ASSIGNMENT 03 - COL786 - ROHIT AGARWAL - 2022ES11332

Part (a) – Group-Level fMRI Analysis using FSL

Objective

The primary goal of this task is to explore **group-level functional MRI analysis** using the **FMRIB Software Library (FSL)**, specifically focusing on **higher-level FEAT (FMRI Expert Analysis Tool) analysis** across multiple subjects. This allows us to evaluate whether certain brain regions show **consistent activation patterns** across individuals for specific motor tasks. The main emphasis is on detecting the **mean group effect** — i.e., identifying whether the group, on average, shows activation for a particular contrast.

This part extends from previous individual-level analysis (Assignment 2) and applies those contrasts at the group level, followed by a **conjunction analysis** to find brain regions commonly activated across conditions.

Theoretical Background

1. Functional MRI (fMRI) and the General Linear Model (GLM)

Functional MRI captures dynamic brain activity by measuring the Blood Oxygen Level Dependent (BOLD) signal. To analyze this time-series data, we employ the **General Linear Model (GLM)** framework, which allows us to model the relationship between the observed brain signal and various task conditions.

In GLM:

$Y=X\beta+\epsilon Y$

- Y is the observed fMRI signal.
- X is the **design matrix**, containing explanatory variables (EVs).
- β is a vector of parameter estimates.
- ϵ is the error term.

Each subject's data is modeled using this GLM to estimate **task-related activation maps**.

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2. Preprocessing Steps

Before group analysis, each subject's data undergoes a standard preprocessing pipeline to enhance signal quality and reduce inter-subject variability:

- **Brain Extraction (BET):** Removes non-brain tissue from images.
- **Motion Correction (MCFLIRT):** Adjusts for head movement during scanning.
- **Spatial Smoothing:** 4mm FWHM Gaussian smoothing improves signal-to-noise ratio and accounts for anatomical variability.
- **High-Pass Temporal Filtering:** Removes low-frequency signal drifts.
- **Standard Space Registration:** Aligns each subject's brain to MNI152 standard space using linear and nonlinear transformations.

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3. Experimental Design and Contrasts

The task involves observing **left-hand motor movement** under different stimulus types: audio and video. The dataset includes fMRI scans for 30 subjects, with 8 task conditions encoded as **Explanatory Variables (EVs)**:

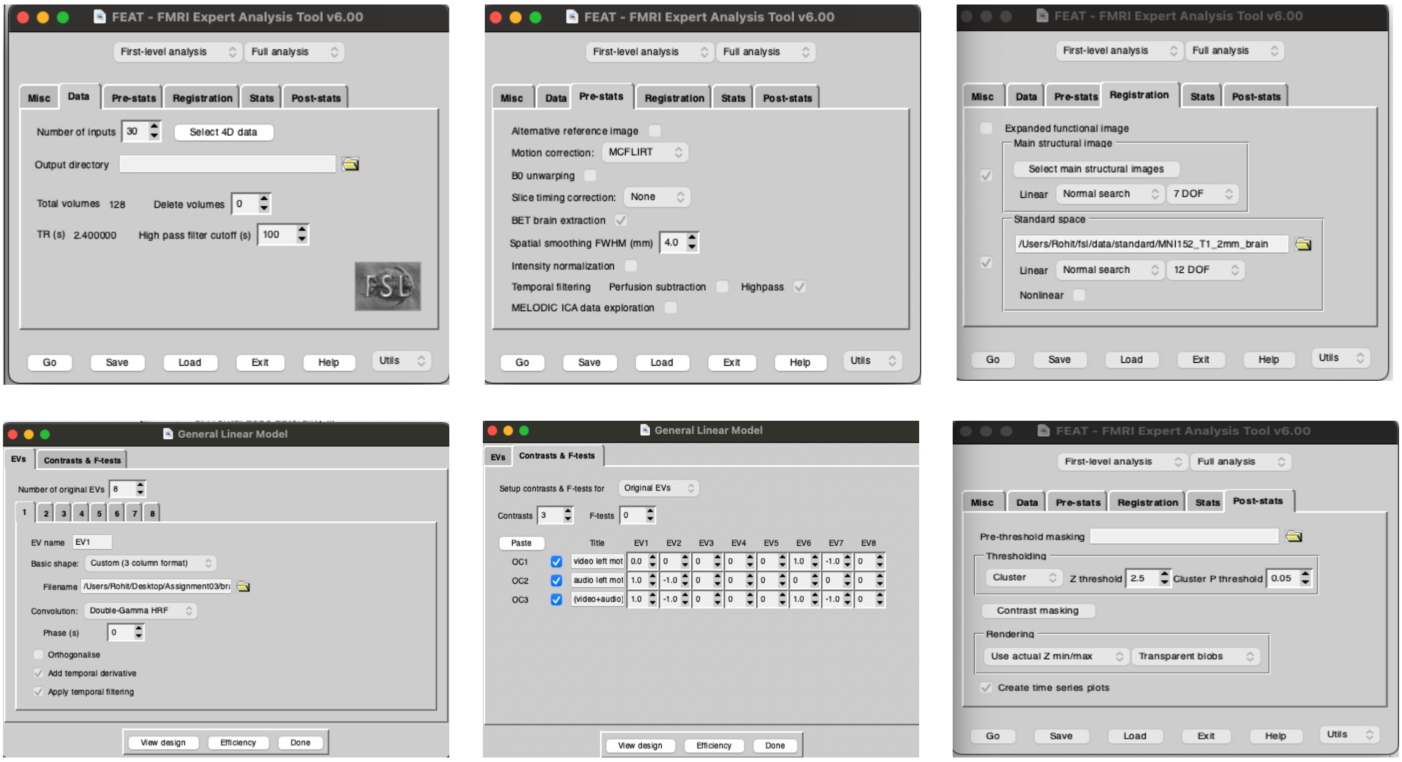
1. Audio Left Hand
2. Audio Right Hand
3. Audio Sentence
4. Horizontal Checkerboard
5. Vertical Checkerboard
6. Video Left Hand
7. Video Right Hand
8. Video Sentence

From these, three key **contrasts** are defined to isolate brain regions involved in **left-hand motor execution**:

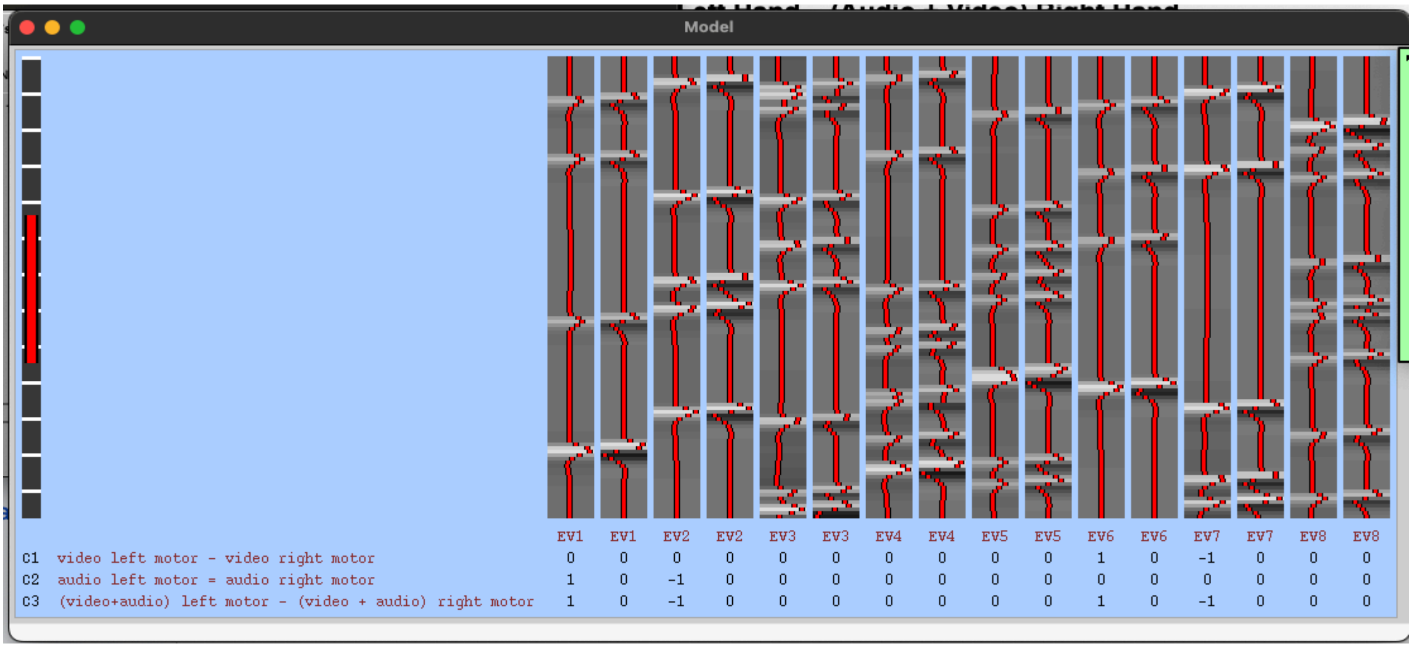
- **C1: Video Left Hand – Video Right Hand**
  Contrast vector: [0, 0, 0, 0, 0, 1, -1, 0]
  This compares motor-related activation from left vs. right hand movements under visual stimuli.
- **C2: Audio Left Hand – Audio Right Hand**
  Contrast vector: [1, -1, 0, 0, 0, 0, 0, 0]
  This isolates activation under auditory-guided motor tasks.

- **C3: (Audio + Video) Left Hand – (Audio + Video) Right Hand**
  Contrast vector: [1, -1, 0, 0, 0, 1, -1, 0]
  This provides a combined measure of motor activation regardless of modality.

Each contrast generates a **statistical parametric map (SPM)** representing task-related brain activation at the single-subject level.



