EEG Analysis of Motor Execution vs. Imagery: Neural Patterns and Dynamics

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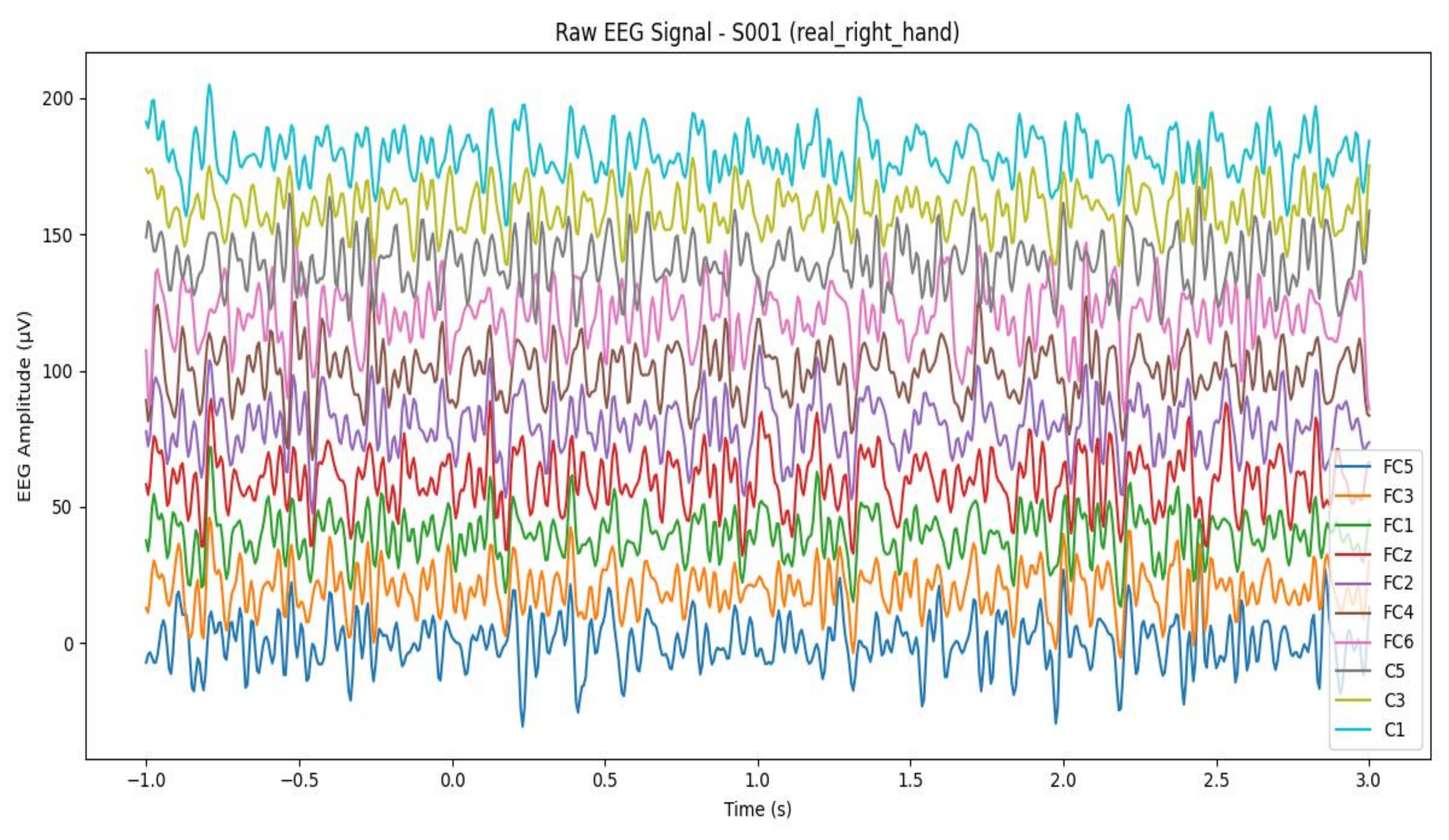
Introduction

- How similar are the neural patterns of real movement and imagined movement?
- Using the PhysioNet EEG Motor Movement/Imagery Dataset
- Prior research suggests they are similar
- Applying multiple techniques to verify this

Data Analysis and Preprocessing

Raw EEG Signal



Preprocessing Pipeline

- Bandpass Filtering (6–30 Hz)
- ICA (Automatic or Manual)
- Extract and Concatenate the Epochs

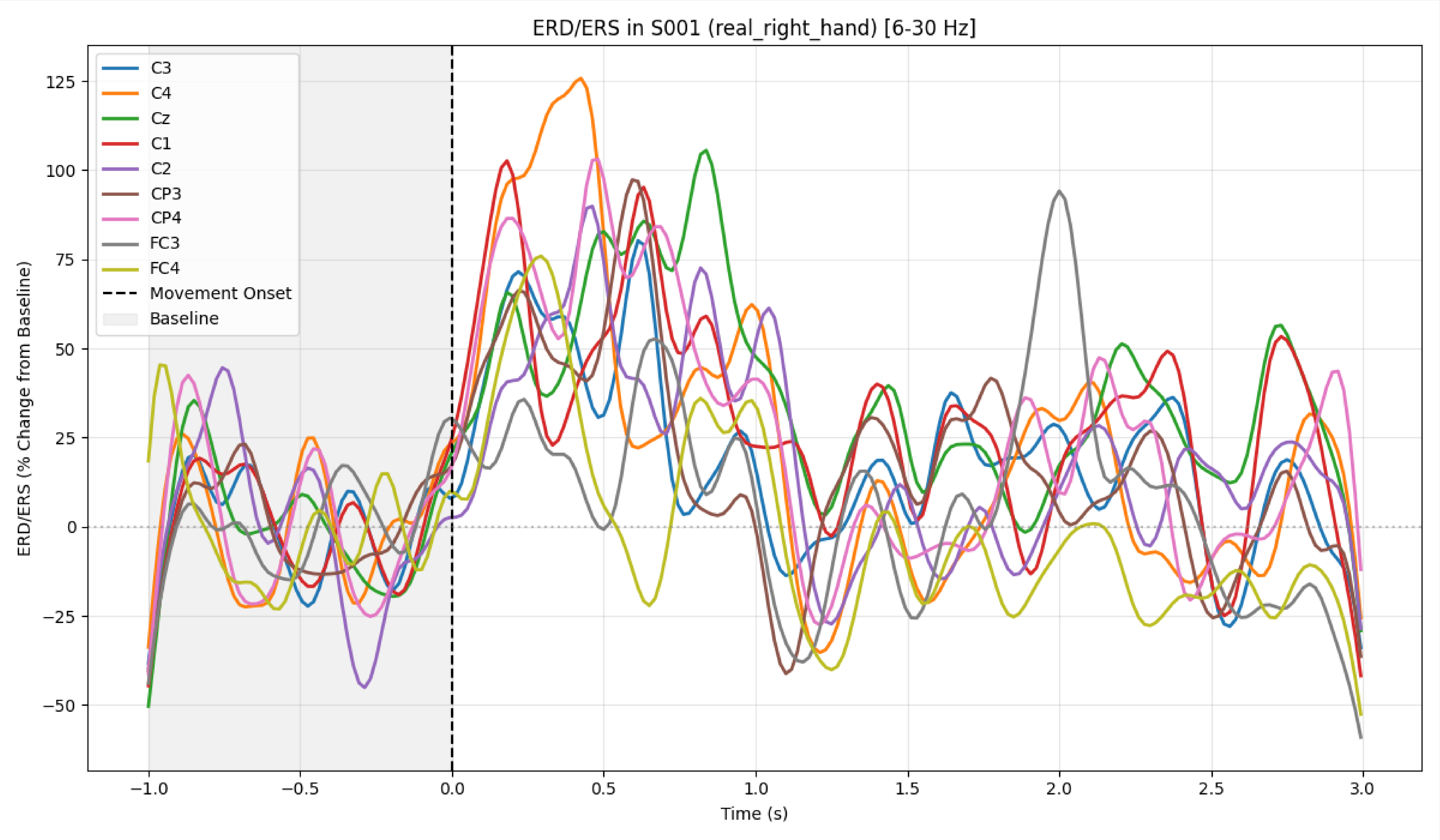
```python
def process_eeg_automatic(subjects, data_path, apply_ica=False, bandpass=(6, 30),
    # Define selected runs for each condition
    selected_runs = {
        "real_right_hand": [3, 7, 11],
        "imagined_right_hand": [4, 8, 12]
    }

    for subject in subjects:
        print(f"\n🔄 Processing {subject}...")
        data_dict[subject] = {"real_right_hand": [], "imagined_right_hand": [], "rest": []}

        for condition, run_numbers in selected_runs.items():
            for run_number in run_numbers:
                run = f"R{str(run_number).zfill(2)}"
                edf_file = os.path.join(data_path, subject, f"{subject}{run}.edf")

                try:
                    # Load raw data
                    raw = mne.io.read_raw_edf(edf_file, preload=True)

                    # Standardize channel names and set montage
                    mne.datasets.eegbci.standardize(raw)
                    montage = mne.channels.make_standard_montage("standard_1005")
                    raw.set_montage(montage)
                    raw.set_eeg_reference("average", projection=True)
                    raw.filter(bandpass[0], bandpass[1], fir_design="firwin")

                    # Apply ICA for artifact removal if requested
                    if apply_ica:
                        raw_clean = _apply_ica(raw, n_ica_components, subject, run)
                    else:
                        raw_clean = raw

                    # Extract epochs for Right Hand and Rest conditions
                    events, event_id = mne.events_from_annotations(raw_clean)
                    if len(events) == 0:
                        print(f"⚠️ No events found for {subject} - {run}, skipping...")
                        continue

                    # Extract "Right Hand" epochs (T2)
                    if "T2" in event_id:
                        epochs = mne.Epochs(
                            raw_clean, events, event_id={"Right Hand": event_id["T2"]},
                            tmin=tmin, tmax=tmax, baseline=(None, 0), preload=True
                        )
                        data_dict[subject][condition].append(epochs["Right Hand"])
                        print(f"✅ Extracted {len(epochs['Right Hand'])} epochs for {subject} - {run} ({condition})")
```

ICA Artifacts

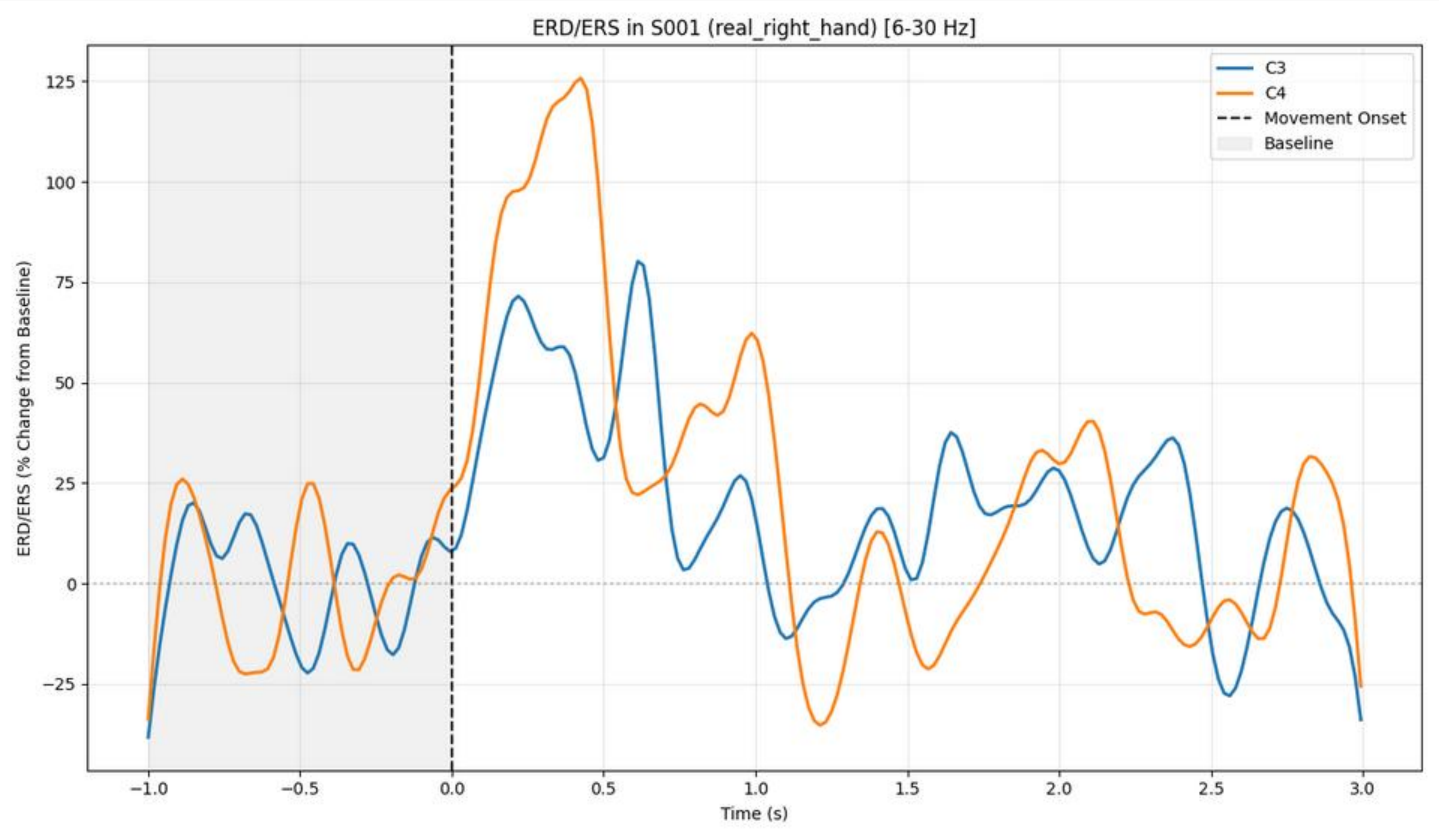
- Find bad EOG
- Find bad ECG
- Find Muscle Artifacts

