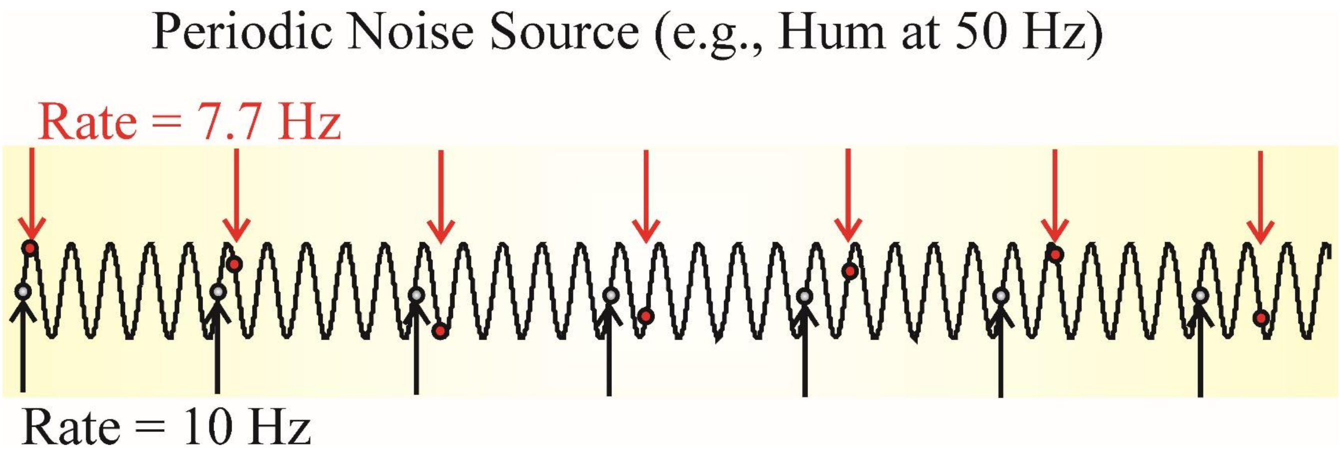
SIGNAL AVERAGING AND NONRANDOM NOISE

The result in the previous section depends heavily on a noise component being random, having **zero mean, and being unrelated** to the signal. A special case occurs when the noise is not random. This situation may affect the performance of the average and even make it impossible to apply the technique without a few critical adaptations.

This problem is often avoided by either **randomizing the stimulus interval** or by using a **noninteger stimulus rate**.



The stimulus-rate and a periodic component (e.g., a 50-Hz or 60-Hz hum artifact) in the unaveraged signal can produce an undesired effect in the average. An average produced with a 10-Hz rate will contain a large 50-Hz signal. In contrast, an average produced at a 7.7-Hz rate will not contain such a strong 50-Hz artifact. This difference is due to the fact that a rate of 10-Hz results in a stimulus onset that coincides with the same phase in the 50-Hz sinusoidal noise source (black dots), whereas the noninteger rate of 7.7 Hz produces a train of stimuli for which the relative phase of the noise source changes with each stimulus (red dots).

Figure 4.5 Signal processing for Neuroscientist, second edition by Wim van Drongelen

Characteristics of Background EEG

- EEG frequency range: 0.01 to 100 Hz
- EEG amplitudes: typically around 100 microvolts
- Power spectral density follows a power law
- EEG divided into five bands: delta, theta, alpha, beta, gamma
- EEG considered stochastic due to limited genuine measurements
- Long-term EEG signals are non-stationary time series
- Short-term EEG signals can be approximately stationary
- Stationary time window lengths vary, typically several seconds to minutes