Screenshots of the FSL-FEAT GUI used for performing single-subject (individual-level) analysis



Design Matrix of the individual subject

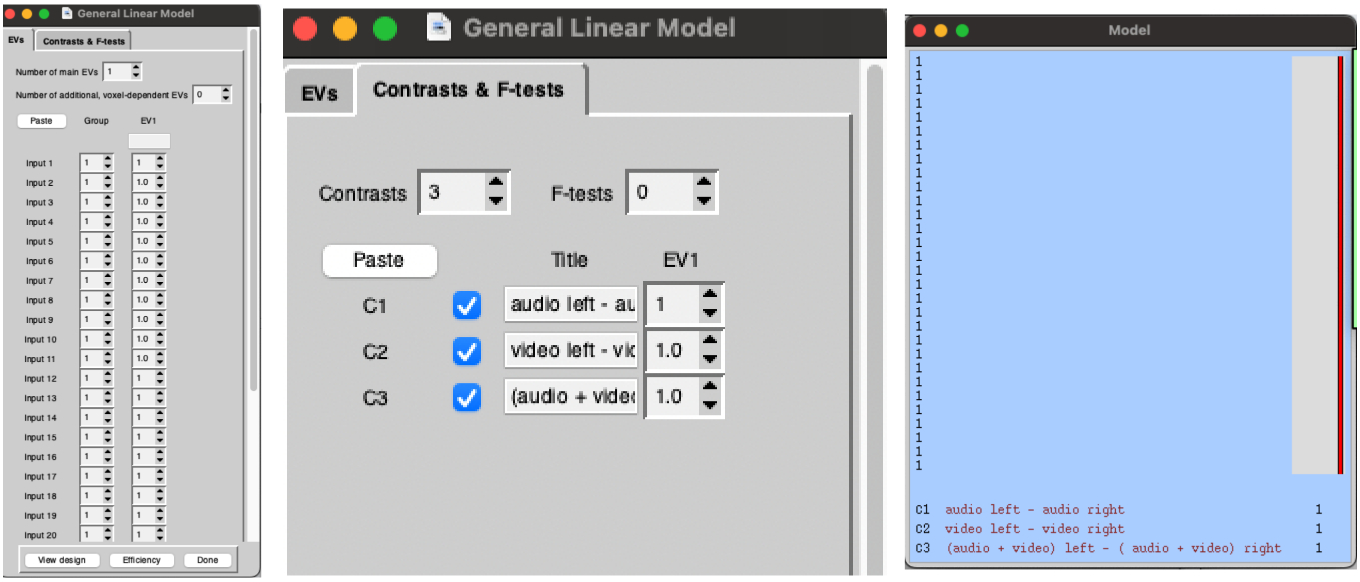
4. Higher-Level Group Analysis (Second-Level FEAT)

To evaluate population-level effects, the individual subject-level maps (COPE files) are combined using higher-level FEAT analysis. The setup includes:

- Input: 30 subject-level `.feat` directories
- Design Matrix: A single group mean regressor (EV1 = 1 for all subjects), assuming each subject contributes equally.
- Contrast Vector: [1] — testing if mean activation across subjects is significantly greater than zero.
- Thresholding:
    - Z-statistic threshold: 2.5
    - Cluster significance: $p < 0.05$ (corrected using Gaussian Random Field theory)

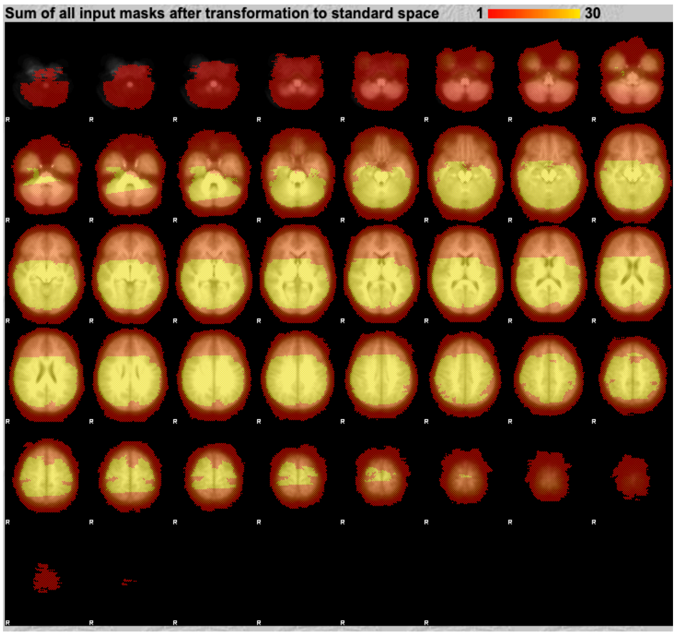
This analysis outputs group-level activation maps highlighting regions significantly engaged by the task.