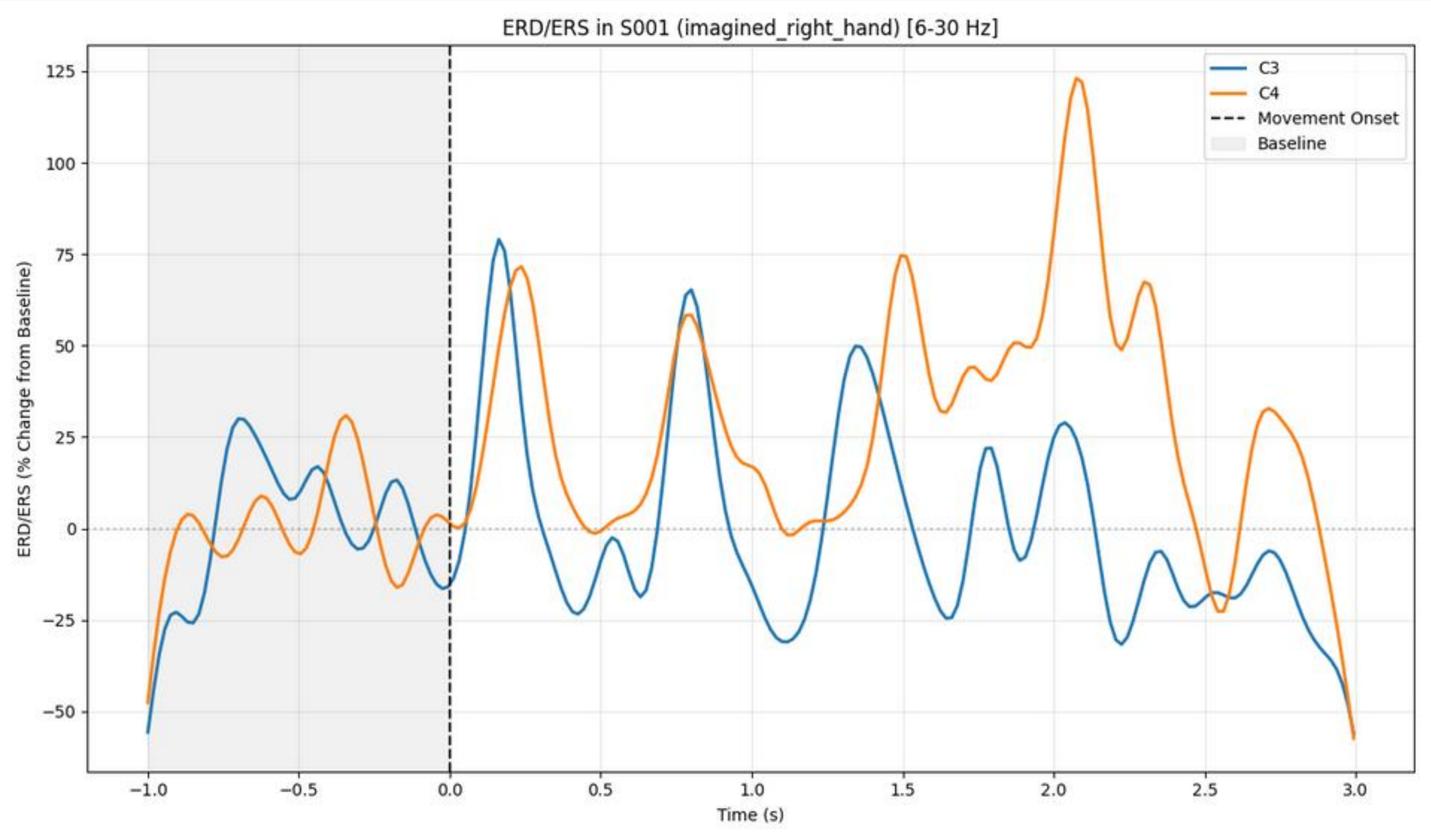
```python
def _fit_ica(raw, n_components, subject, run):
    """Helper function to fit ICA and detect artifacts"""
    ica = ICA(n_components=n_components, random_state=42, method="fastica", max_iter=500)
    ica.fit(raw)

    # EOG artifact detection
    eog_indices = []
    frontal_channels = [ch for ch in raw.ch_names
                        if ch.lower().startswith(('fp', 'f'))
                        and not ch.lower().startswith(('fc', 'ft'))][:2]

    if frontal_channels:
        eog_indices, _ = ica.find_bads_eog(raw, ch_name=frontal_channels)
    eog_indices = eog_indices[:2] if len(eog_indices) > 2 else eog_indices

    # ECG artifact detection using kurtosis
    ica_sources = ica.get_sources(raw).get_data()
    kurtosis_values = stats.kurtosis(ica_sources, axis=1)

    # Z-score kurtosis values
    kurt_z = (kurtosis_values - np.median(kurtosis_values)) / (
        np.median(np.abs(kurtosis_values - np.median(kurtosis_values))) + 1e-6
    )
    ecg_indices = np.where(kurt_z > 2.5)[0].tolist()[:2]

    # Muscle artifact detection
    muscle_indices, _ = ica.find_bads_muscle(raw, threshold=0.5, l_freq=7, h_freq=45)

    # Combine artifacts
    all_artifact_indices = list(set(eog_indices + ecg_indices + muscle_indices))
    ica.exclude = all_artifact_indices
    print(f"⚠️ Detected {len(ica.exclude)} artifact components: {ica.exclude}")

    return ica
```