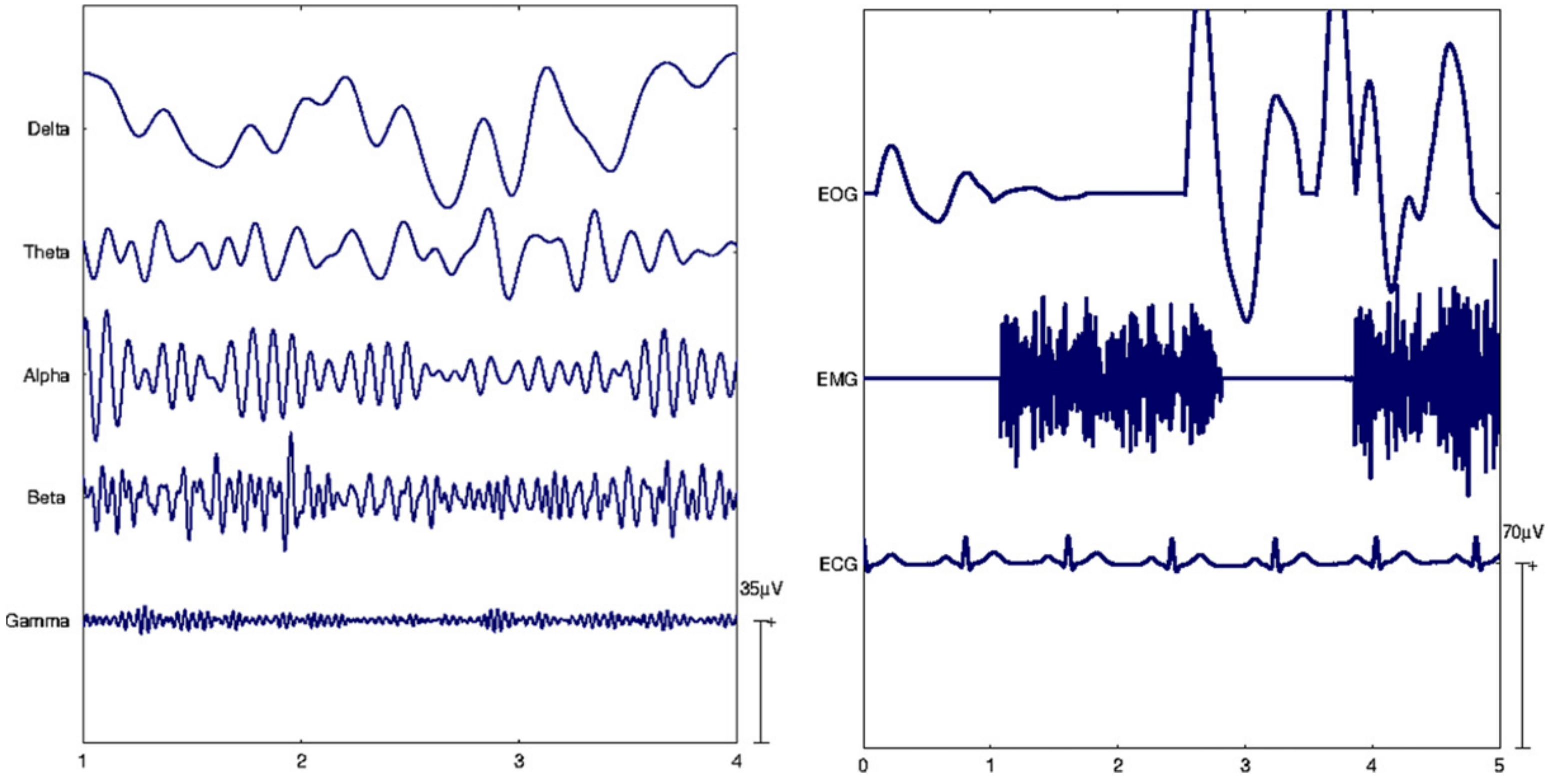


Figure 1. (a) Five normal brain rhythms, from low to high frequencies. Delta, theta, alpha, beta and gamma rhythms comprise the background EEG spectrum. (b) Three different kinds of artifacts. Ocular, muscular and cardiac artifacts are the most frequent physiological contaminants in the literature on EEG artifact removal.

Figure 1, J.A. Urigüen 2015

Power Line Noise Removal

- Notch filtering used to eliminate line noise at 50 or 60 Hz
- Implemented with a certain frequency width (e.g., 10 Hz)
- Successful in removing line noise but may distort signal components between 50 and 70 Hz
- Notch filter can generate transient oscillation in baseline activity, impacting data interpretation
- Follow-up low-pass filtering below 50 Hz may address issues but can alter EEG temporal structures or cause spurious interactions between channels

Example:

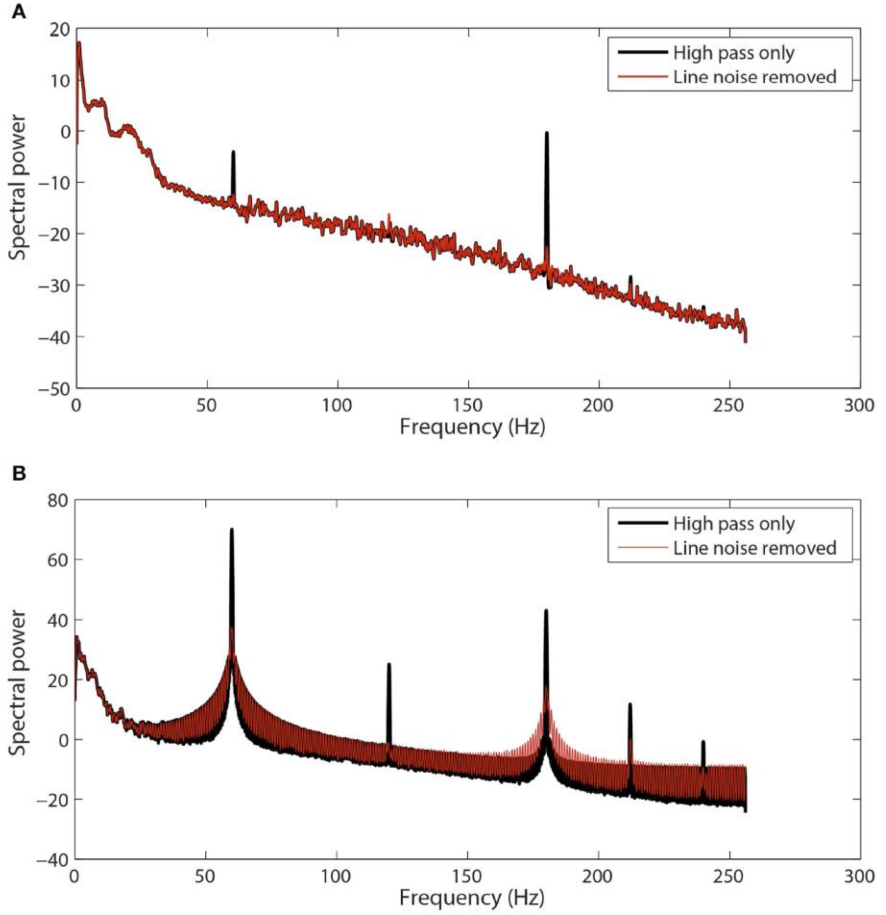
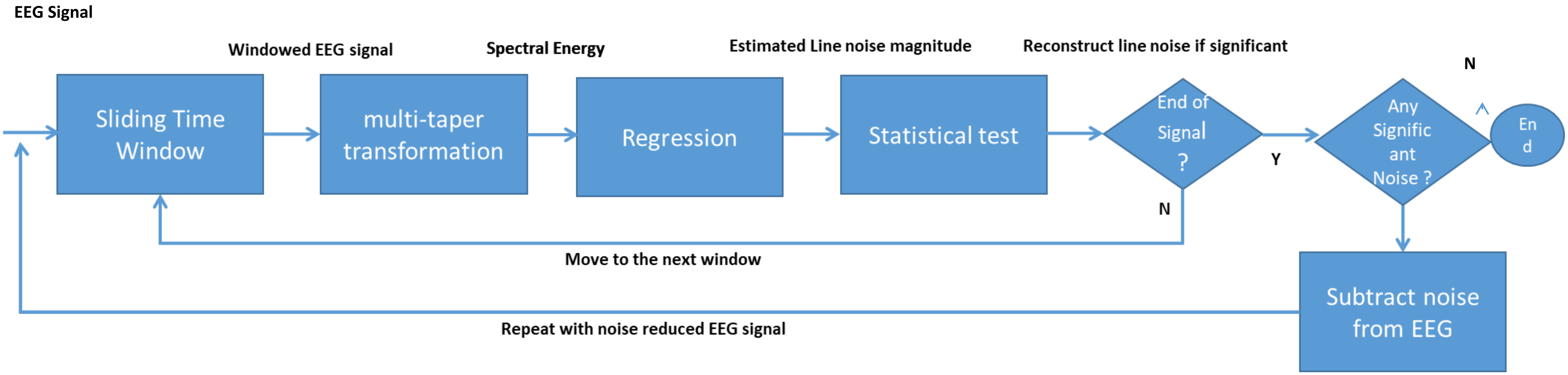


FIGURE 1 | Selected channel spectra from 64-channel Biosemi EEG before and after line noise removal. Spectral power is in units of $10\log_{10}\left(\mu V^2\right)$. Data was high-pass filtered at 1 Hz prior to line noise removal. **(A)** A channel with sharp peaks at 60 and 180 Hz. **(B)** A channel contaminated by non-stationary transformer noise. This channel is interpolated at a later stage in the pipeline.