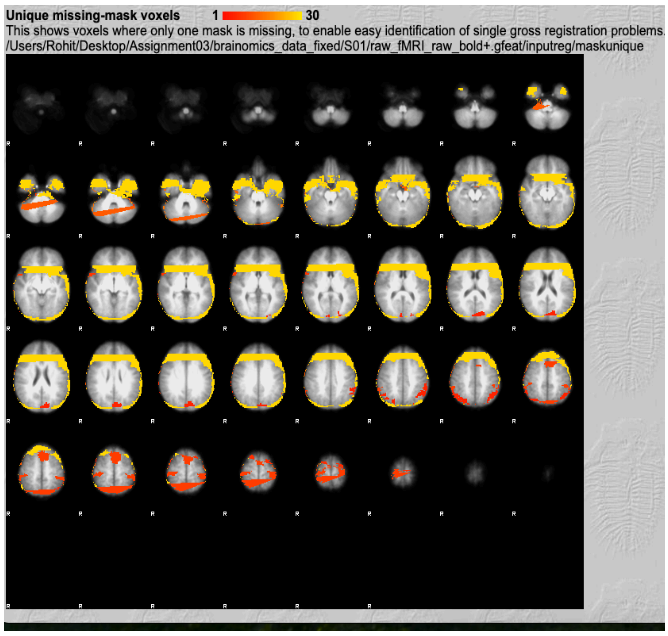
GLM MODEL SETUP



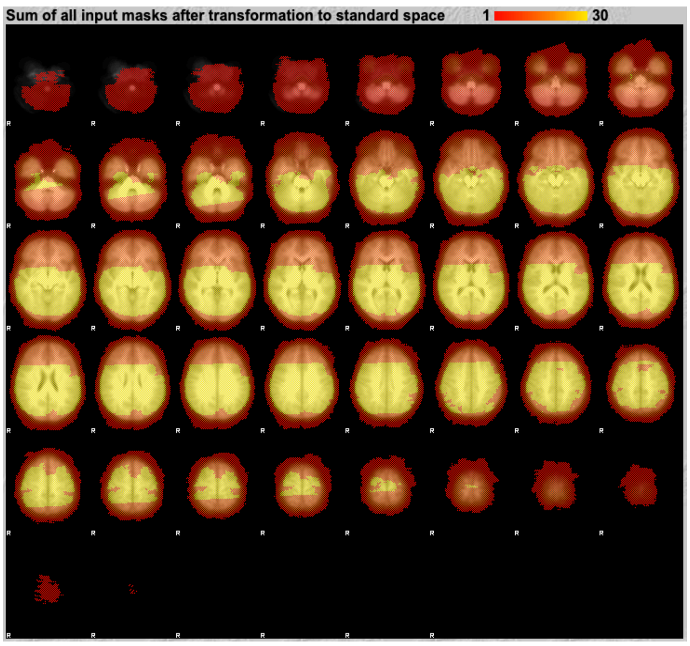
Registration

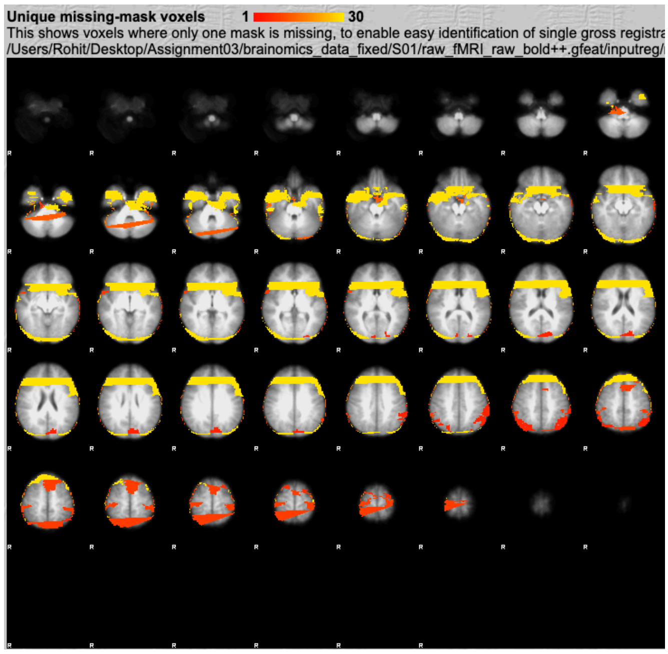
Left Hand





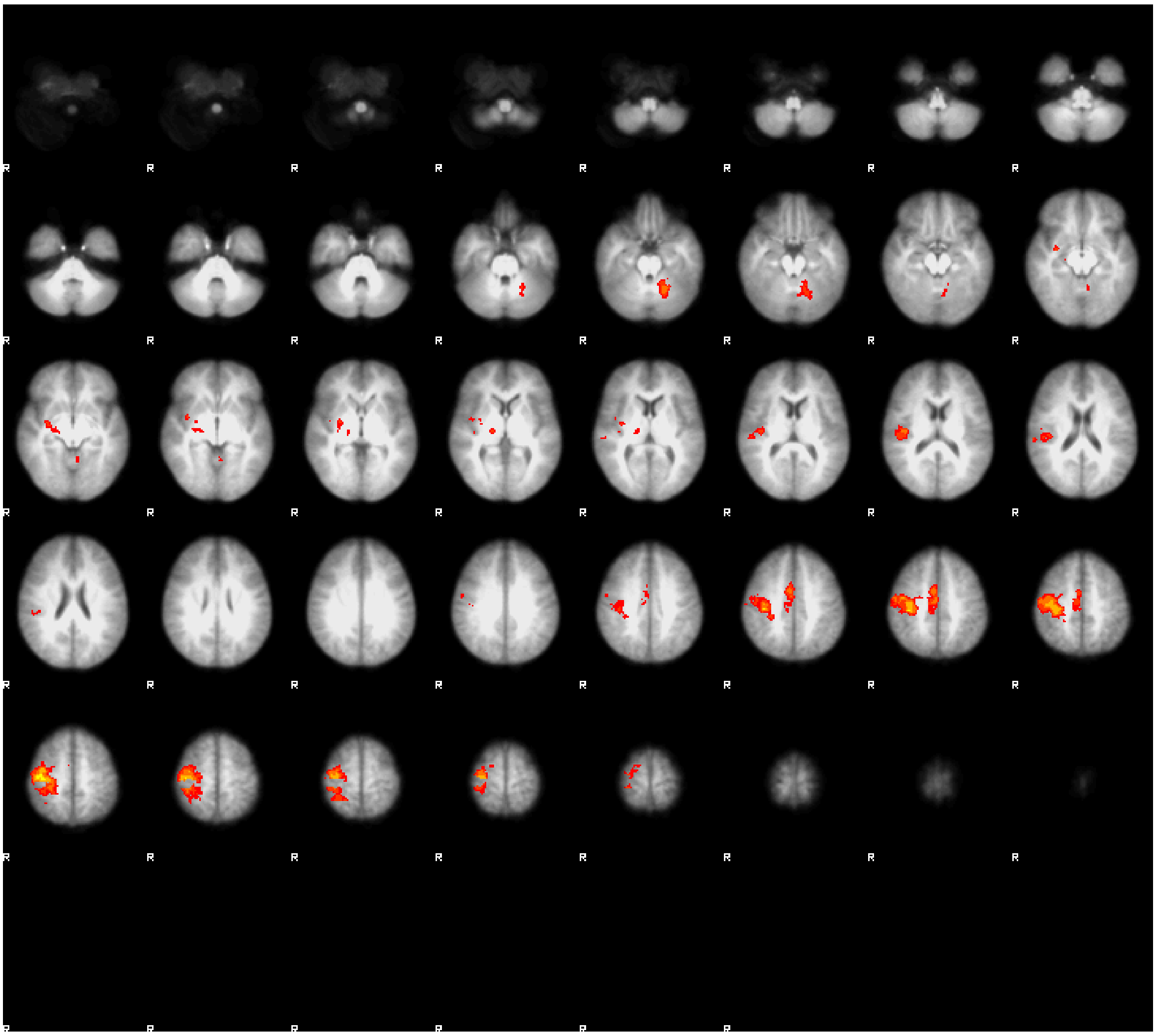
Right Hand





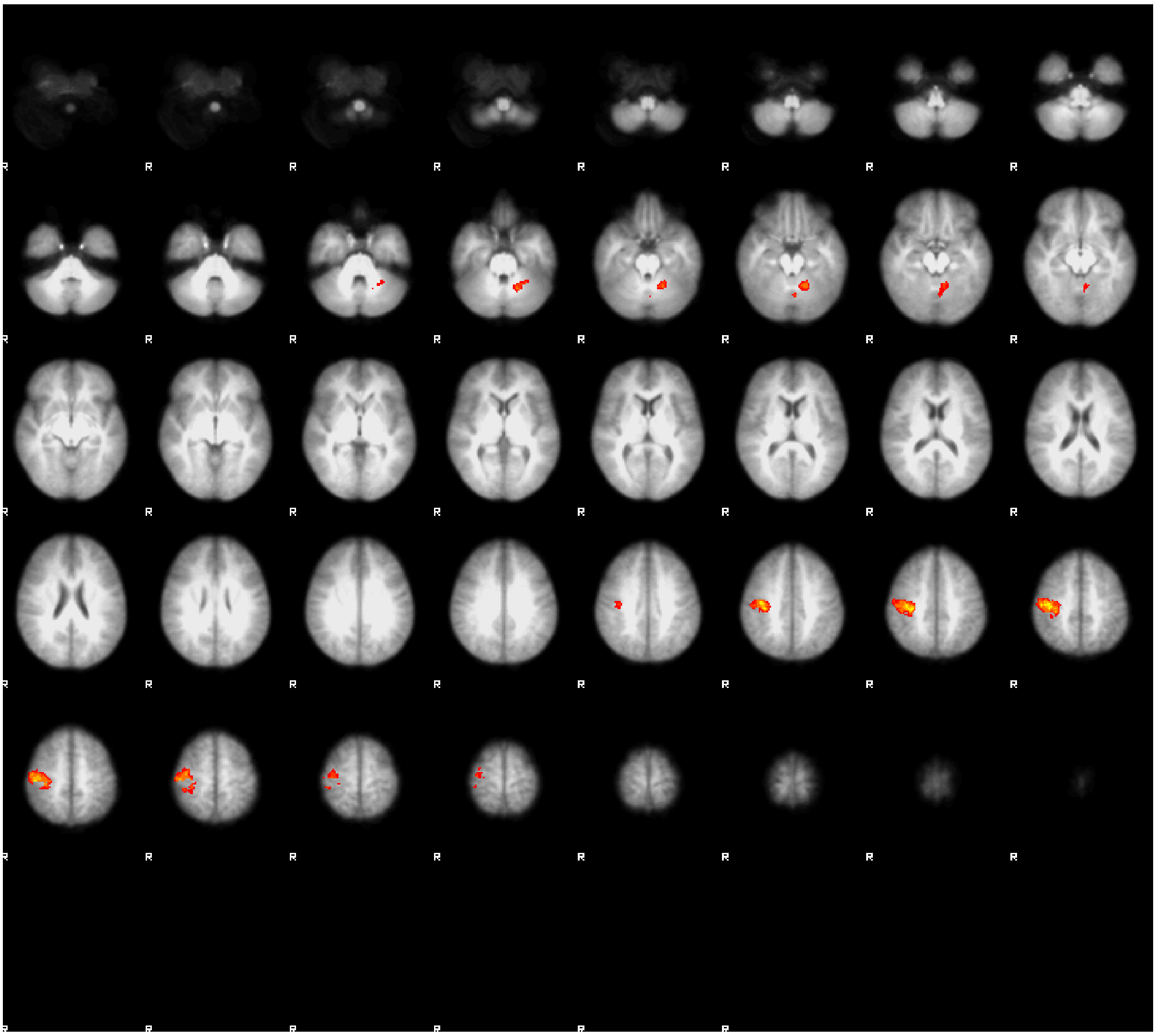
Higher-Level FEAT - LEFT HAND

C1 - Video Left Motor - Video Right Motor



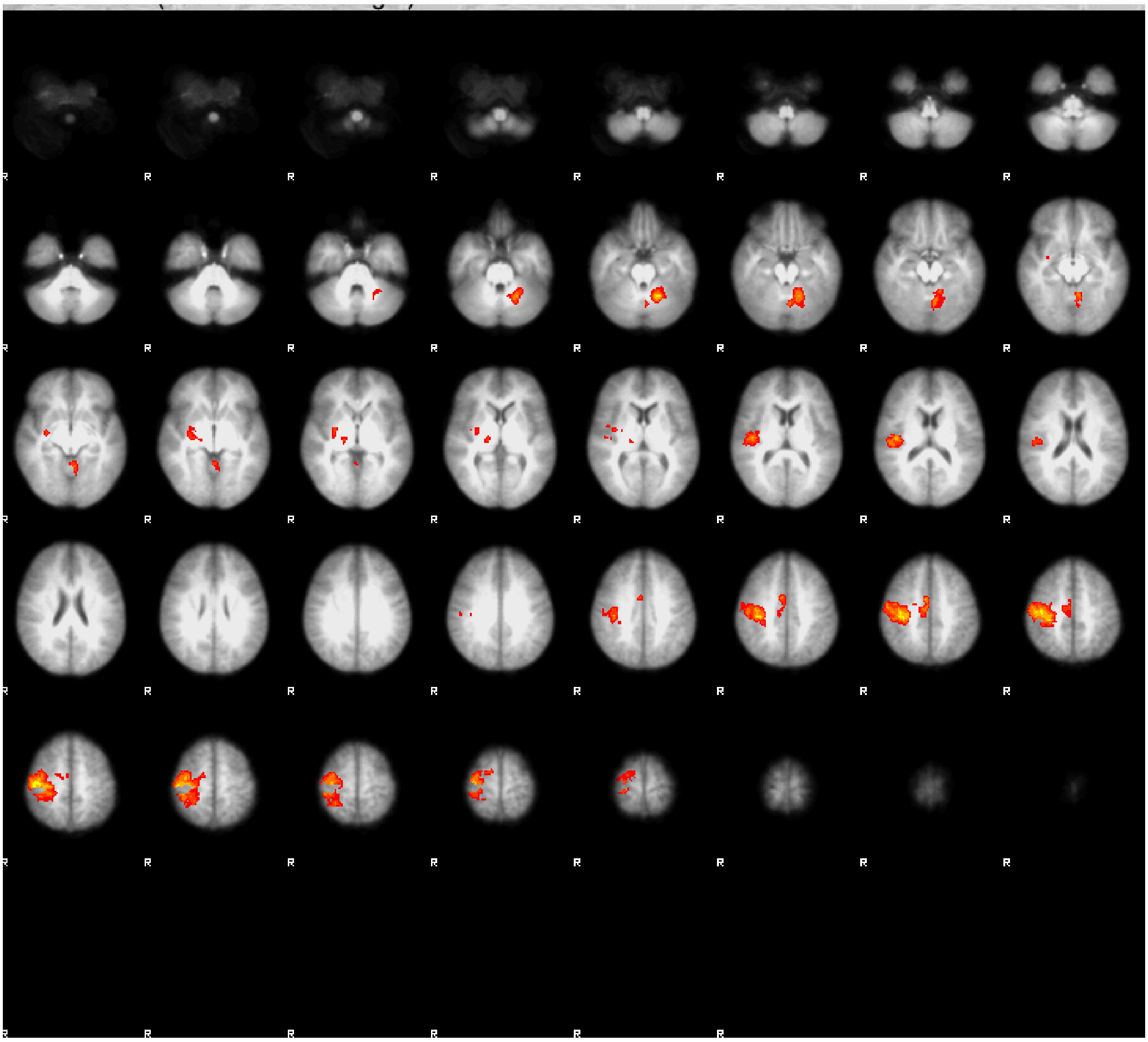
Cluster Index	Voxels	Z-Max	P	-log10 (P)	X (mm)	Y (mm)	Z (mm)	Brain region
4	2480	5.64	2.18e-22	21.7	46	-18	56	Precentral Gyrus
3	492	4.53	8.94e-07	6.05	8	0	45	Central Opercular Cortex
2	364	4.11	2.66e-05	4.58	-20	-54	-24	Cerebellum

C2 - Audio Left Motor - Audio Right Motor



Cluster Index	Voxels	Z-Max	P	-log10 (P)	X (mm)	Y (mm)	Z (mm)	Brain region
2	1187	5.11	1.56e-13	12.8	36	-24	46	Precentral Gyrus
1	325	4.01	5.92e-05	4.23	-18	-54	-20	Cerebellum

C3 - (Video + Audio) Left Motor - (Video + Audio) Right Motor



Cluster Index	Voxels	Z-Max	P	-log10 (P)	X (mm)	Y (mm)	Z (mm)	Brain region
3	3211	5.79	3.02e-27	26.5	38	-26	48	Precentral Gyrus
2	842	5.33	2.13e-10	9.67	-18	-54	-24	Cerebellum
1	686	4.97	6.63e-09	8.18	44	-16	14	Central Opercular Cortex

Conjunction Analysis – Identifying Common Activation Across Contrasts

To pinpoint brain regions that are **consistently activated** during left-hand movement across different sensory modalities, we performed a **conjunction analysis** combining the results of all three contrasts:

- **C1:** Video Left Hand – Video Right Hand
- **C2:** Audio Left Hand – Audio Right Hand
- **C3:** Combined (Audio + Video) Left Hand – Right Hand

This method allows us to isolate voxels that show significant activation **in all three conditions**, ensuring that the observed activations are not specific to just one type of stimulus but are **robust across modalities**.

Command Used for Conjunction Computation:

```
fslmaths cope1.feat/thresh_zstat1 \ -mas cope2.feat/thresh_zstat2 \ -mas cope3.feat/thresh_zstat3 \ conjunction_result
```

This command uses fslmaths to perform a voxel-wise intersection (`-mas`) of the thresholded Z-statistic maps from the three contrasts. The resulting image (`conjunction_result.nii.gz`) contains only those voxels that are commonly significant across all three contrasts, effectively representing regions that are selectively involved in left-hand movement irrespective of stimulus type.