Event-Related Des/Synchronization



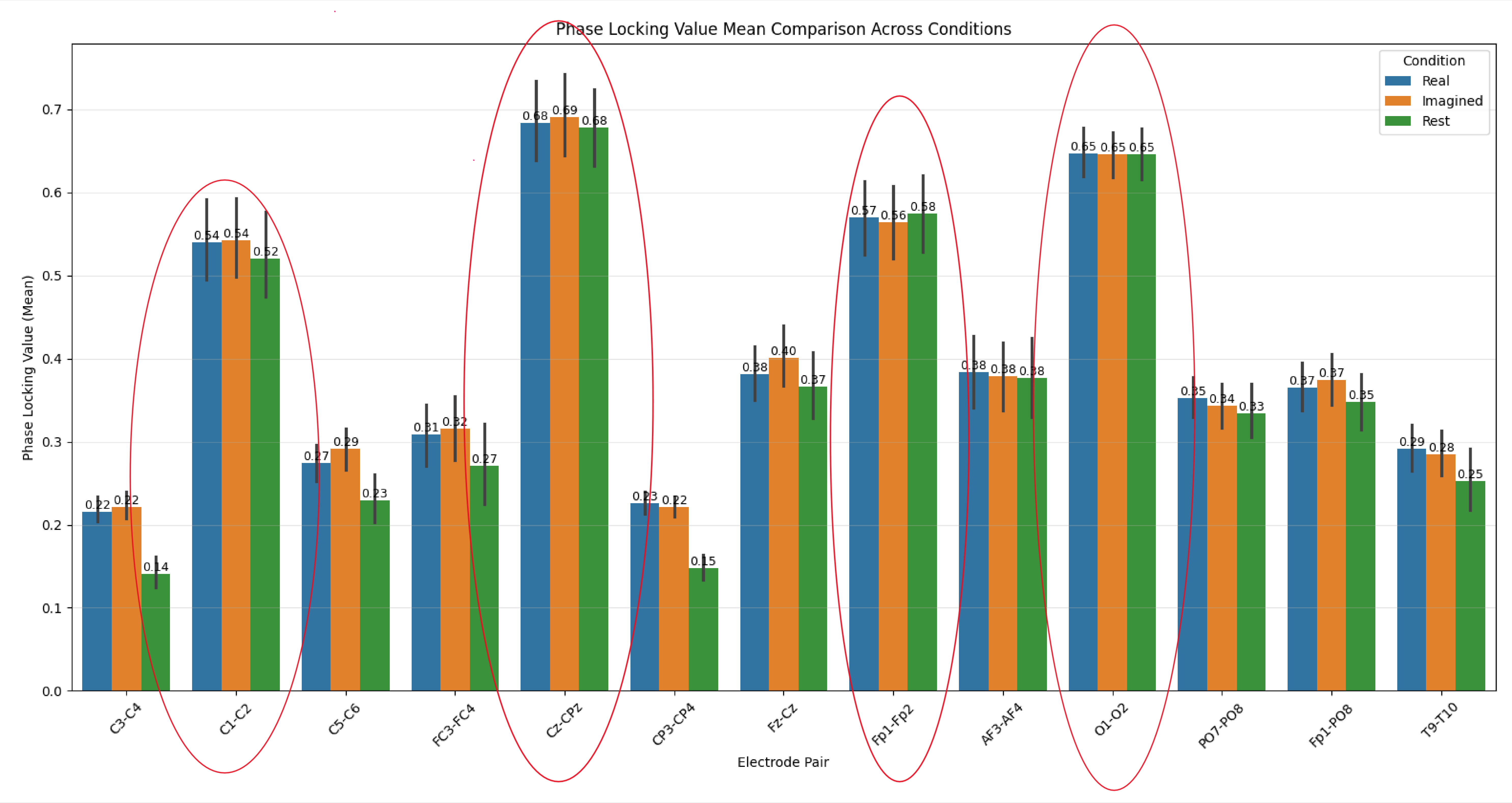
ERD/ERS in Real and Imagined Movement

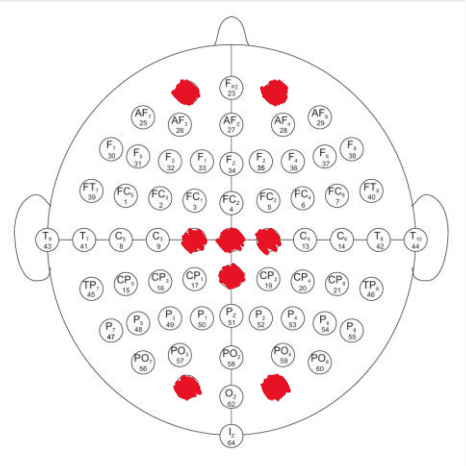




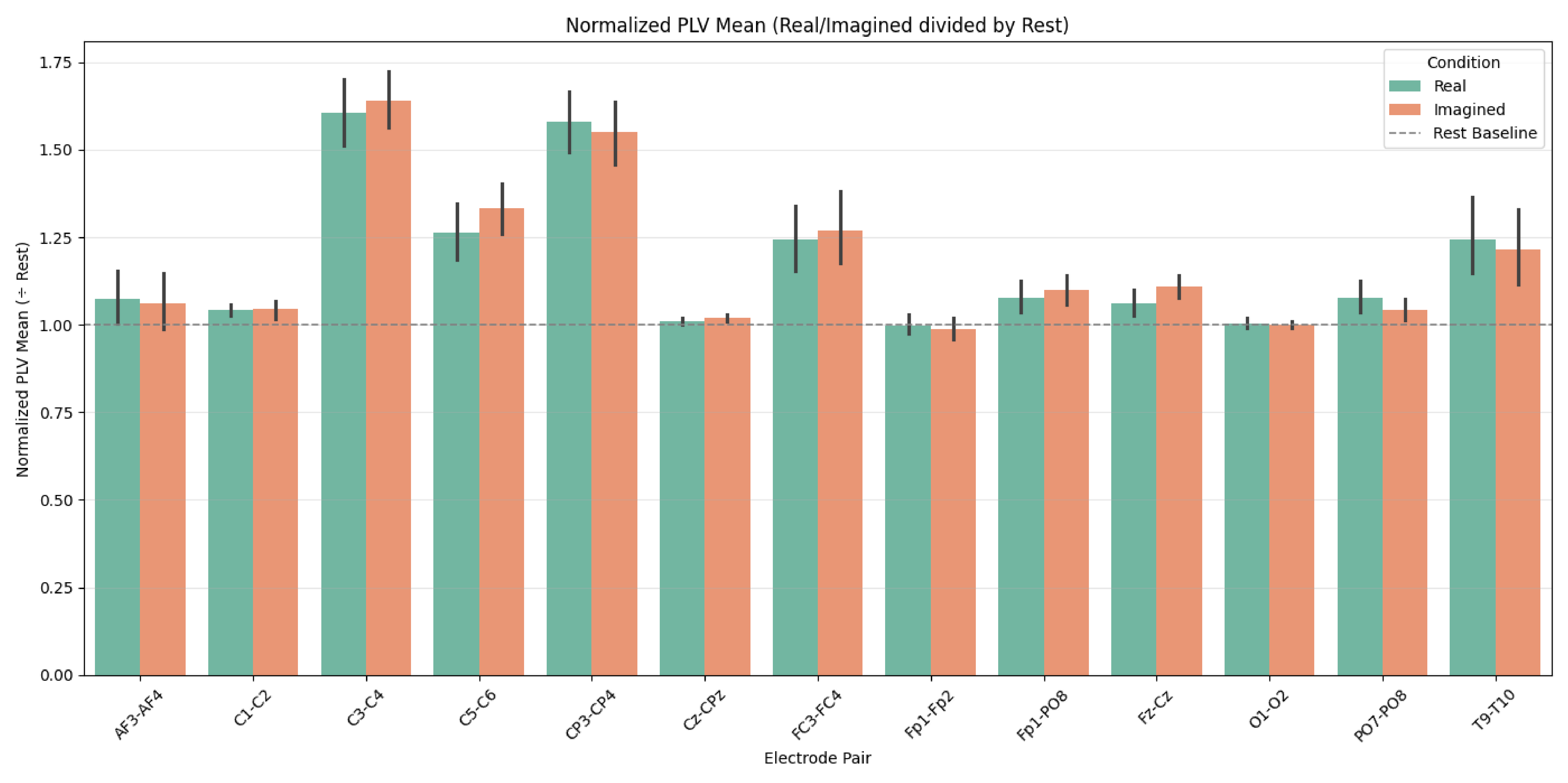
Connectivity Metrics

PLV Mean

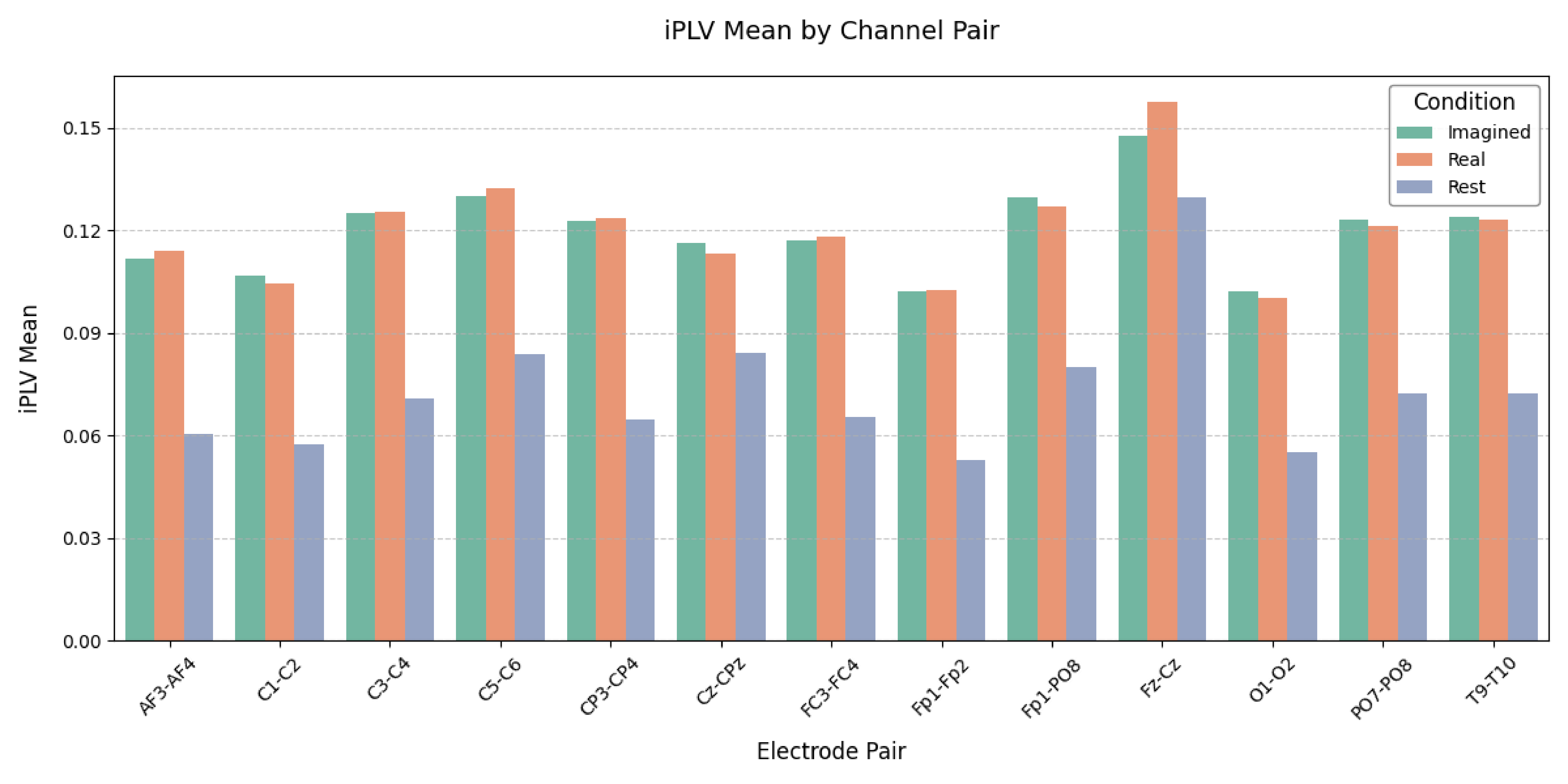

Phase Locking Value Mean Comparison Across Conditions
Phase Locking Value (Mean)
Electrode Pair
Condition
Real
Imagined
Rest
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.22 0.22 0.14
0.54 0.54 0.52
0.27 0.29 0.23
0.31 0.32 0.27
0.68 0.69 0.68
0.23 0.22 0.15
0.38 0.40 0.37
0.57 0.56 0.58
0.38 0.38 0.38
0.65 0.65 0.65
0.35 0.34 0.33
0.37 0.37 0.35
0.29 0.28 0.25
C3-C4
C1-C2
C5-C6
FC3-FC4
Cz-CPz
CP3-CP4
Fz-Cz
Fp1-Fp2
AF3-AF4
O1-O2
PO7-PO8
Fp1-PO8
T9-T10