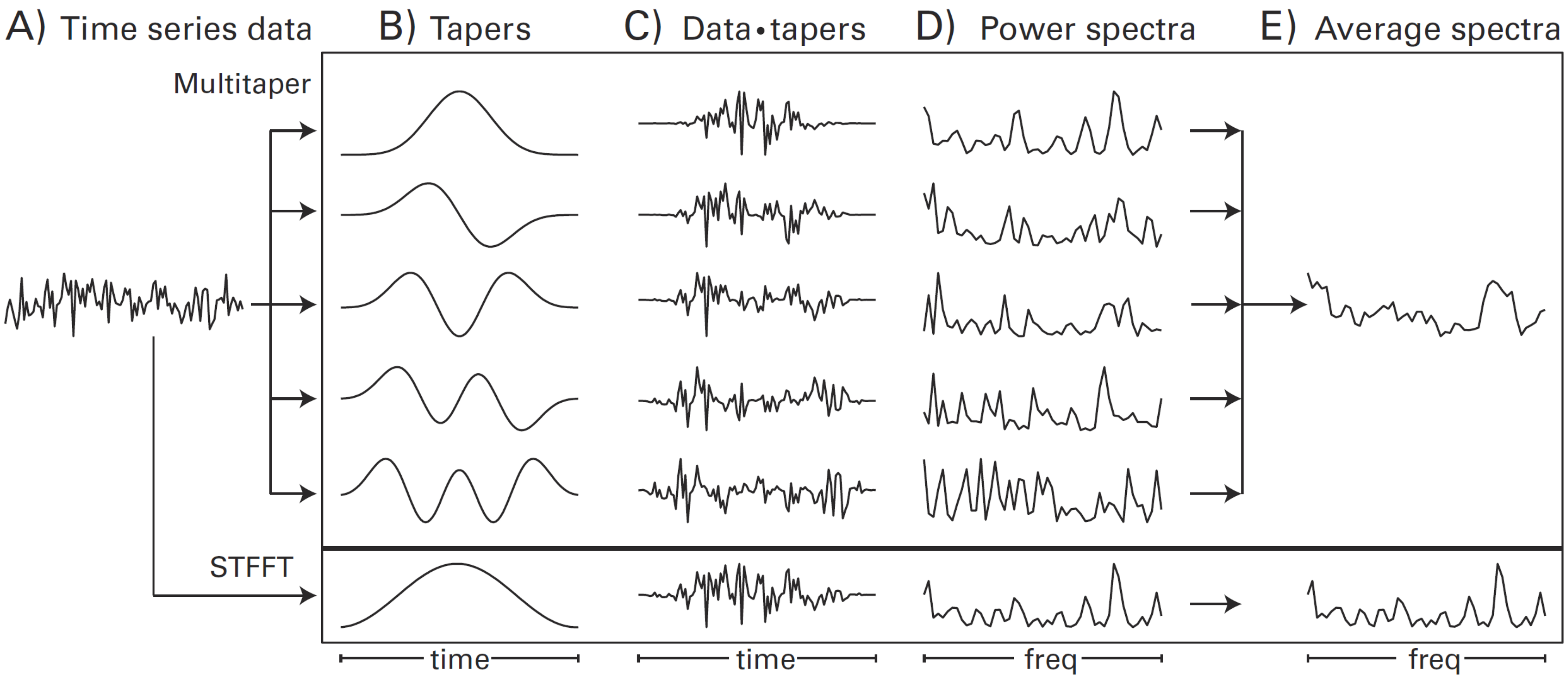
Bigdely-Shamlo et al. 2015

multi-taper decomposition

Estimate and subtract line noise in EEG signals using multi-taper decomposition, regression modelling, and significance testing for effective removal without damaging background spectral components.



Multitapper tranfromation



- Multitaper method is useful for low signal-to-noise ratio situations.
- Particularly effective for higher-frequency activity or single-trial estimates of power.
- Frequencies lower than around 30 Hz may make multitaper less appropriate.
- Signal-to-noise ratio is already relatively high at lower frequencies.
- Spectral smoothing from multitaper may impede frequency isolation.
- Activities from multiple frequency bands can become averaged together.