Cluster Detection and Localization:

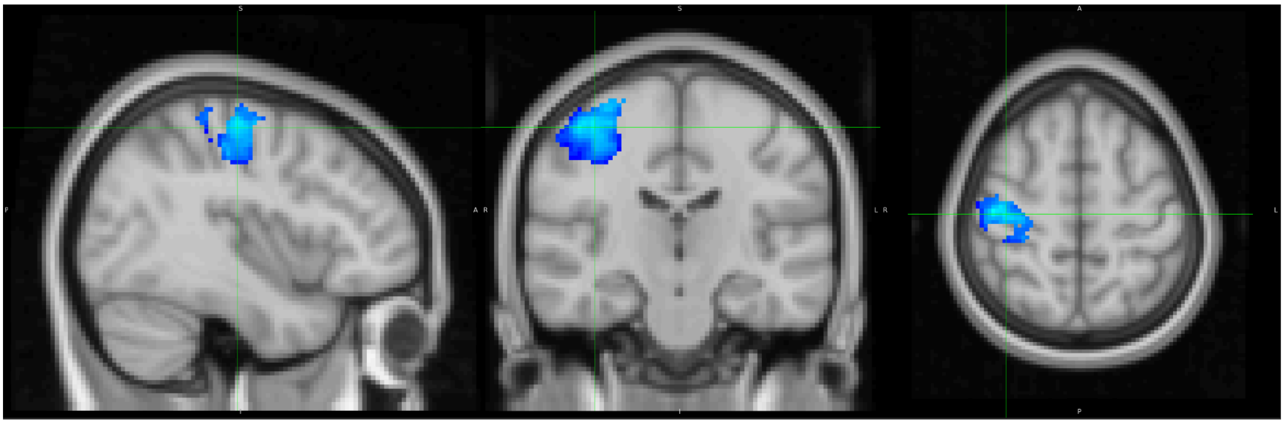
To extract and label the significant clusters from the conjunction result, we applied the FSL `cluster` command with the following parameters:

```
cluster --in=conjunction_result.nii.gz --thresh=2.5 \ --oindex=cluster_index --olmax=local_max
```

- The threshold `Z > 2.5` filters out low-significance voxels.
- `--oindex` outputs a labeled cluster index map.
- `--olmax` reports the **peak activation coordinates (local maxima)** for each cluster.

This step identifies spatially contiguous clusters of voxels showing strong task-related activation across all three contrasts. The output includes:

- Cluster size (voxel count)
- Peak Z-statistics
- Corrected p-values
- MNI coordinates of peak activation
- Anatomical region (e.g., Precentral Gyrus)



Cluster Index	Voxels	Z-Max	P	-log10(P)	X (mm)	Y (mm)	Z (mm)	Brain region
1	1086	5.12	5.64e-09	8.24	28	-21	48	Precentral Gyrus

Discussion of Conjunction Analysis Findings - Left Hand

The conjunction analysis successfully revealed **brain regions that were commonly activated** across all three task conditions related to left-hand movement. Among these, the **most prominent and statistically significant cluster** was located in the **Precentral Gyrus**. This area corresponds to the **primary motor cortex**, which plays a central role in initiating and controlling voluntary motor activity, particularly of the contralateral (right) side of the body — in this case, the **left hand**.

The consistent activation of the Precentral Gyrus across **auditory**, **visual**, and **combined stimuli** highlights its modality-independent involvement in motor function. In other words, regardless of whether the movement was cued by an audio or visual instruction, this region showed strong and reliable engagement, indicating a **core motor execution role**.

Beyond the primary motor cortex, additional regions such as the **Cerebellum** and the **Central Opercular Cortex** were also activated in multiple contrasts. These areas are known to contribute to **motor coordination**, **timing**, and **sensorimotor integration**:

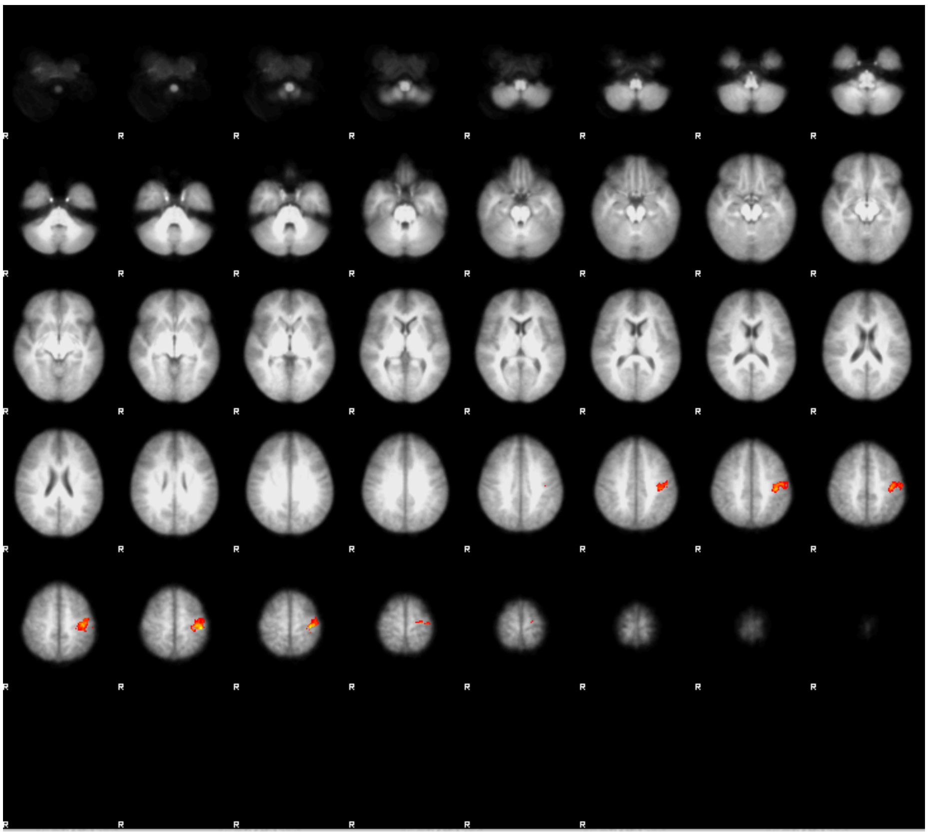
- The **Cerebellum** supports smooth and precise movement execution by integrating sensory input with motor output.

- The **Central Opercular Cortex** is involved in **higher-order motor control** and may play a role in integrating sensory information to guide voluntary movement.

The identification of these regions across multiple contrasts reinforces the idea that **left-hand motor execution is supported by a distributed network** of motor-related brain areas, which work together regardless of the sensory modality guiding the action. This finding demonstrates not only the robustness of the activation but also the **neural redundancy and integration** present in motor control systems.