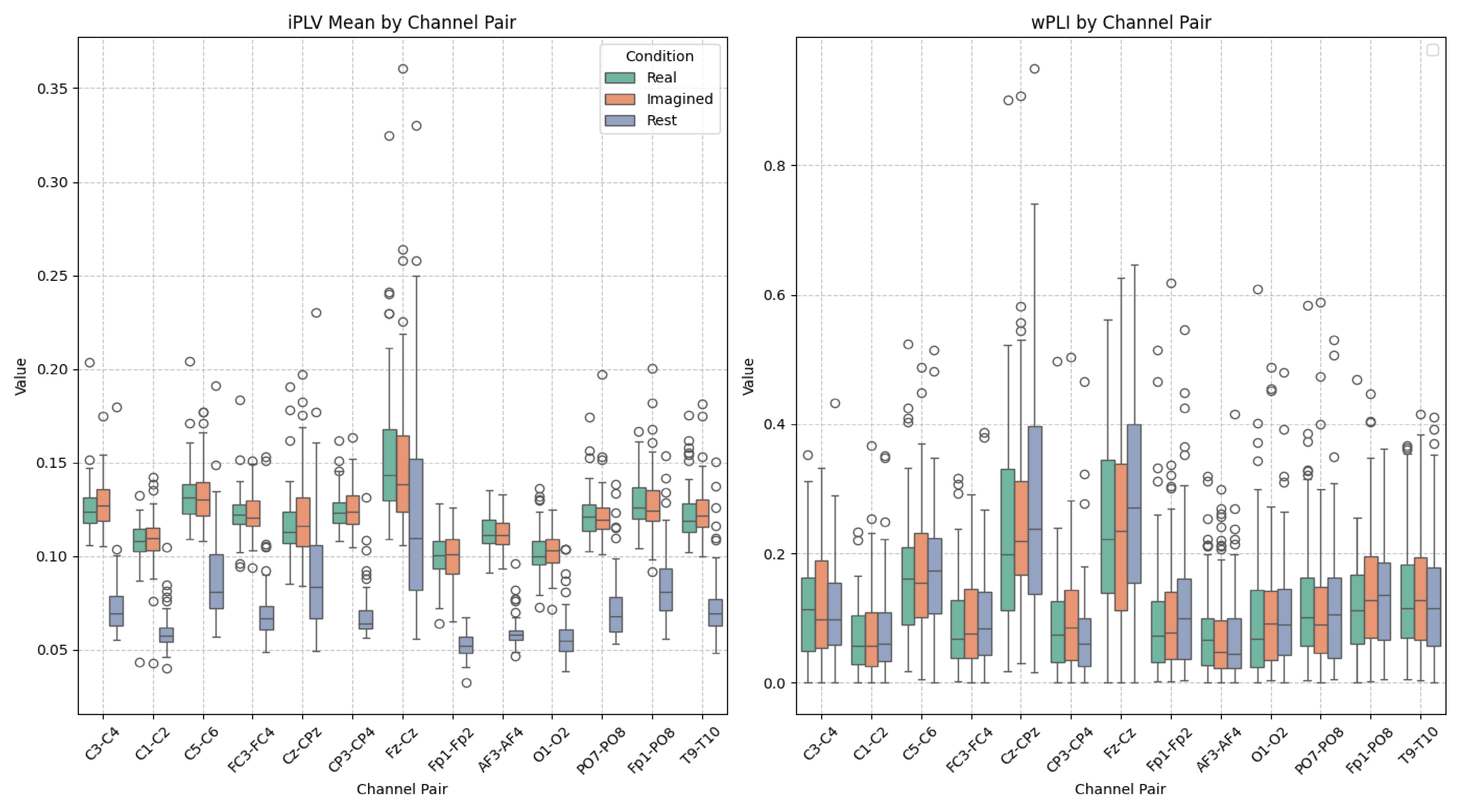


Normalized PLV Mean



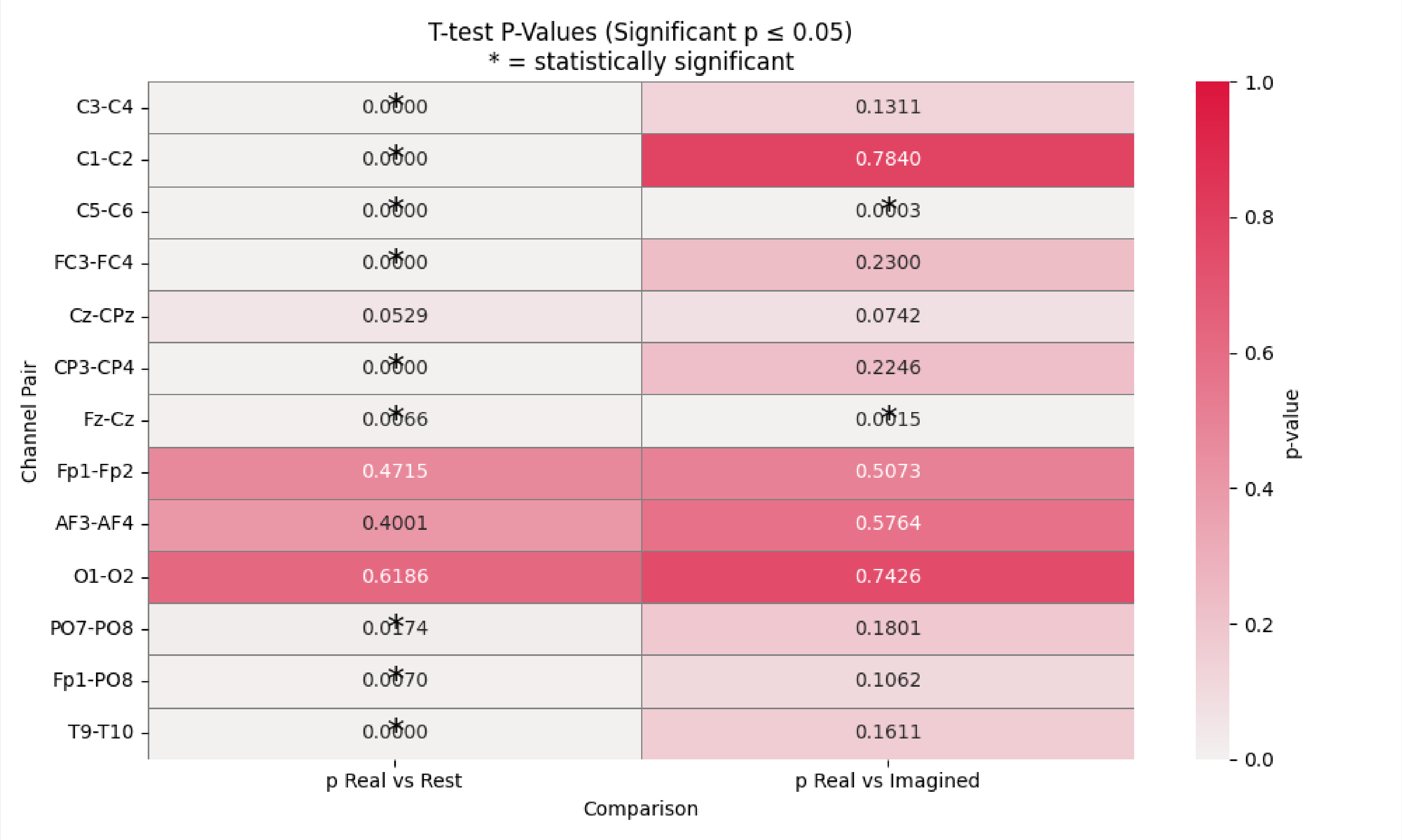
iPLV Mean

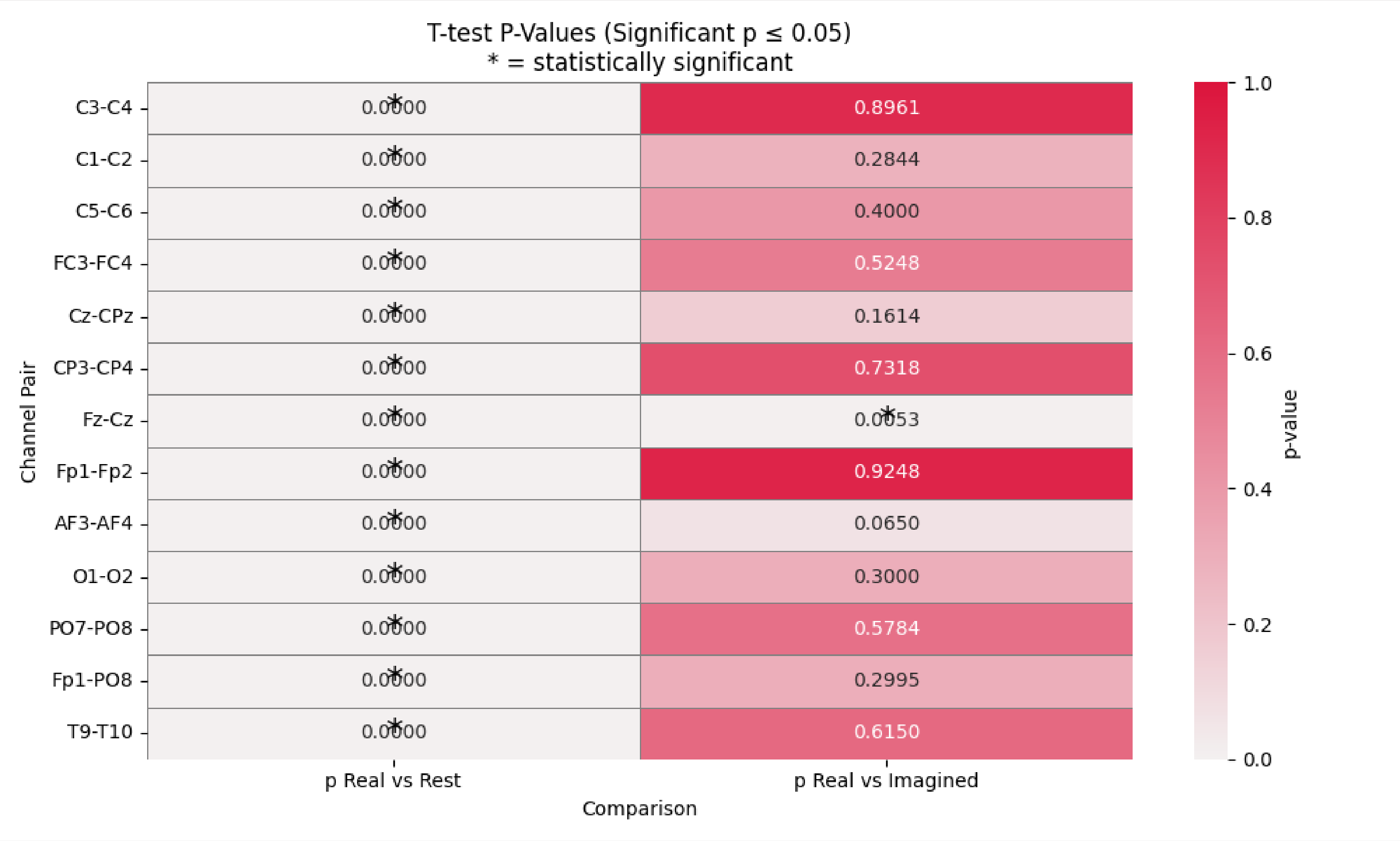

iPLV Mean by Channel Pair
Condition
Imagined
Real
Rest
iPLV Mean
0.00
0.03
0.06
0.09
0.12
0.15
AF3-AF4
C1-C2
C3-C4
C5-C6
CP3-CP4
Cz-CPz
FC3-FC4
Fp1-Fp2
Fp1-PO8
Fz-Cz
O1-O2
PO7-PO8
T9-T10
Electrode Pair



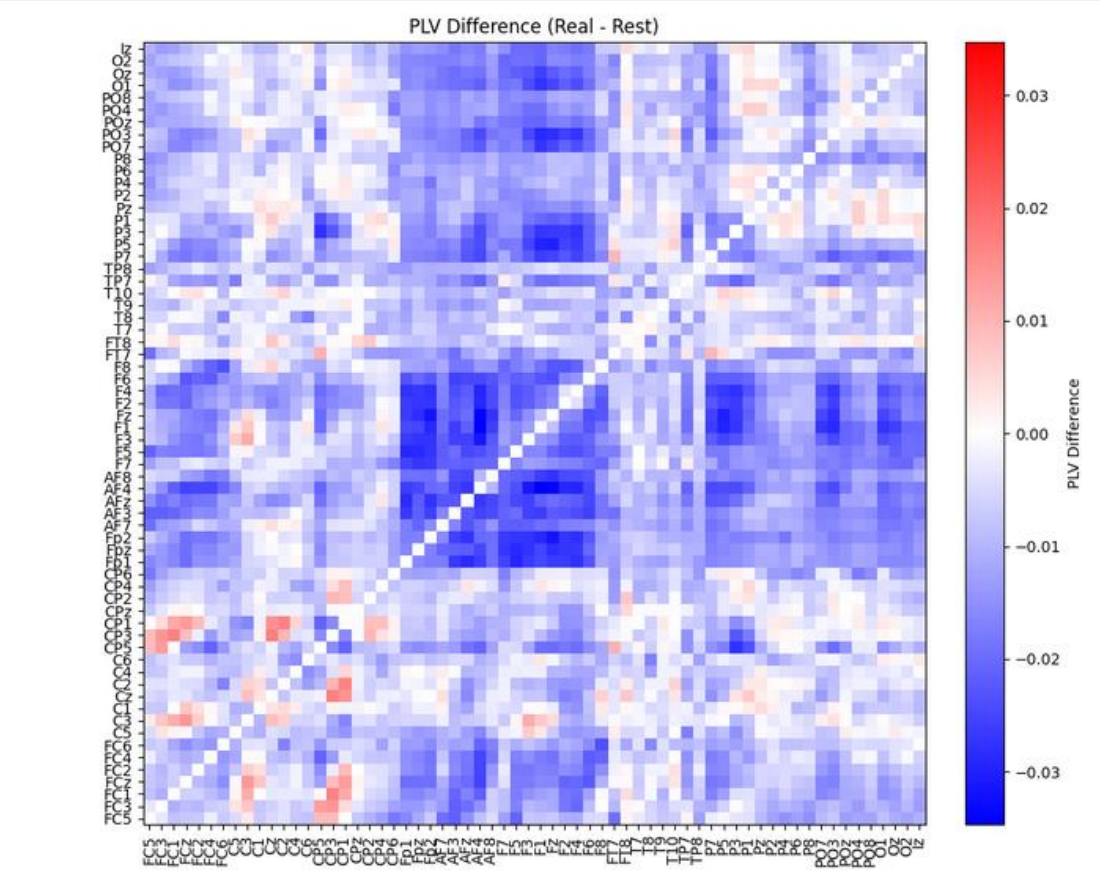
iPLV Mean by Channel Pair
Condition
Real
Imagined
Rest
Value
0.35
0.30
0.25
0.20
0.15
0.10
0.05
C3-C4
C1-C2
C5-C6
FC3-FC4
Cz-CPz
CP3-CP4
Fz-Cz
Fp1-Fp2
AF3-AF4
O1-O2
PO7-PO8
Fp1-PO8
T9-T10
Channel Pair
wPLI by Channel Pair
Value
0.8
0.6
0.4
0.2
0.0
C3-C4
C1-C2
C5-C6
FC3-FC4
Cz-CPz
CP3-CP4
Fz-Cz
Fp1-Fp2
AF3-AF4
O1-O2
PO7-PO8
Fp1-PO8
T9-T10
Channel Pair