Referencing

- Standard practice: Subtract reference signal with the same time resolution from original EEG signal at each channel.

- Common reference choices:

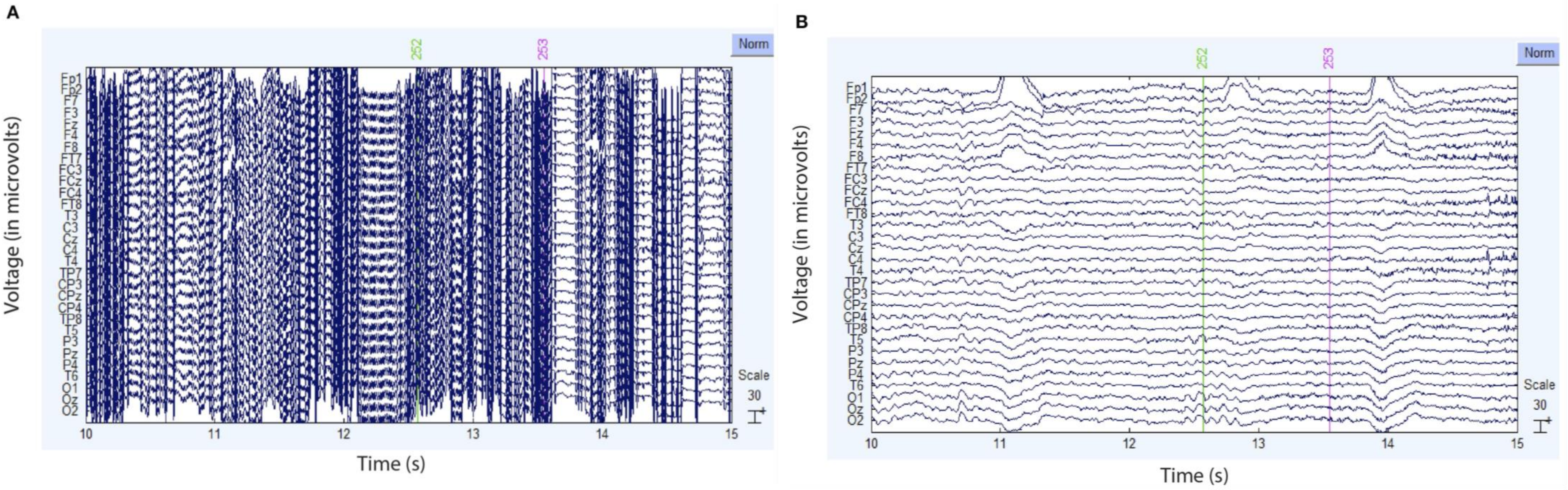
mastoid channel, specific EEG channel, average of two mastoid signals, or average of all EEG channels.

- Importance: Chosen reference should remain unchanged relative to EEG signals, ensuring effective representation of brain activity.

- Caution: Carefully inspect chosen reference signal for comparable amplitude levels and no correlation with task-induced brain activity.

- Common Average Reference (CAR): Reduces single-point failure impact but may suffer from outlier channels.
    - Solution: Detect and remove bad channels before using CAR.

Example:



Comparison of theordinary and robustaverage references

(A) Example signal after ordinary average referencing.

(B) Same signal using robust average referencing.

Bigdely-Shamlo 2015, frontrier, Figure 4.

Bad Channel Detection

1. **Detecting Noisy or Bad Channels:**
    - Identify channels with excessively large amplitudes.
    - Use robust z-score to detect extreme amplitudes.
    - Bad channel determined if robust z-score exceeds a threshold.
2. **Correlation-based Detection:**
    - Investigate correlation of a single channel with others.
    - Normal EEG shows low-frequency correlations across channels.
    - Detect bad channels by correlating one channel after low-pass filtering.
    - Attempt prediction if two bad channels are correlated.
3. **Frequency-based Detection:**
    - Measure ratio of high-frequency power to low-frequency power.
    - Detect bad channels with a ratio higher than a threshold.

Bad Channel Detection

4. Replacement of Bad Channels:

- Replace bad channels with virtual healthy channels.
- Reconstruction of global brain responses.

