception of motion cues in the stimuli or the integration of motion information with other visual features, could recruit the lateral occipital cortex, superior division, to some extent. Further research would be necessary to determine the precise involvement of this region in the flanker task.

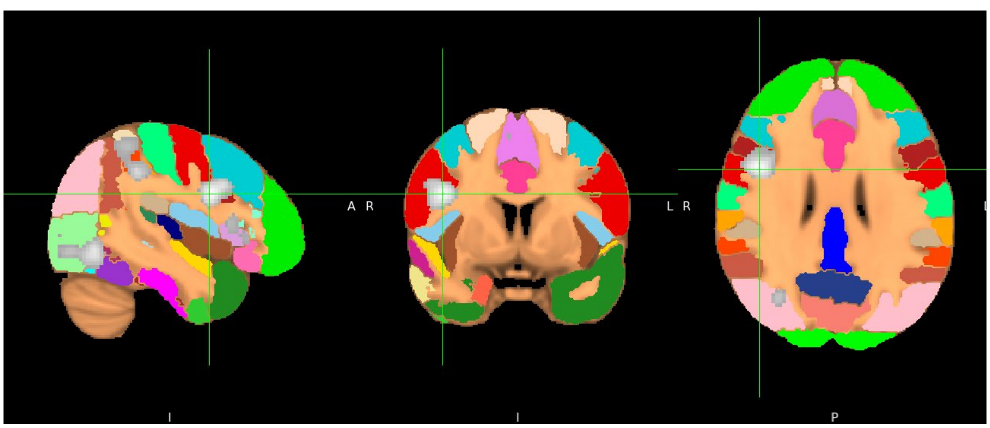

Figure 19. Cluster 4 (Precentral Gyrus) [Silver Color].

From Figure 19, it can be observed that the relationship between the flanker task and the "Precentral Gyrus" is indirect. The precentral gyrus is primarily associated with motor control and movement initiation. Although the flanker task does not directly involve motor responses, it requires participants to inhibit and suppress unwanted or conflicting responses. These cognitive control and response inhibition processes are supported by regions such as the anterior cingulate cortex (ACC), dorsolateral prefrontal cortex (DLPFC), and inferior frontal gyrus (IFG). These regions, in turn, communicate with the precentral gyrus to execute the motor responses necessary to perform the task accurately. Therefore, while the precentral gyrus itself may not be directly involved in the cognitive processes of the flanker task, it is part of the broader neural network underlying response execution and motor control during the task.

CONCLUSION

After completing our analysis, it is evident that we did not find a direct relationship between the confirmed clusters and the flanker task. In future analyses, it would be worthwhile to expand our investigation by examining the regions that have a direct relationship with the flanker task and explore their connection to the extracted clusters obtained in this study. Additionally, a comprehensive review paper encompassing all our analyses could be produced to summarize our findings.

REFERENCES

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- Soares JM, Magalhães R, Moreira PS, Sousa A, Ganz E, Sampaio A, Alves V, Marques P and Sousa N (2016) A Hitchhiker’s Guide to Functional Magnetic Resonance Imaging. Front. Neurosci. 10:515. doi: 10.3389/fnins.2016.00515
- AndysBrainBook website (https://andysbrainbook.readthedocs.io/en/latest/)

BASH SCRIPTS

Ubuntu-20.04 > home > mahmoud-dev > flanker_dataset > $ main.sh

```bash
#!/bin/bash

# Generate the subject IDs using seq command
for id in $(seq -w 1 26); do
    subj="sub-$id"
    echo "===> Starting processing of $subj"
    cd "$subj"

    # If the brain mask doesn’t exist, create it
    if [ ! -f "anat/${subj}_T1w_brain.nii.gz" ]; then
        echo "Skull-stripped brain not found, using bet with a fractional intensity threshold of 0.3"
        # Note: This fractional intensity appears to work well for most of the subjects in the
        # Flanker dataset. You may want to change it if you modify this script for your own study.
        bet2 "anat/${subj}_T1w.nii.gz" "anat/${subj}_T1w_brain.nii.gz" -f 0.3
    fi

    for run in "run1" "run2"; do
        echo "===> Starting feat for $run"
        cp "../design_1stLevel.fsf" "design_$run.fsf"
        sed -i "s|sub-01|$subj|g" "design_$run.fsf"
        sed -i "s|run1|$run|g" "design_$run.fsf"
        feat "design_$run.fsf"
        echo
    done

    # Go back to the directory containing all of the subjects, and repeat the loop
    cd ..
done

echo

```

SUBMISSION

The report is done by Mahmoud Yaser Salman and Submitted to Prof. Makary.