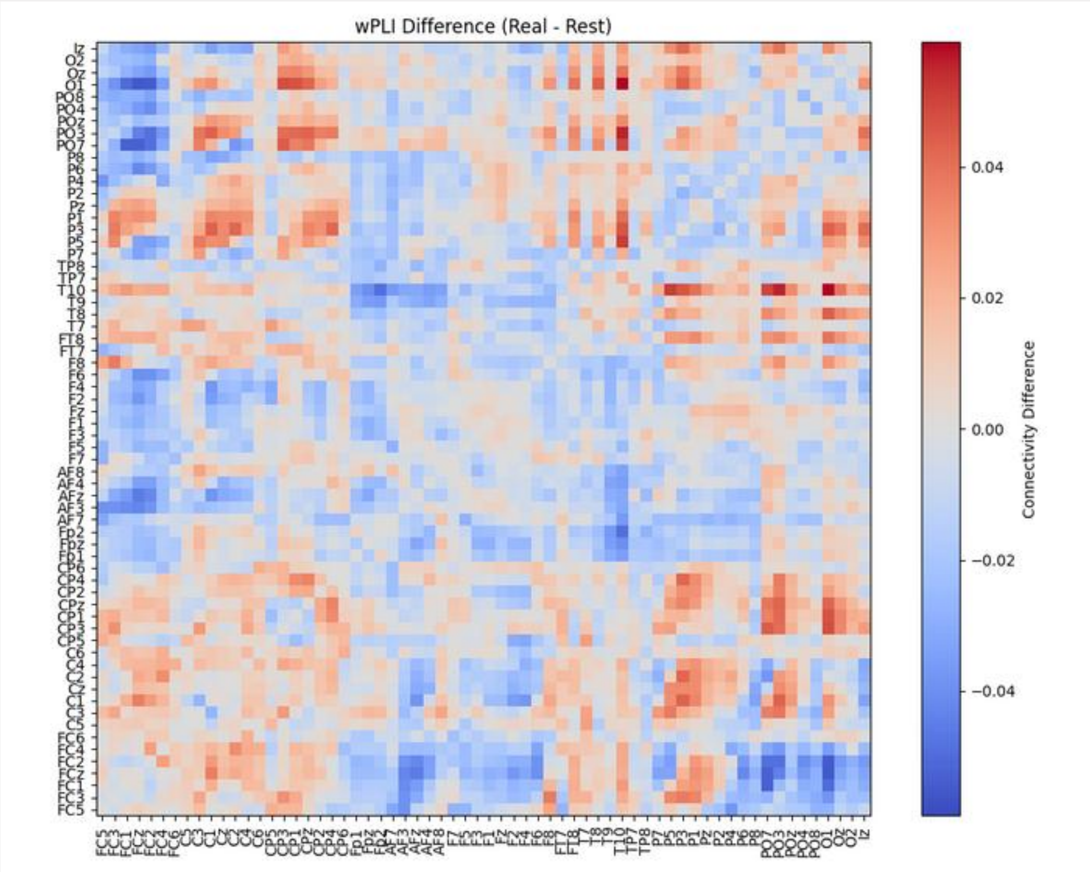
T-Test for PLV and iPLV

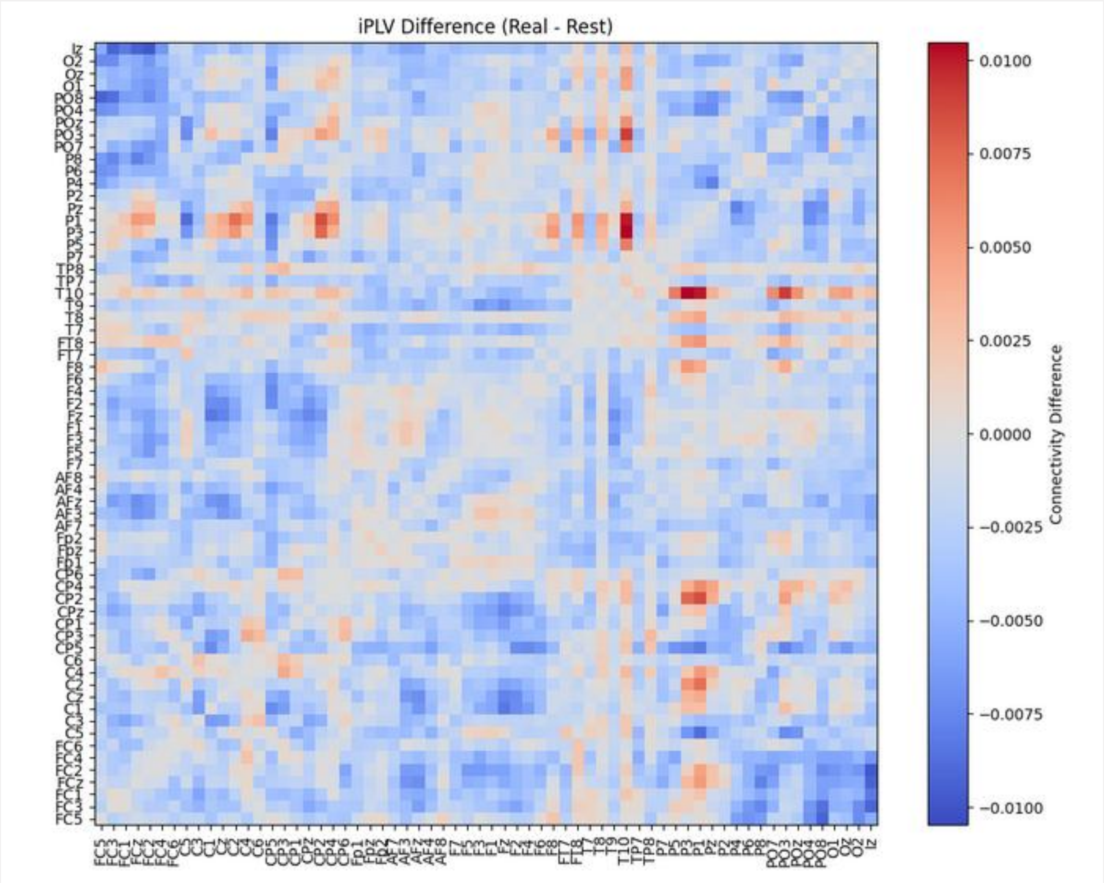




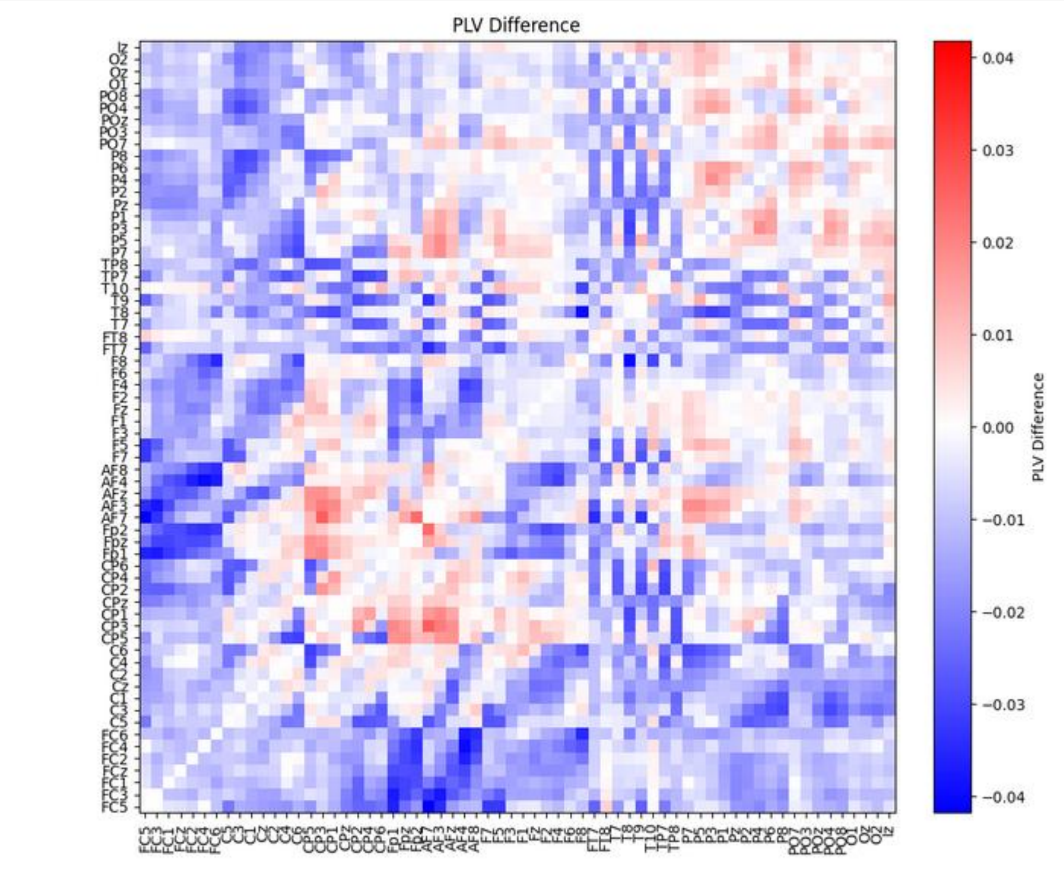
Matrix differences for Real vs Rest

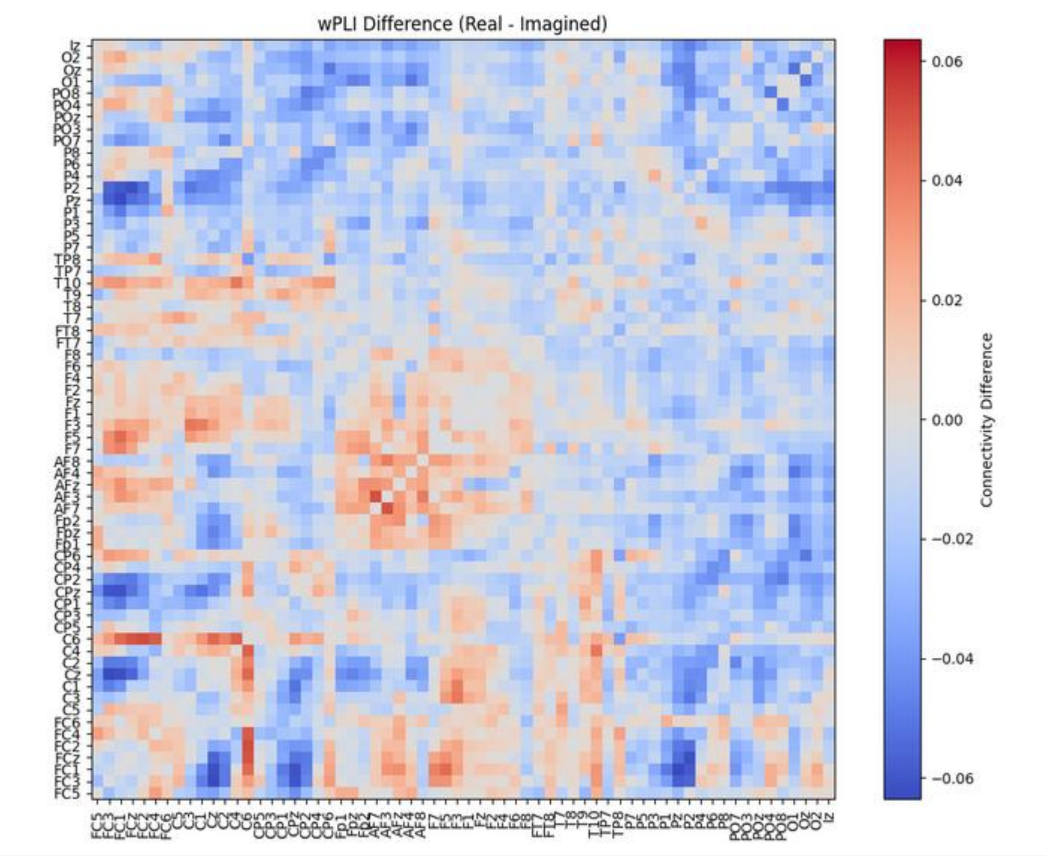


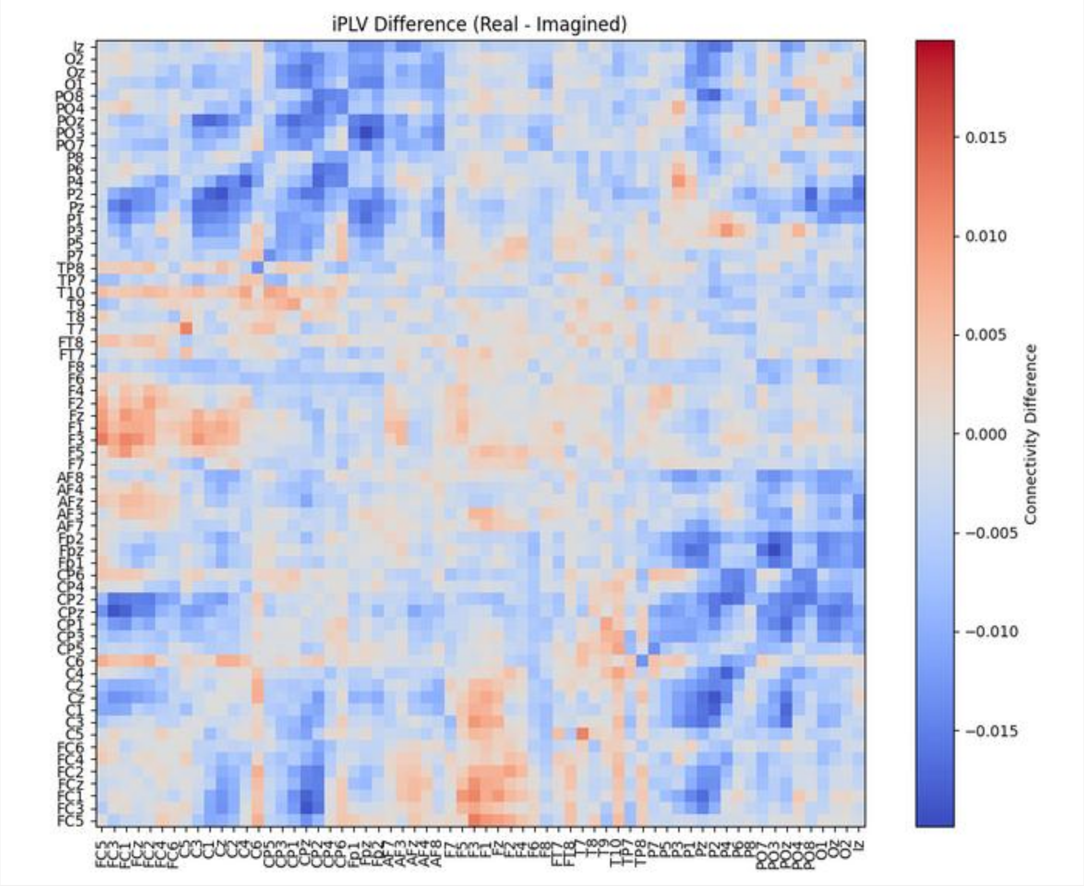




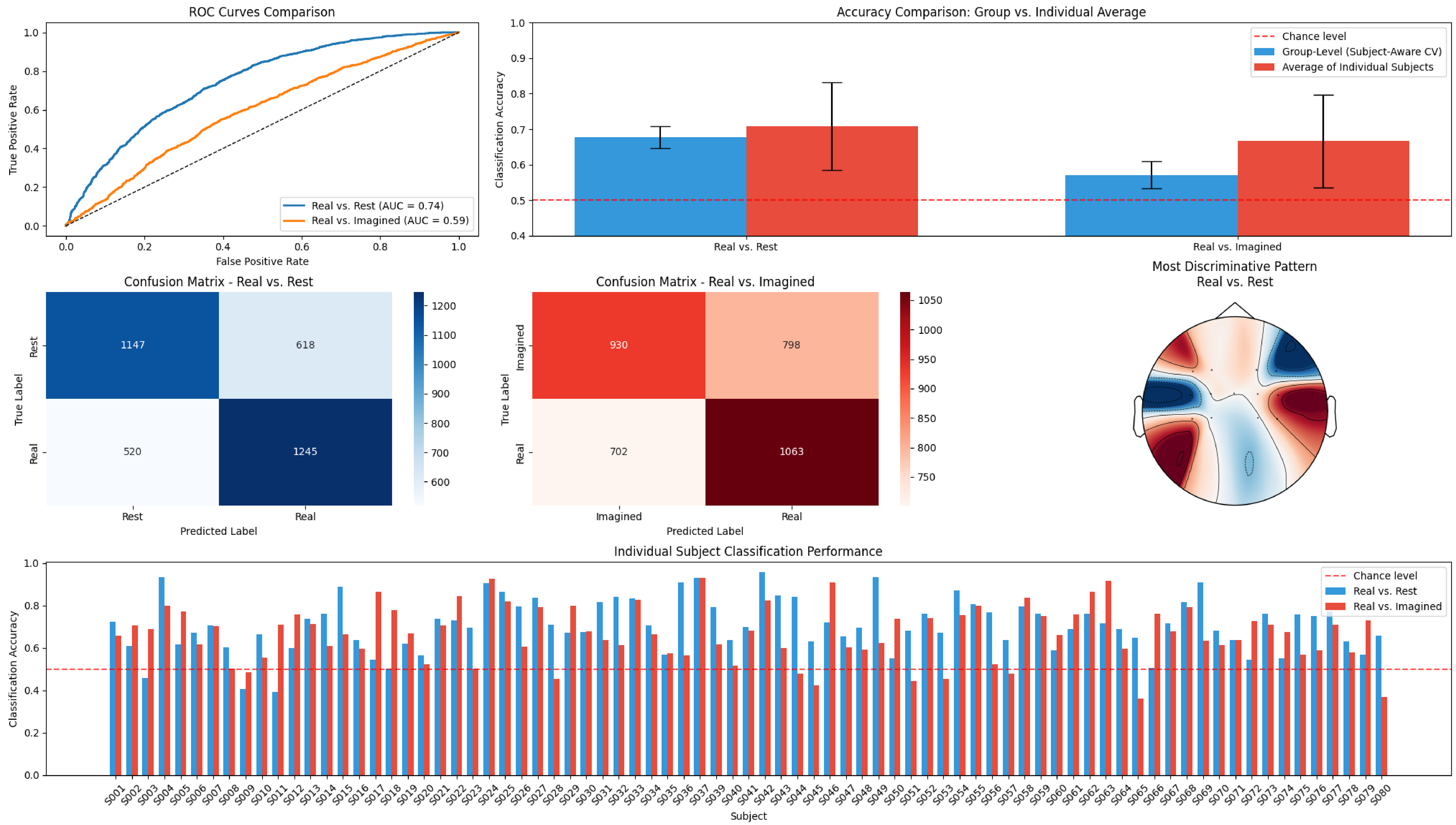
Matrix differences for Real vs Imagined



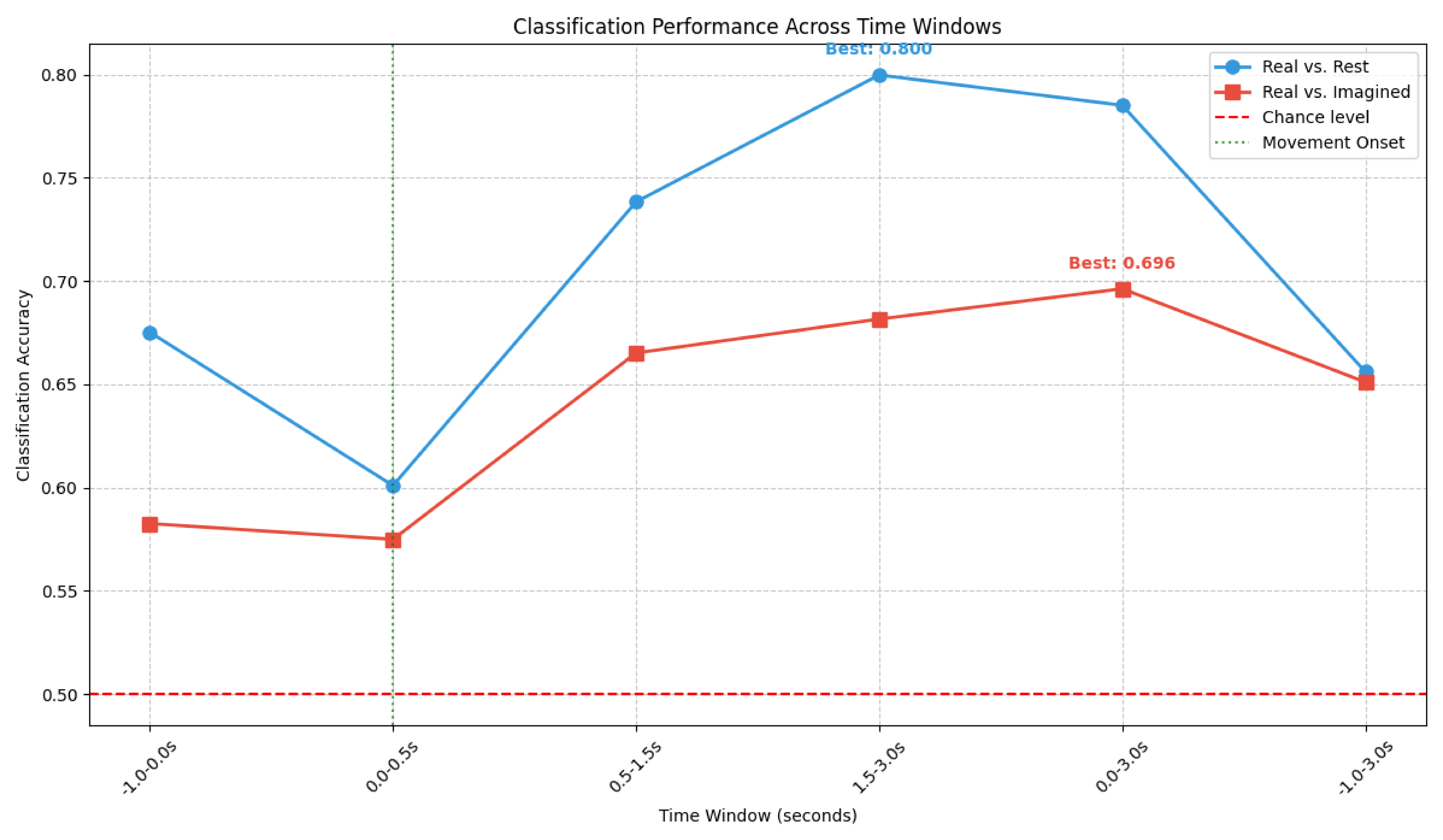


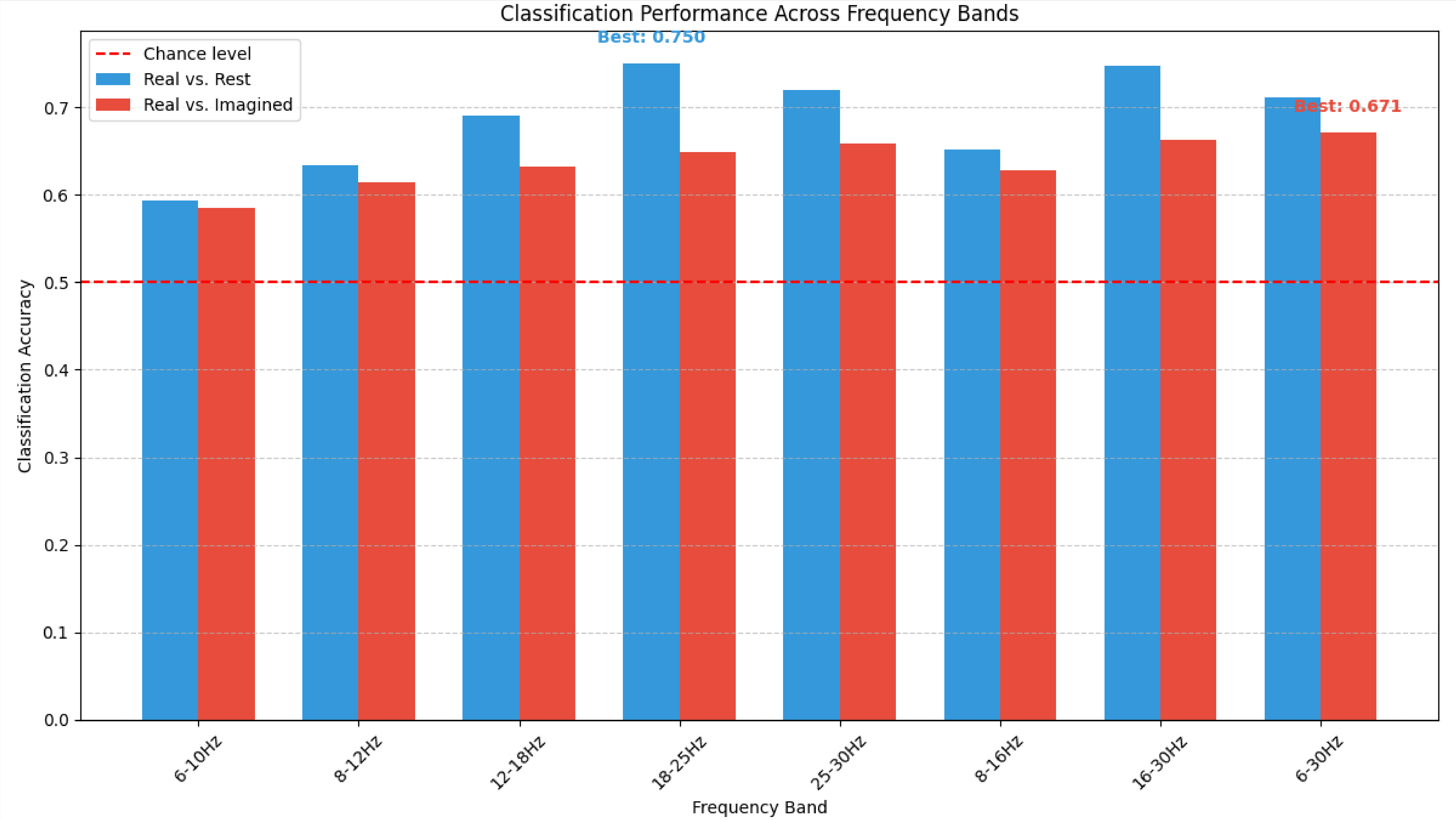


Classification



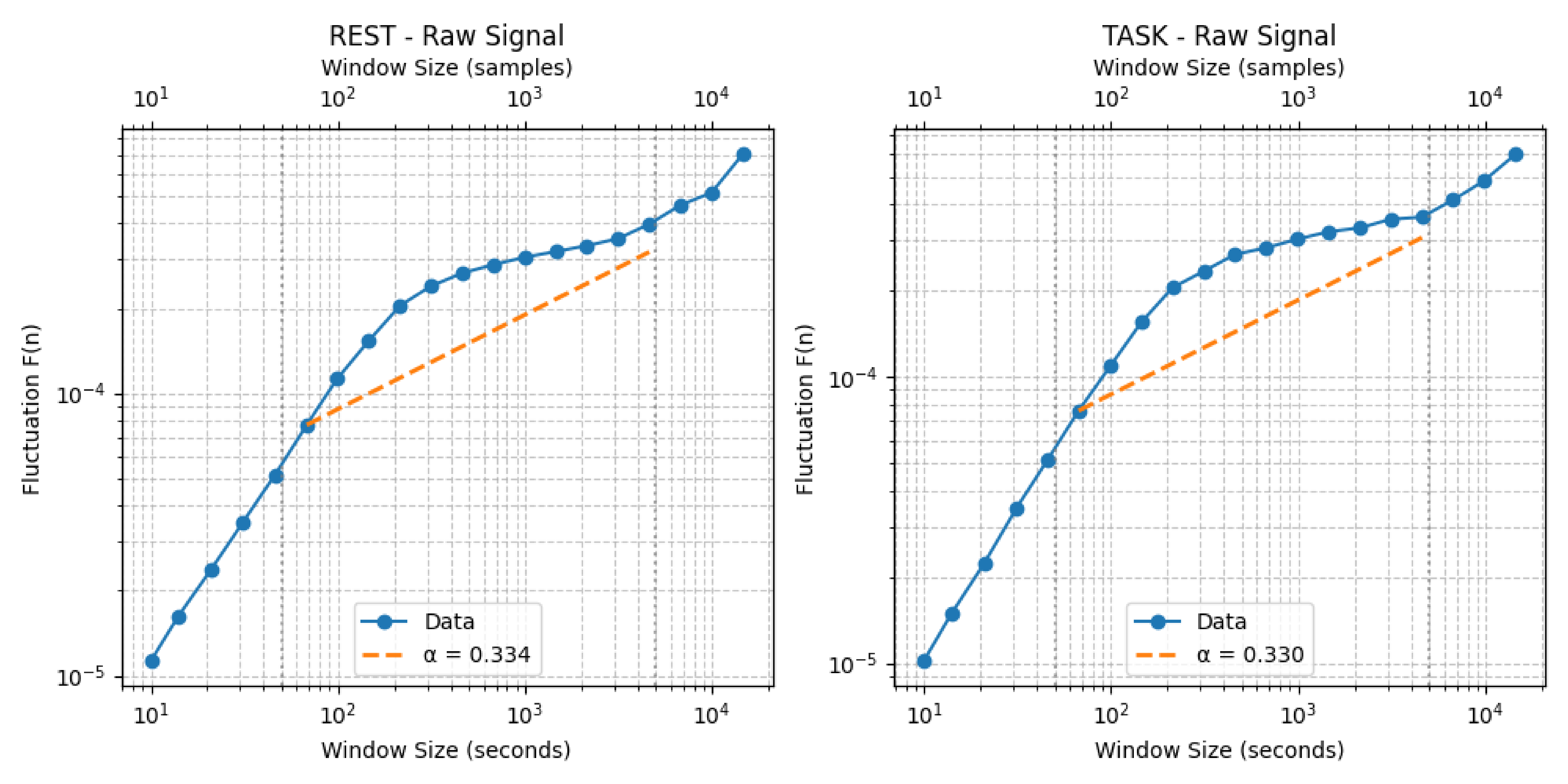
ROC Curves Comparison
True Positive Rate
False Positive Rate
Real vs. Rest (AUC = 0.74)
Real vs. Imagined (AUC = 0.59)
Accuracy Comparison: Group vs. Individual Average
Classification Accuracy
Chance level
Group-Level (Subject-Aware CV)
Average of Individual Subjects
Real vs. Rest
Real vs. Imagined
Confusion Matrix - Real vs. Rest
True Label
Predicted Label
Rest
Real
1147
618
520
1245
Confusion Matrix - Real vs. Imagined
Imagined
Real
930
798
702
1063
Most Discriminative Pattern
Real vs. Rest
Individual Subject Classification Performance
Classification Accuracy
Subject
Chance level
Real vs. Rest
Real vs. Imagined


Classification Performance Across Time Windows
Best: 0.800
Best: 0.696
Real vs. Rest
Real vs. Imagined
Chance level
Movement Onset
Classification Accuracy
0.80
0.75
0.70
0.65
0.60
0.55
0.50
-1.0-0.0s
0.0-0.5s
0.5-1.5s
1.5-3.0s
0.0-3.0s
-1.0-3.0s
Time Window (seconds)