5. Interpolation Schemes:

- Various interpolation schemes for channel reconstruction:
  - Spherical splines
  - Higher-order polynomials
  - Nearest-neighbor averaging
  - Radial basis function

Advantages of Interpolation Methods:

- Spherical splines provide accurate scalp potential estimation with dense electrode mapping.
- Statistical methods like radial basis functions offer cost-effectiveness with lower computational loads.

Artifact Removal

1. EEG Artifact Sources:

- Categorized into two classes: internal and external sources.
- Internal sources: physiological systems like heart, eyes, and muscles.
- External sources: signals from environments (e.g., wireless signals, electrode attachment, recording equipment).

***2.* Importance of Handling External Artifacts:**

- Essential as EEG applications move towards in-home healthcare systems.
- External sources can be inhibited once identified.

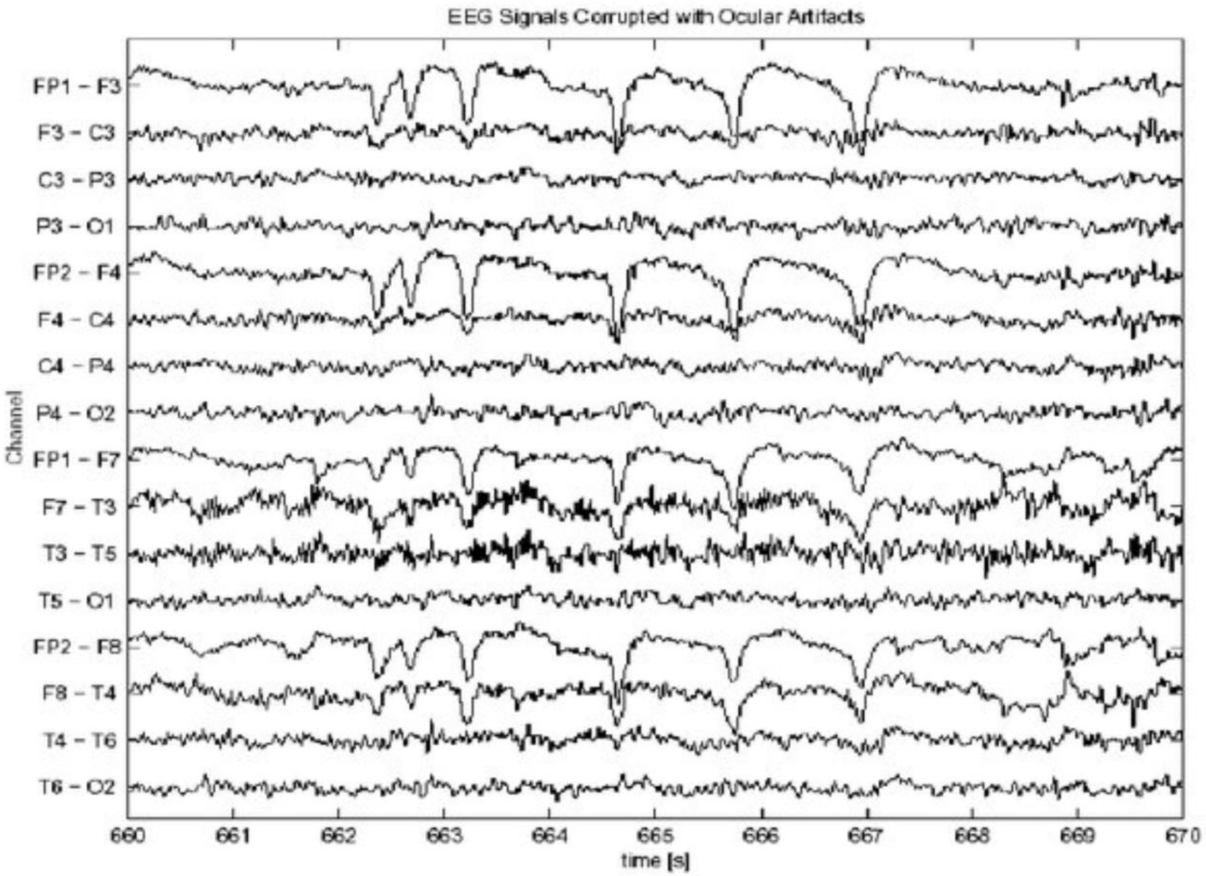
3. **Focus on Internal Artifacts:**

- Internal artifacts permeate EEG, making prevention challenging.
- Most artifact removal methods focus on dealing with internal artifacts.