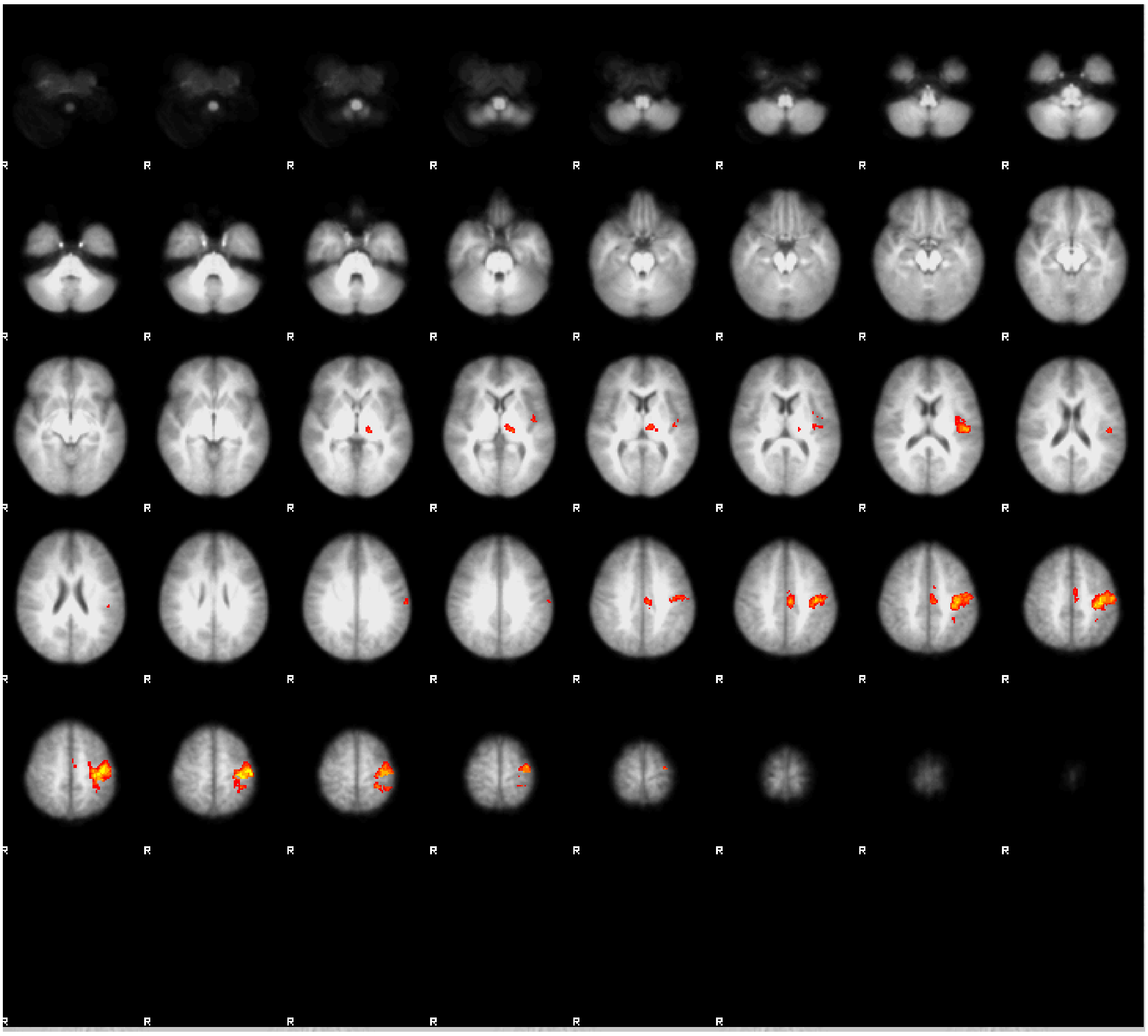
Higher-Level FEAT - RIGHT HAND

C1 - Video Left Motor - Video Right Motor



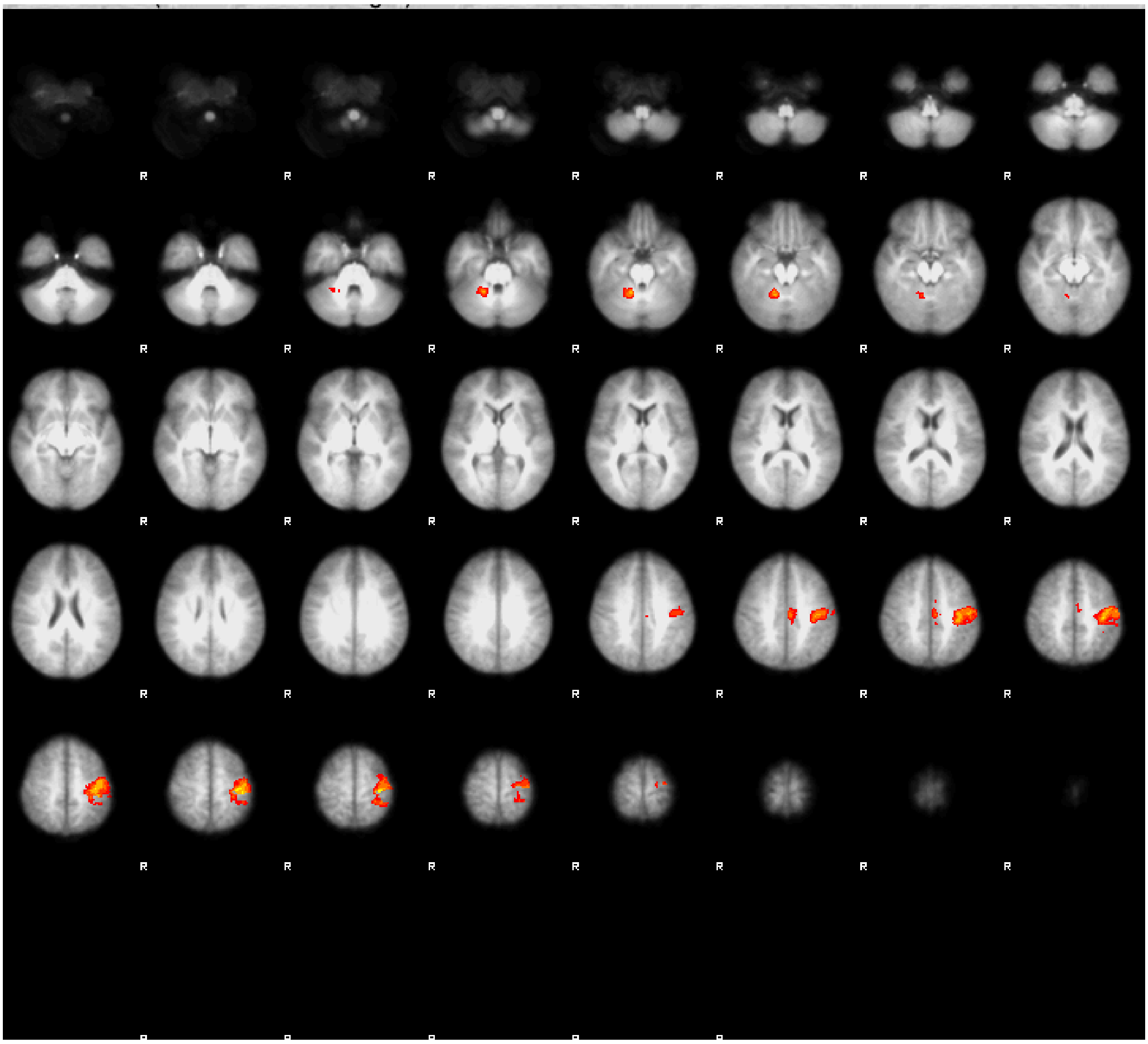
Cluster Index	Voxels	Z-Max	P	-log10 (P)	X (mm)	Y (mm)	Z (mm)	Brain region
1	743	4.97	2.08e-09	8.68	-40	-28	60	Postcentral Gyrus

C2 - Audio Left Motor - Audio Right Motor



Cluster Index	Voxels	P	-log10 (P)	Zmax	X (mm)	Y (mm)	Z (mm)	Brain region
4	1601	1.01e-16	16	4.99	-44	-18	60	Post Central Gyrus
3	261	0.000454	3.34	4.32	-48	-20	16	Central Opercular Cortex
2	240	0.000891	3.05	4.51	-6	-22	42	Cingulate Gyrus
1	135	0.0366	1.44	3.88	-16	-22	2	Left thalamus

C3 - (Video + Audio) Left Motor - (Video + Audio) Right Motor



Cluster Index	Voxels	P	-log10 (P)	Zmax	X (mm)	Y (mm)	Z (mm)	Brain region
3	1858	1.23e-18	17.9	5.56	-32	-24	64	Postcentral Gyrus
2	306	0.000111	3.95	4.78	16	-50	-26	Cerebellum
1	166	0.0112	1.95	4.36	-4	-20	46	Left Cerebral Cortex

Conjunction Analysis – Identifying Overlapping Activation for Right-Hand Movement

To pinpoint brain regions that are consistently engaged during right-hand motor tasks across different sensory conditions, we performed a conjunction analysis across the following three contrasts:

- C1: Video Right Hand – Video Left Hand
- C2: Audio Right Hand – Audio Left Hand
- C3: Combined (Audio + Video) Right Hand – Left Hand

This analysis helps isolate areas of the brain that are selectively activated during right-hand movement, regardless of whether the movement was guided by auditory or visual stimuli. By examining only those voxels that are significantly activated in all three contrasts, we can identify regions of robust, modality-independent motor involvement.

Conjunction Computation Command:

```
fslmaths cope1.feat/thresh_zstat1 \ -mas cope2.feat/thresh_zstat2 \ -mas cope3.feat/thresh_zstat3 \ conjunction_result
```

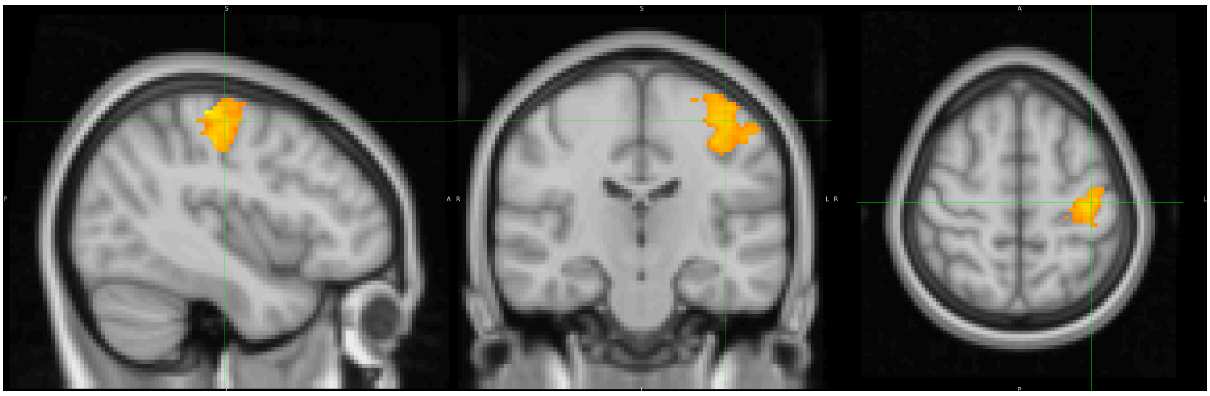
This command utilizes the `-mas` (mask) operation in **FSL's `fslmaths` tool** to compute a voxel-wise intersection of the three thresholded statistical maps. The resulting image (`conjunction_result.nii.gz`) contains only those voxels that exceeded the significance threshold in **all three conditions**, thus representing brain areas with **consistent activation during right-hand movement**.

Cluster Detection and Localization:

After generating the conjunction image, we used the `cluster` **command in FSL** to identify and characterize clusters of significant activation:

```
cluster --in=conjunction_result.nii.gz --thresh=2.5 \ --oindex=cluster_index
--olmax=local_max
```

- The threshold `Z > 2.5` filters out low-significance voxels.
- `--oindex` outputs a labeled cluster index map.
- `--olmax` reports the **peak activation coordinates (local maxima)** for each cluster.



Cluster Index	Voxels	Z-Max	P	-log10(P)	X (mm)	Y (mm)	Z (mm)	Brain region
1	1076	5.11	1.69e-07	6.77	-38	-28	61	Postcentral Gyrus

Discussion of Conjunction Analysis Findings - Right Hand

The conjunction analysis of the three right-hand movement contrasts revealed **consistent and robust activation in the Postcentral Gyrus**, a region widely recognized as the **primary somatosensory cortex**. This finding aligns with its known role in processing **tactile and proprioceptive information**, particularly for the contralateral side of the body — in this case, the **right hand**. Importantly, the Postcentral Gyrus was activated across all three sensory contexts (video, audio, and combined stimuli), indicating that **its involvement in right-hand movement is independent of the type of external cue**.

Beyond the somatosensory cortex, **notable activation was also observed in the Cerebellum and Thalamus**, both of which are critical to **motor control and coordination**:

- The **Cerebellum** plays a key role in **fine-tuning motor actions**, maintaining balance, and ensuring smooth execution of movement. Its consistent engagement suggests it supports both the planning and adjustment of right-hand movement under varying sensory instructions.

- The **Thalamus**, a deep brain structure, acts as a **relay center**, channeling motor and sensory signals between the body and cortex. Its activation likely reflects its function in **integrating sensory feedback during motor execution**.

The analysis also identified **the Central Opercular Cortex and Cingulate Gyrus** as active regions, particularly during auditory-guided movement tasks. These areas are involved in **higher-level motor control**, including:

- **Sensorimotor integration**: combining sensory input with motor commands.

- **Attention and action selection**: especially important when interpreting auditory instructions to initiate movement.

Additionally, activation of the **Superior Frontal Gyrus** suggests the involvement of **motor planning and decision-making processes**. This region is associated with **executive control and voluntary action selection**, which is critical when responding to complex stimuli or preparing for deliberate hand movements.

Collectively, these results indicate that **right-hand movement recruits a distributed and hierarchical network of brain regions**, ranging from primary sensory-motor areas to **subcortical structures and frontal control regions**, all of which coordinate to ensure accurate and timely execution of motor tasks across different sensory contexts.

Part (b) – Language Laterality Index Estimation from fMRI Data

Objective

The purpose of this part is to quantitatively assess **language lateralization** in the human brain using functional MRI (fMRI) data. Specifically, we aim to calculate the **Language Laterality Index (LI)** for each subject, both globally across the whole brain and locally within specific cortical lobes — namely, the **temporal** and **frontal** lobes. These indices provide insight into whether a subject's language processing is **left-dominant**, **right-dominant**, or **bilaterally distributed**.