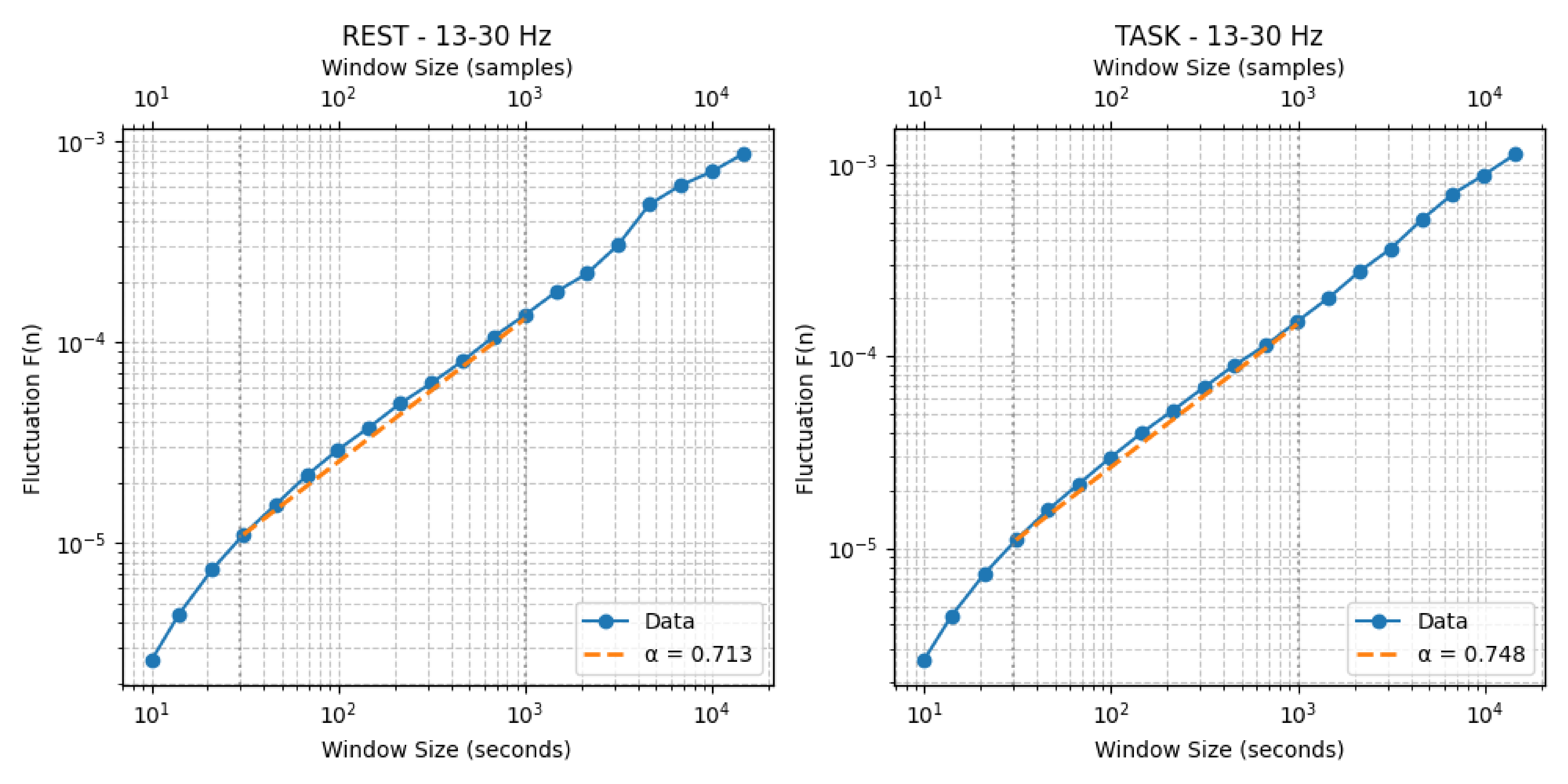

Classification Performance Across Frequency Bands
Chance level
Real vs. Rest
Real vs. Imagined
Best: 0.750
Best: 0.671
Classification Accuracy
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
6-10Hz
8-12Hz
12-18Hz
18-25Hz
25-30Hz
8-16Hz
16-30Hz
6-30Hz
Frequency Band