Artifact Removal

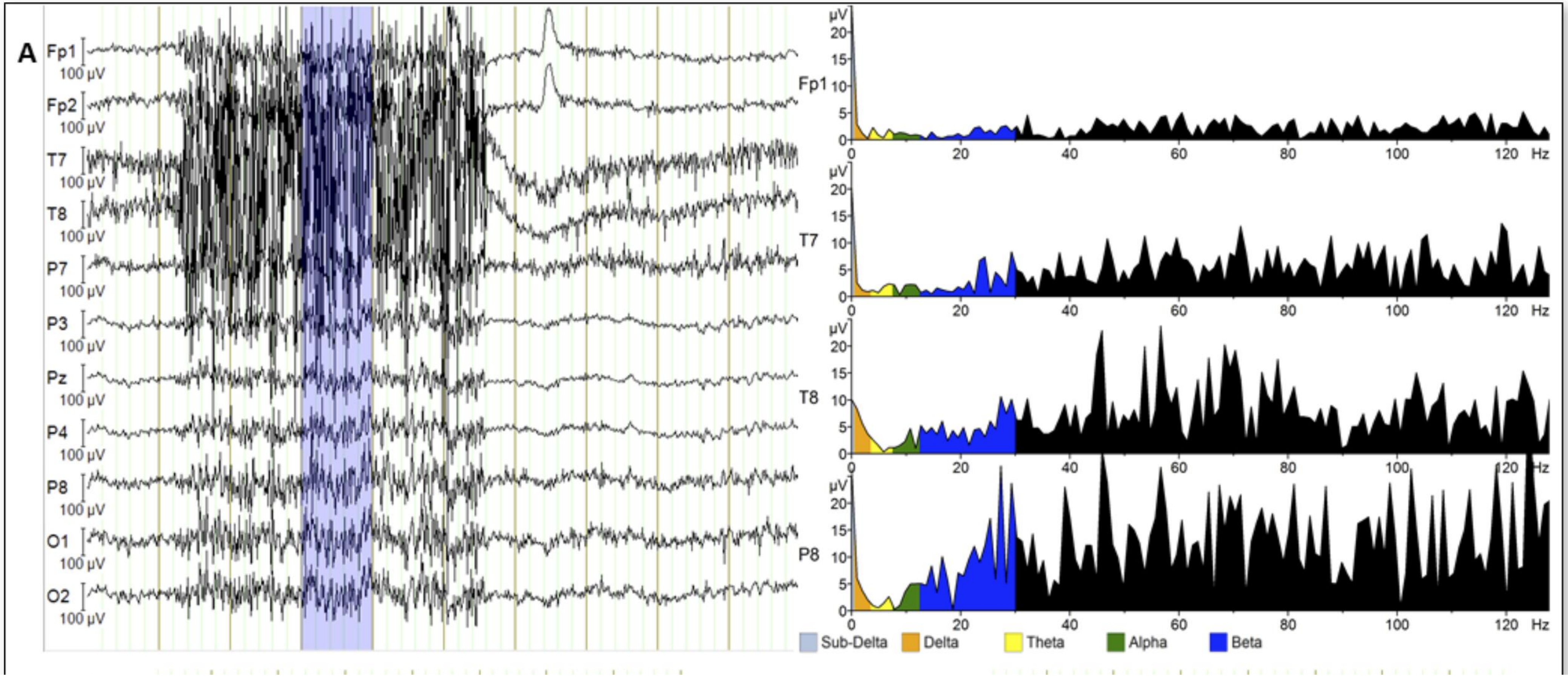
4. Ocular Artifacts:

- Originating from eye movements or blinking.
- Strong enough to be visible in EEG waveforms
- EEG channels near eyes are more vulnerable.
- Detection through electrooculogram (EOG) measurements.