Theoretical Background

1. Understanding Language Lateralization

Language processing in the brain is not always symmetrically distributed. For most individuals (especially right-handed), language functions such as comprehension and production are primarily managed by the **left hemisphere**. However, in some individuals (e.g., left-handed or neurologically diverse populations), these functions may be right-lateralized or bilaterally represented.

To study this phenomenon, we compute the **Language Laterality Index (LI)** using the formula:

$LI=(L-R)/(L+R)$

where:

- L = Number of language-related voxels activated in the **left hemisphere**
- R = Number of language-related voxels activated in the **right hemisphere**

The LI value ranges from -1 to +1:

- LI ≈ +1 → Strong **left** hemisphere dominance
- LI ≈ -1 → Strong **right** hemisphere dominance
- LI ≈ 0 → **Bilateral** language processing

2. Region-Specific Laterality Indices

To obtain a more detailed view, we compute LIs at different anatomical levels:

- **Full Brain LI**: Considers all activated language voxels across the entire cortex.
- **Temporal Lobe LI**: Focuses on areas like **Wernicke's area**, important for language comprehension.
- **Frontal Lobe LI**: Captures activity in regions like **Broca's area**, associated with language production and planning.

Methodology

a. Language Localization using fMRI Contrasts

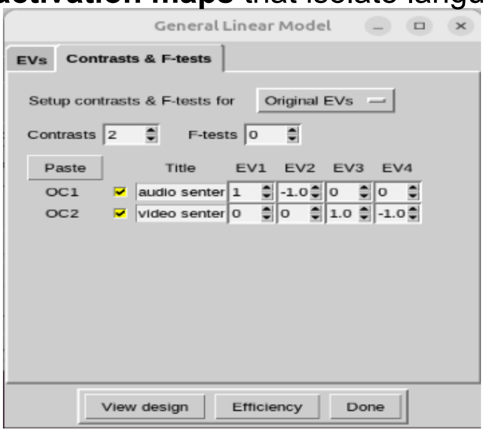
To isolate brain regions involved in language processing, the following **contrasts** were defined and applied, derived from Assignment 2:

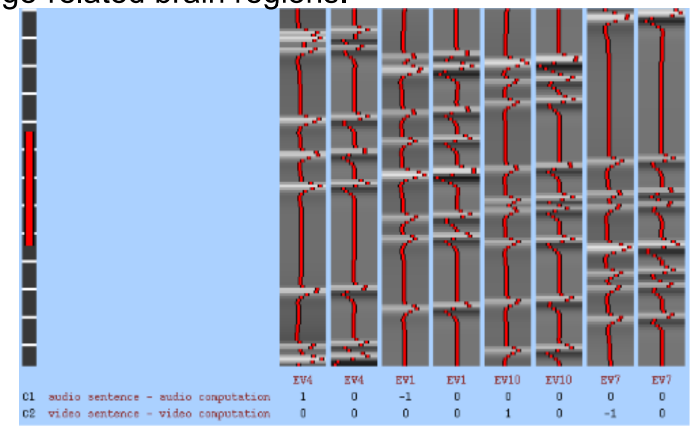
1. **Audio Sentence Processing – Audio Computation**
 Contrast=EV4−EV1 Isolates language-specific processing from general auditory activity.

2. **Video Sentence Processing – Video Computation**
 Contrast=EV10−EV7
 Removes visual and non-linguistic processing to capture language comprehension from video stimuli.

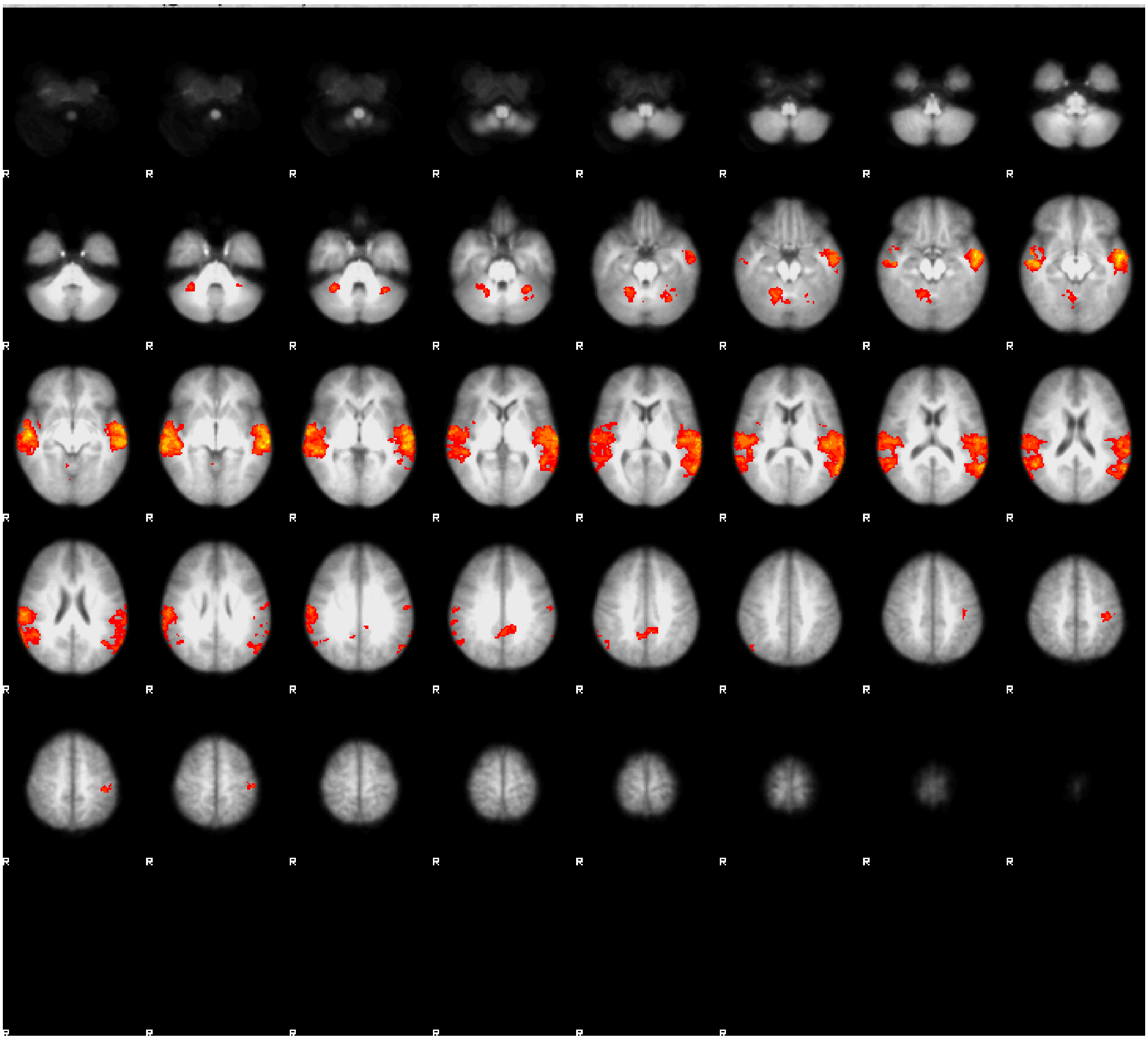
3. **Conjunction of Audio and Video Sentence Contrasts**
 Contrast=(EV4−EV1)∩(EV10−EV7)
 Identifies **common language areas across modalities**, increasing specificity to language functions.

Each subject's fMRI data was analyzed using these contrasts to produce **binarized activation maps** that isolate language-related brain regions.



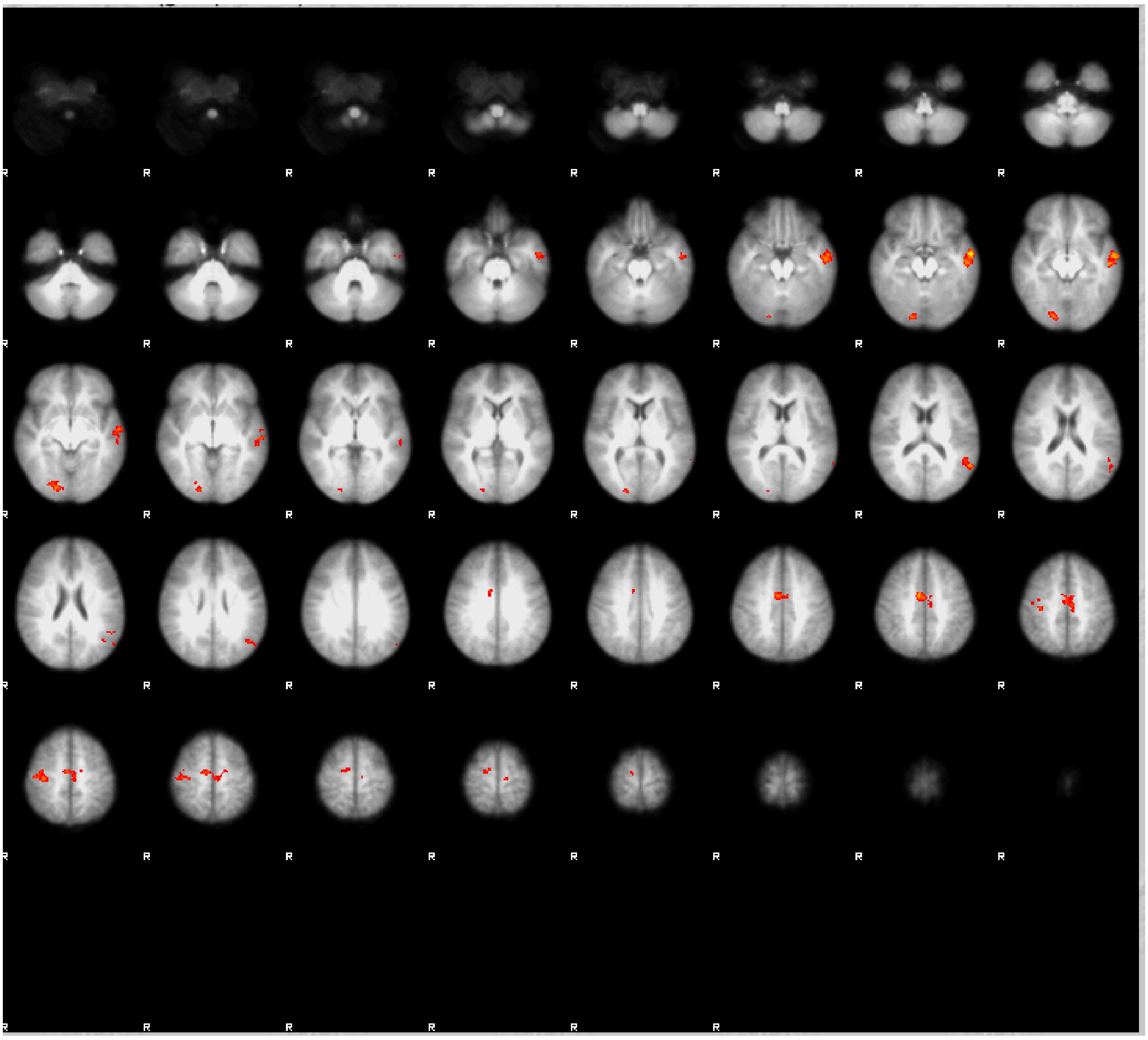


C1 (Audio Sentence - Audio Computation)