DFA Metric

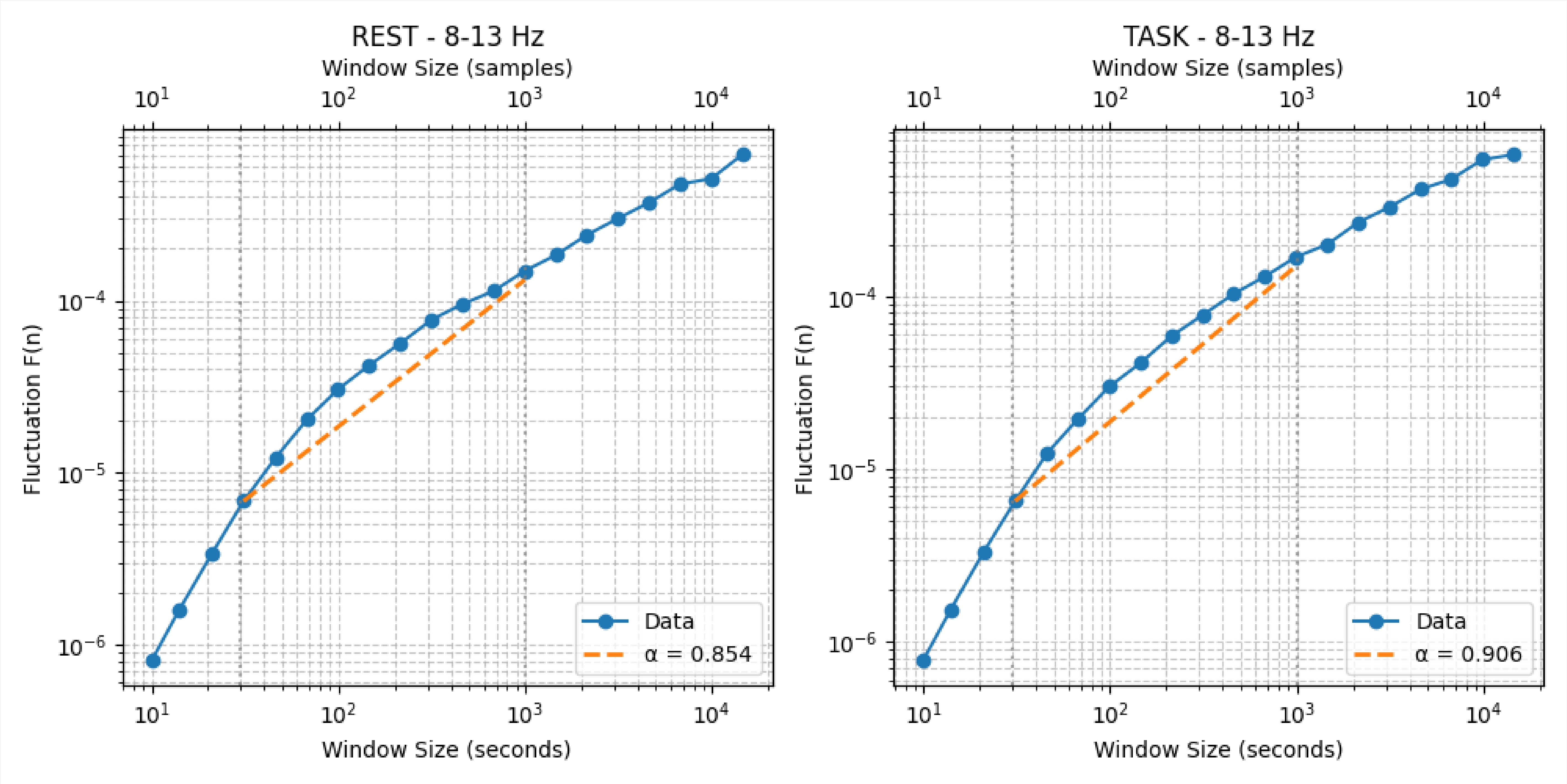
DFA Applied on Raw Signal

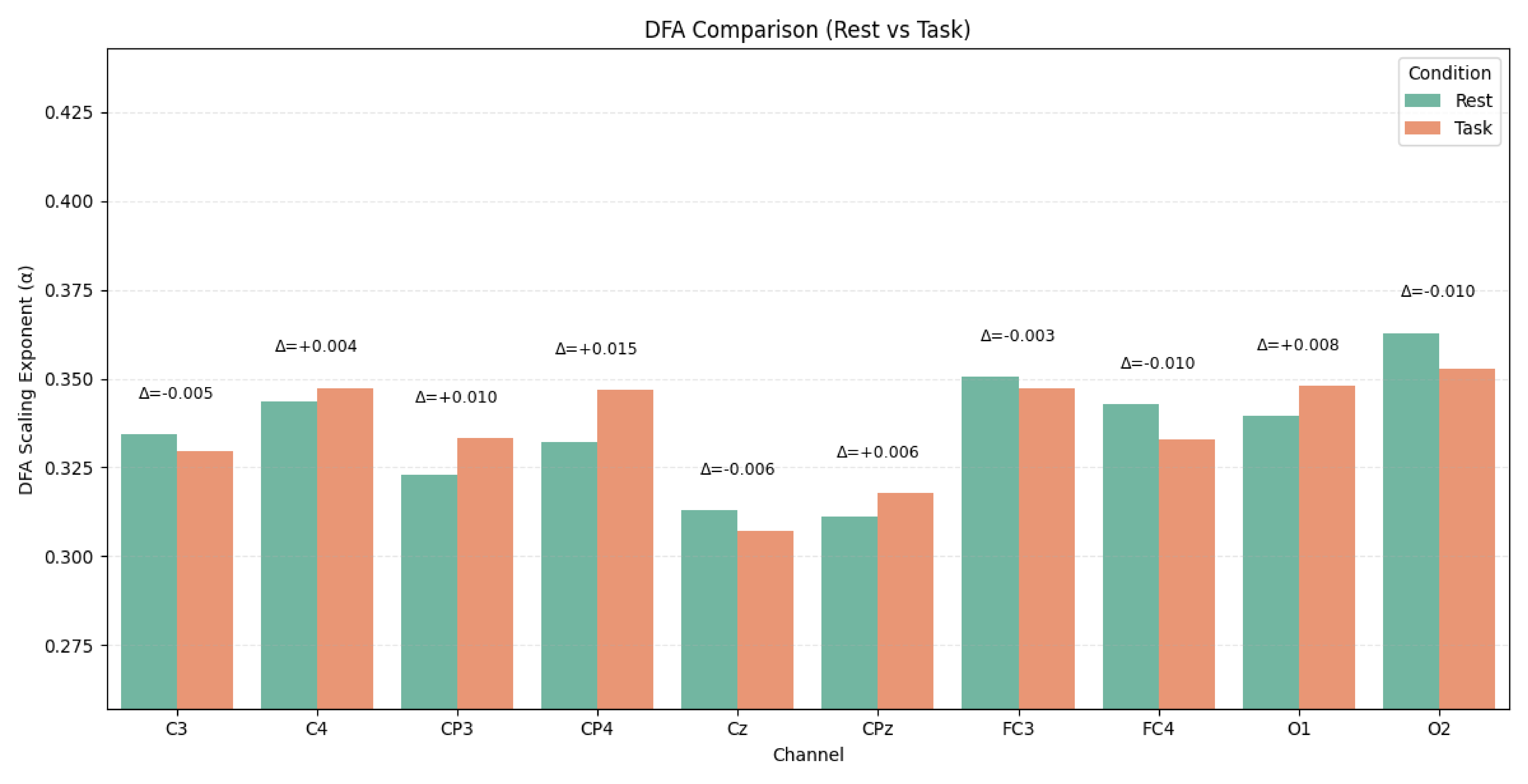


DFA Applied on β Band

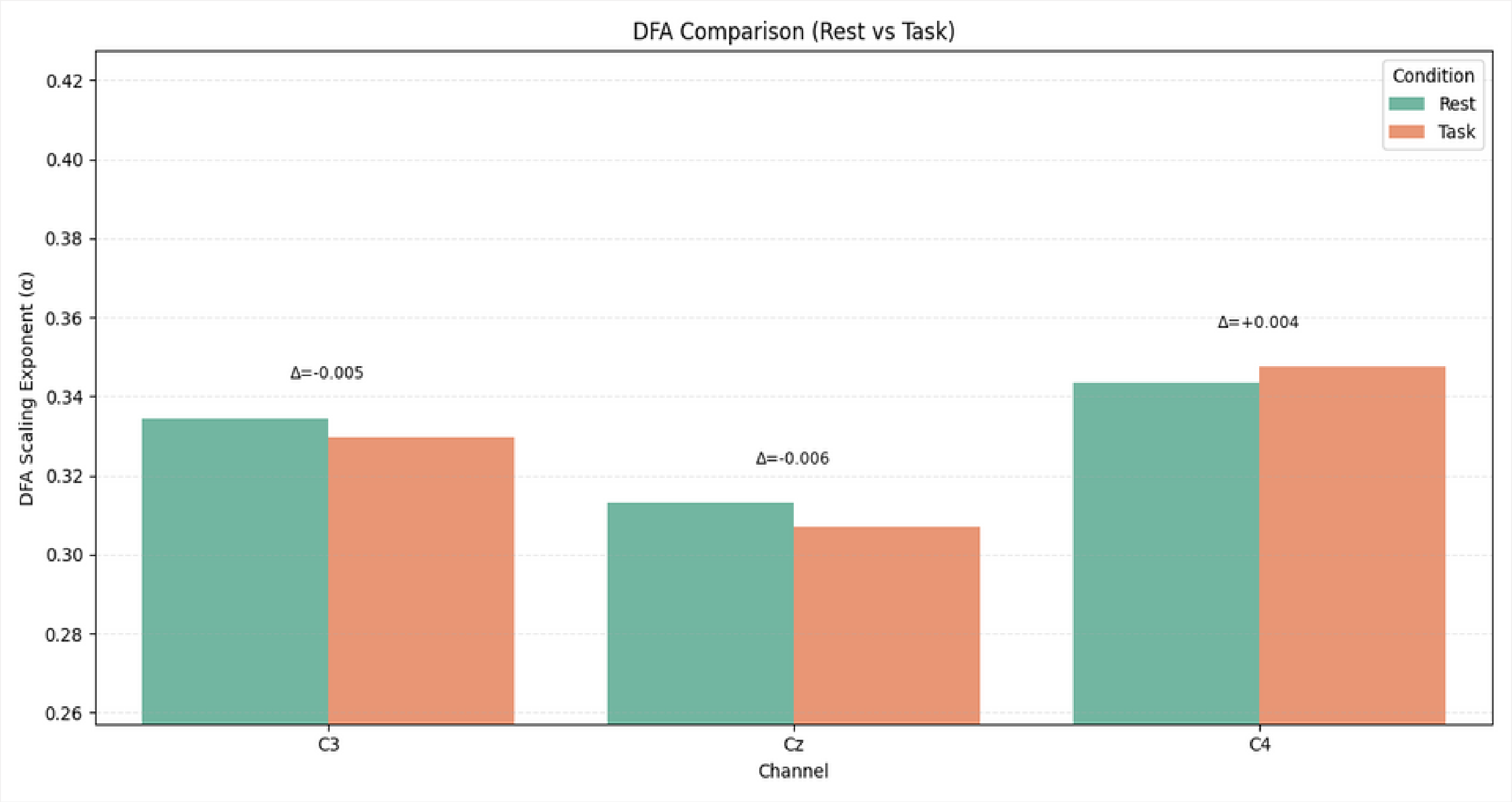


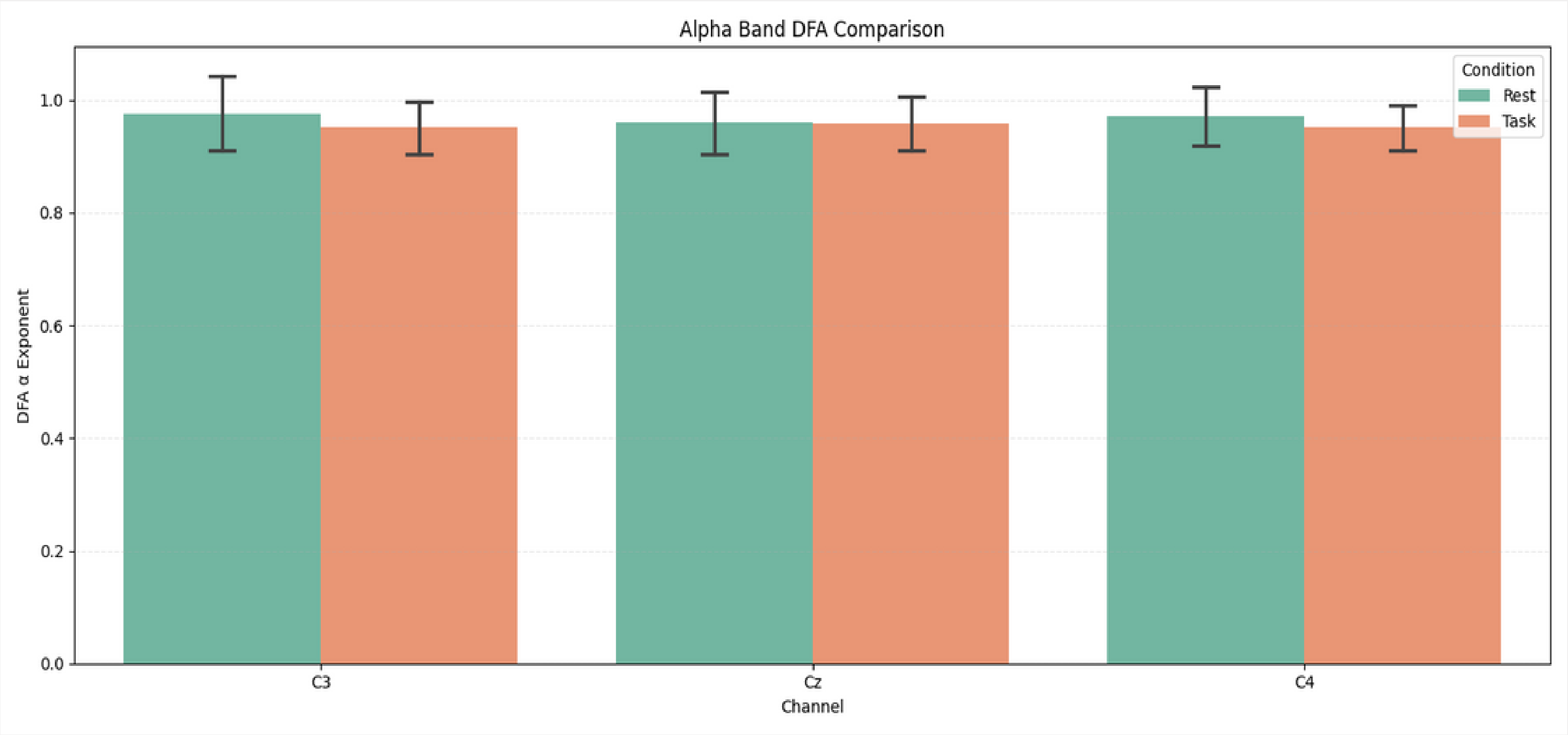
DFA Applied on α Band

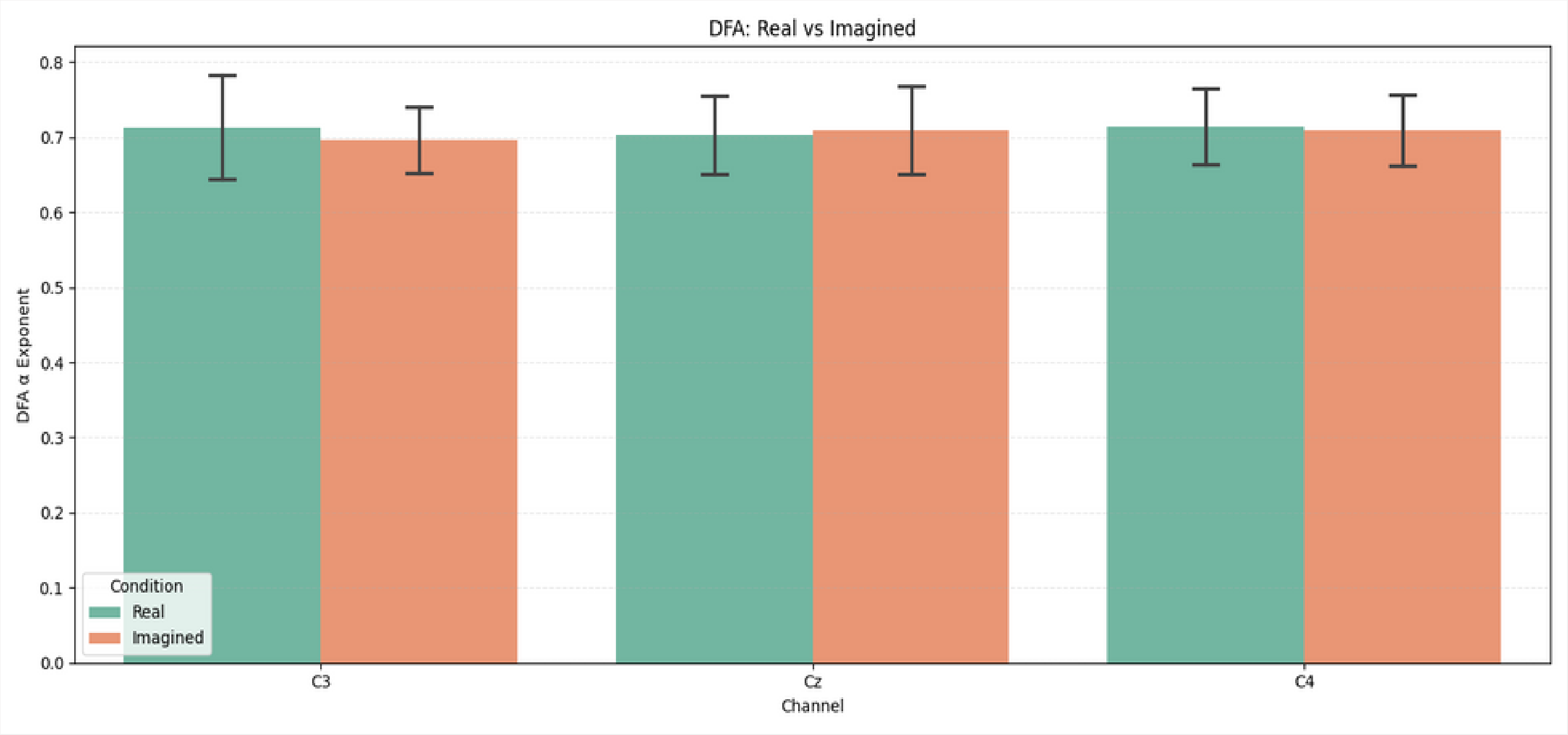


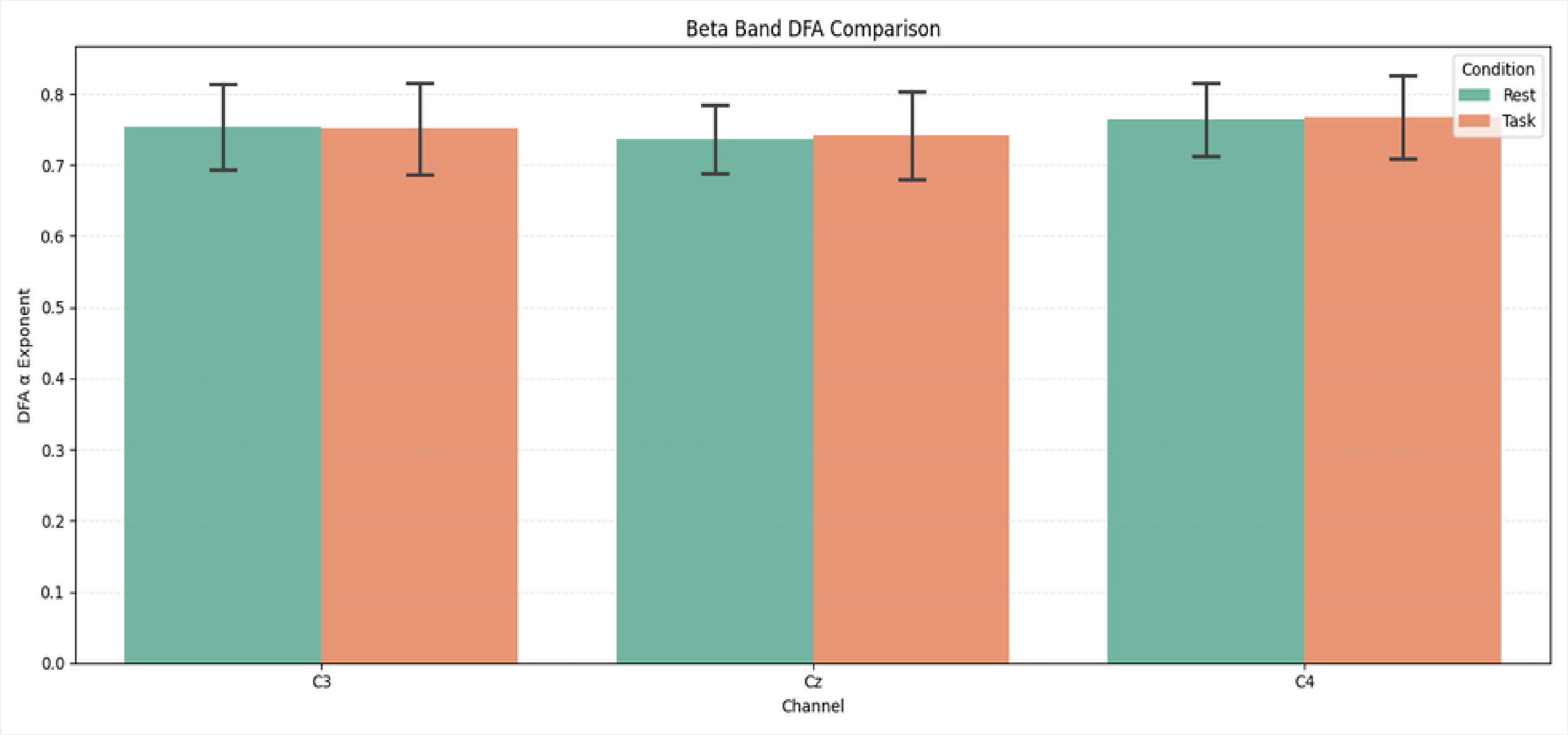


DFA Comparison (Rest vs Task)
Condition
Rest
Task
0.425
0.400
0.375
0.350
0.325
0.300
0.275
DFA Scaling Exponent (α)
Δ=-0.005
Δ=+0.004
Δ=+0.010
Δ=+0.015
Δ=-0.006
Δ=+0.006
Δ=-0.003
Δ=-0.010
Δ=+0.008
Δ=-0.010
C3
C4
CP3
CP4
Cz
CPz
FC3
FC4
O1
O2
Channel


DFA Comparison (Rest vs Task)
Condition
Rest
Task
Δ=-0.005
Δ=-0.006
Δ=+0.004
DFA Scaling Exponent (α)
C3
Cz
C4
Channel


Alpha Band DFA Comparison
Condition
Rest
Task
DFA α Exponent
C3
Cz
C4
Channel


DFA: Real vs Imagined
Condition
Real
Imagined
DFA α Exponent
C3
Cz
C4
Channel


Beta Band DFA Comparison
Condition
Rest
Task
DFA α Exponent
C3
Cz
C4
Channel

Conclusion (Real vs Imagined movement)

- They have similar activation
- They have similar activation patterns
- They have similar DFA values

"The latter outcome is not tragic, as failure is what scientists experience every day in the lab. Resilience to failure, humiliation, and rejection are the most important ingredients of a scientific career."

– György Buzsáki, in The Brain from Inside Out

References

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- Yuan, Han, Christopher Perdoni, and Bin He. "Relationship between speed and EEG activity during imagined and executed hand movements." *Journal of neural engineering* 7.2 (2010): 026001.
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- Alomari, Mohammad H., Aya Samaha, and Khaled AlKamha. "Automated classification of L/R hand movement EEG signals using advanced feature extraction and machine learning." arXiv preprint arXiv:1312.2877 (2013).