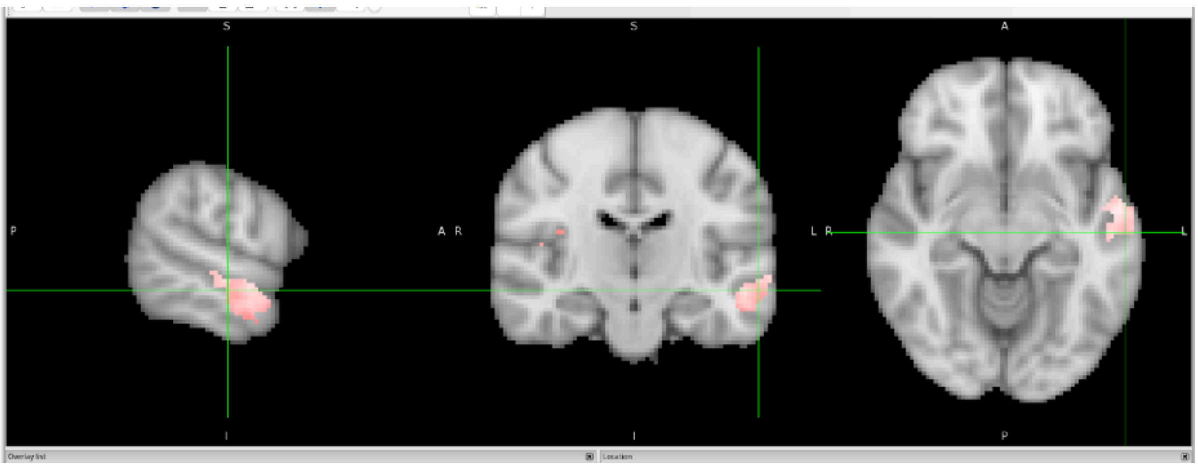
Cluster Index	Voxels	P	-log10(P)	Z-MAX	Z-MAX X (mm)	Z-MAX Y (mm)	Z-MAX Z (mm)	Z-COG X (mm)	Z-COG Y (mm)	Z-COG Z (mm)
6	6203	3.47e-37	36.5	6.1	-54	-6	-14	-56.1	-29.6	5.3
5	5588	1.33e-34	33.9	5.65	56	-14	-8	57.3	-28.8	8.9
4	652	2.38e-07	6.62	4.24	24	-50	-24	19	-53.5	-22.2
3	268	0.00164	2.78	4.1	-30	-60	-26	-28.9	-53.3	-27
2	254	0.0024	2.62	3.98	-2	-46	38	-3.37	-46.7	37.4
1	164	0.0337	1.47	3.66	-38	-28	54	-40.3	-26.2	53.9

C2 (Video Sentence - Video Computation)



Cluster Index	Voxels	P	-log10(P)	Z-MAX	Z-MAX X (mm)	Z-MAX Y (mm)	Z-MAX Z (mm)	Z-COG X (mm)	Z-COG Y (mm)	Z-COG Z (mm)
5	544	6.56e-07	6.18	4.52	-58	-6	-14	-56.9	-12.6	-14.9
4	514	1.37e-06	5.86	3.86	8	-4	48	1.79	-11.5	53.3
3	222	0.00318	2.5	3.76	18	-86	-18	18.6	-85.2	-8.01
2	183	0.011	1.96	3.63	34	-22	56	38	-18.5	56.2
1	163	0.0216	1.67	4.02	-58	-58	16	-53	-58.2	19.8

Conjunction of C1 and C2



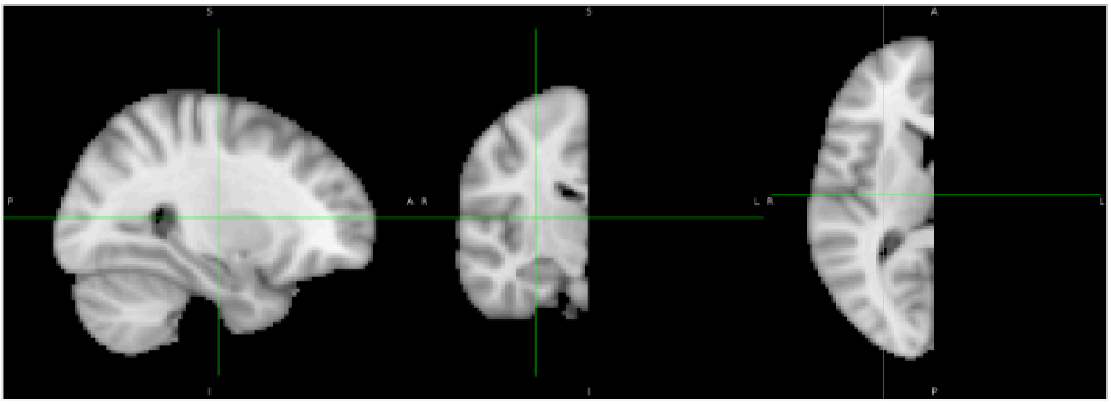
Mask Creation for Region-Based Analysis

To enable region-specific voxel counting, we generated **binary masks** for each anatomical region using FSL tools:

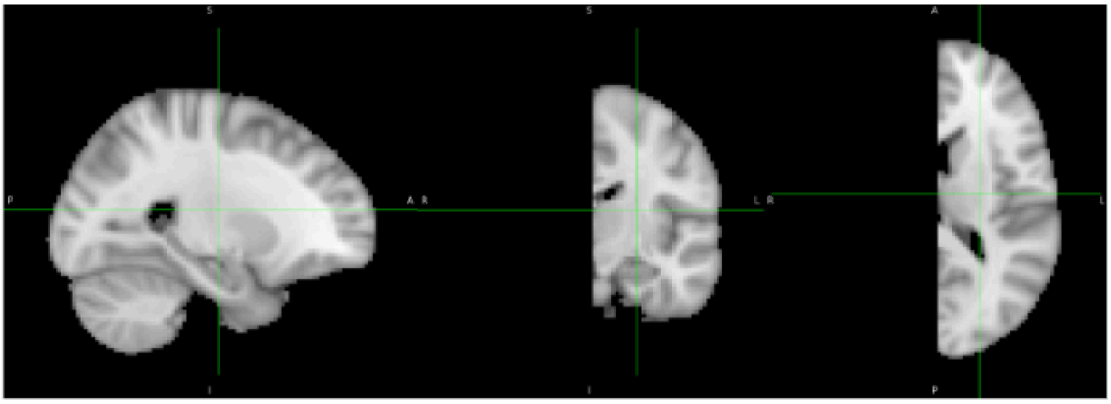
- **Hemispheric Masks**:
  - The **left hemisphere mask** was created by selecting the left half of the MNI brain template.
  - The **right hemisphere mask** was similarly derived for the right half.
- **Lobar Masks**:
  - The **temporal and frontal lobe masks** were extracted from the **Harvard-Oxford cortical atlas** by thresholding specific label indices corresponding to these regions.
- **Combined Regional Masks**:
  These masks were then combined using voxel-wise multiplication:
  - `temporal_mask_L = temporal_mask * lh_mask`
  - `temporal_mask_R = temporal_mask * rh_mask`
  - `frontal_mask_L = frontal_mask * lh_mask`
  - `frontal_mask_R = frontal_mask * rh_mask`

These composite masks allowed for **precise voxel counting** of activated regions specific to both hemisphere and lobe, forming the foundation for accurate LI computation across subjects.

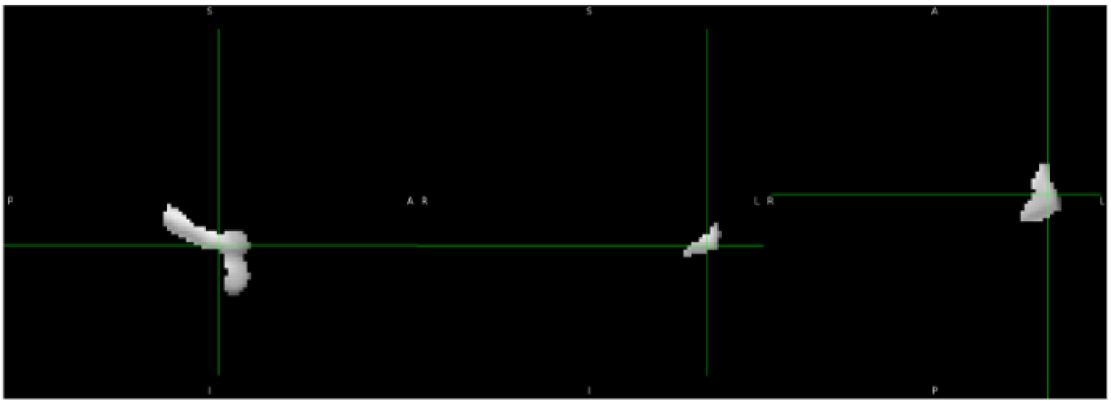
Right hemisphere:



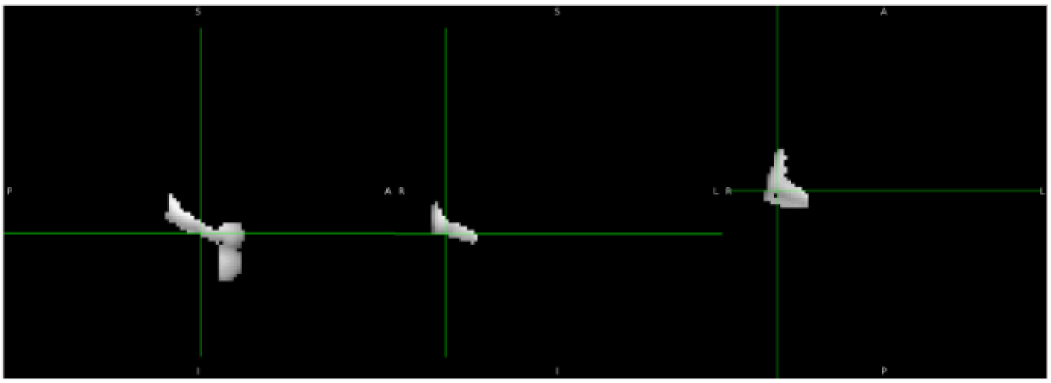
Left Hemisphere



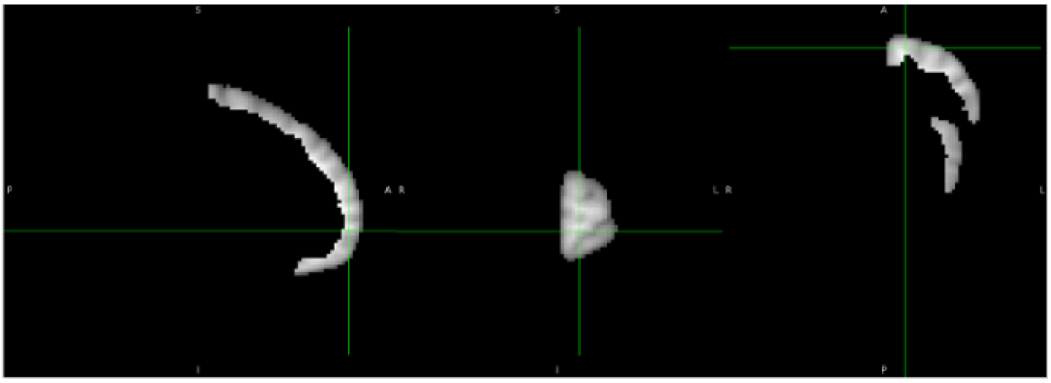
Left hemisphere of temporal lobe



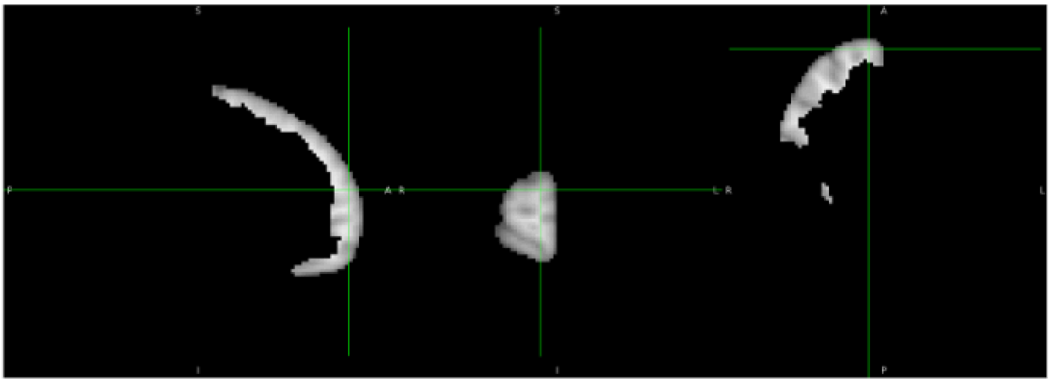
Right Hemisphere of Temporal Lobe



Left Hemisphere of frontal lobe



Right Hemisphere of Frontal Lobe



Mask Generation and Subject-Level Laterality Index Computation

To accurately quantify the lateralization of language processing in specific brain regions, it was necessary to generate **binary masks** corresponding to anatomical boundaries within the brain. These masks were used to **isolate activated voxels** within each hemisphere and within the temporal and frontal lobes, enabling **region-specific Laterality Index (LI)** calculations.

1. Hemispheric Masks

To distinguish between the left and right hemispheres of the brain, spatially-separated masks were created using the standard **MNI152_T1_2mm brain template** available in FSL. The brain volume was divided along the midline using the `-roi` (region of interest) option in `fslmaths`:

Left Hemisphere Mask:

```
fslmaths $FSLDIR/data/standard/MNI152_T1_2mm_brain.nii.gz \
    -roi 0 45 0 -1 0 -1 0 -1 lh_mask.nii.gz
```

This selects voxels from the left half (x = 0 to 45) of the brain.

- **Right Hemisphere Mask:**

```
fslmaths $FSLDIR/data/standard/MNI152_T1_2mm_brain.nii.gz \
    -roi 46 45 0 -1 0 -1 0 -1 rh_mask.nii.gz
```

This selects the right half (x = 46 to end) of the brain volume.

2. Temporal and Frontal Lobe Masks

To restrict analysis to **functionally relevant lobes**, masks for the **temporal** and **frontal** regions were extracted using the **Harvard-Oxford cortical atlas**. This was achieved by thresholding label indices corresponding to each lobe:

- **Temporal Lobe Mask:**

```
fslmaths
$FSLDIR/data/atlases/HarvardOxford/HarvardOxford-cort-maxprob-thr25-2mm.nii.gz
-thr 9 -uthr 11 -bin temporal_mask.nii.gz
```

This isolates structures labeled as part of the temporal cortex.

- **Frontal Lobe Mask:**

fslmaths
$FSLDIR/data/atlases/HarvardOxford/HarvardOxford-cort-maxprob-thr25-2mm.nii.gz
\ -thr 1 -uthr 6 -bin frontal_mask.nii.gz

This extracts the frontal lobe regions.

3. Hemisphere-Specific Lobar Masks

To further refine analysis, each lobe mask was combined with the left and right hemisphere masks using voxel-wise multiplication:

- **Left Hemisphere Masks:**

fslmaths temporal_mask.nii.gz -mul lh_mask.nii.gz temporal_mask_L.nii.gz
fslmaths frontal_mask.nii.gz -mul lh_mask.nii.gz frontal_mask_L.nii.gz

Right Hemisphere Masks:
fslmaths temporal_mask.nii.gz -mul rh_mask.nii.gz temporal_mask_R.nii.gz
fslmaths frontal_mask.nii.gz -mul rh_mask.nii.gz frontal_mask_R.nii.gz

These resulting masks were used to precisely quantify the number of active voxels restricted to both anatomical and hemispheric boundaries.

The complete code and table of L,R,Li of brain region, temporal and frontal can be found in the link here
Untitled7.ipynb

Subject ID	L	R	LI	L_temporal	R_temporal	LI_temporal	L_frontal	R_frontal	LI_frontal
S01	537	0	1.0000	0	0	0	11	0	1.0000
S02	0	430	-1.0000	0	307	-1.0000	0	0	
S03	0	0	nan	0	0	0	0	0	
S04	0	0	nan	0	0	0	0	0	
S05	0	0	nan	0	0	0	0	0	
S06	0	763	-1.0000	0	205	-1.0000	0	0	
S07	0	787	-1.0000	0	0	0	0	0	
S08	0	0	nan	0	0	0	0	0	
S09	335	236	0.1734	0	0	0	266	235	0.0619
S10	243	3259	-0.8612	0	576	-1.0000	45	539	-0.8459
S11	0	0	nan	0	0	0	0	0	
S12	0	0	nan	0	0	0	0	0	
S13	0	2378	-1.0000	0	0	0	0	997	-1.0000
S14	246	0	1.0000	68	0	1.0000	0	0	
S16	649	629	0.0156	0	0	0	0	0	
S17	0	0	nan	0	0	0	0	0	
S18	0	0	nan	0	0	0	0	0	
S19	2541	687	0.5743	0	0	0	133	185	-0.1635
S20	0	0	nan	0	0	0	0	0	
S21	0	3111	-1.0000	0	0	0	0	715	-1.0000
S22	53	486	-0.8033	0	0	0	0	0	
S23	344	2670	-0.7717	0	0	0	0	0	
S24	0	0	nan	0	0	0	0	0	
S25	78	1214	-0.8793	0	0	0	0	0	
S27	0	0	nan	0	0	0	0	0	
S28	0	0	nan	0	0	0	0	0	
S29	3011	718	0.6149	170	159	0.0334	24	0	1.0000

S30	0	0	nan	0	0	0	0	0	
S31	0	0	nan	0	0	0	0	0	
S32	0	0	nan	0	0	0	0	0	

Interpretation of Language Laterality Index (LI) Results

1. Full Brain Laterality Index (LI)

The **Full Brain LI** measures overall hemispheric dominance for language processing across the entire cortex.

- **Strong Left-Lateralized Subjects**
  Subjects like **S01**, **S14**, and **S29** have **LI values ≥ 0.6**, indicating strong **left-hemispheric dominance**, which aligns with classical language organization, especially in right-handed individuals.

- **Strong Right-Lateralized Subjects**
  Subjects such as **S02, S06, S07, S10, S13, S21, S22, S23, S25** show **LI values near -1.0000**, indicating that **language activity is dominantly right-hemispheric**. While atypical, such patterns can occur in left-handed individuals, or due to neural reorganization from early life experiences.

- **Bilateral or Weakly Lateralized Subjects**
  Subjects like **S09 (LI = 0.1734)** and **S16 (LI = 0.0156)** exhibit **near-zero LI**, suggesting **bilateral language representation**, meaning both hemispheres contribute roughly equally to language tasks.

- **Subjects with NaN LI**
  Many subjects (e.g., **S03, S04, S05, S08, S11, S12, S17, S18, S20, S24, S27, S28, S30–S32**) showed **no significant activation** under the contrast used. This might result from:

  - Lack of engagement during the task

  - Weak language-related signals

  - Misalignment in data or poor preprocessing

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2. Temporal Lobe Laterality Index (Temporal LI)

The **Temporal Lobe LI** isolates laterality specifically in the temporal regions responsible for **language comprehension**, such as **Wernicke's area**.

- **Strong Left Temporal Dominance**
  Only **S14** shows **clear left-lateralization (LI = 1.0000)** in the temporal lobe, indicating textbook **left-dominant comprehension**.

- **Strong Right Temporal Dominance**
  Subjects like **S02, S06, S10** exhibit **LI = -1.0000**, implying their **right temporal lobe** is more engaged in language tasks—a rare but documented phenomenon.

- **Bilateral or Mild Dominance**
  S29 shows **very weak laterality (LI = 0.0334)**, indicating **bilateral activation** in the temporal lobe.

- **Missing Values (NaN or 0 values)**
  Most subjects showed **no significant activation** in temporal lobes (either L=0, R=0, or both), making the LI undefined. This is likely because the task contrast used emphasized **sentence comprehension** without strongly isolating **temporal lobe activation** in many subjects.

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3. Frontal Lobe Laterality Index (Frontal LI)

Frontal LI targets areas like **Broca's area**, essential for **language production** and **motor planning** related to speech.

- **Strong Left Frontal Activation**
  S01 (LI = 1.0000) shows classic **left-dominant frontal activation**, matching traditional expectations for language production.

- **Strong Right Frontal Activation**
  Subjects like **S10 (LI = -0.8459)** and **S13 (LI = -1.0000)** exhibit **dominant right-hemispheric frontal activity**, which is less common and may point to **alternative neural strategies** or **developmental reorganization**.

- **Bilateral Activation**
  S09 (LI = 0.0619) shows **mild bilateral activation**, reflecting a more **even contribution from both frontal lobes**.

- **Subjects with No Activation in Frontal Lobe**
  The majority of subjects had **zero or missing values**, meaning that the **frontal lobe did not show significant activation** under the selected contrast. This is expected, as the task may have been more focused on **comprehension rather than production**, which limits frontal involvement.