Vuribindi Krishnaveni et al 2005

Example



A
Fp1
100 µV
Fp2
100 µV
T7
100 µV
T8
100 µV
P7
100 µV
P3
100 µV
Pz
100 µV
P4
100 µV
P8
100 µV
O1
100 µV
O2
100 µV
µV
20
15
10
5
0
Fp1
T7
T8
P8
0
20
40
60
80
100
120
Hz
Sub-Delta
Delta
Theta
Alpha
Beta

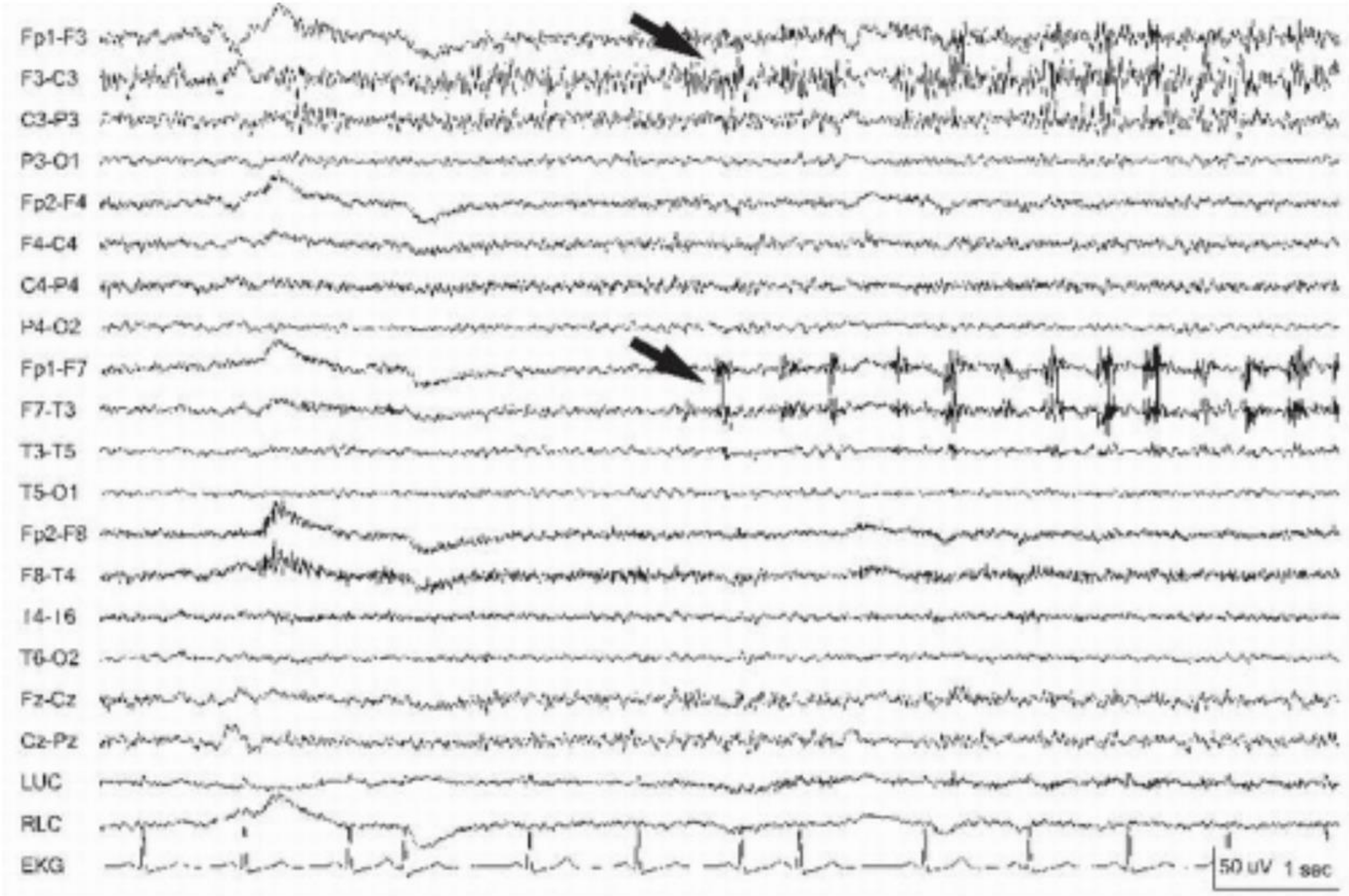
. Muscle Artifacts:

- Originating from muscle contractions in various body parts.
- More diverse forms compared to ocular artifacts.
- Detected through electromyogram (EMG).
- Widespread sources make it challenging to identify true profiles.
- Spatial distribution is wider and almost uniform over the entire scalp.
- Temporal patterns often associated with tasks, making removal challenging.

6. Challenges in Muscle Artifact Removal:

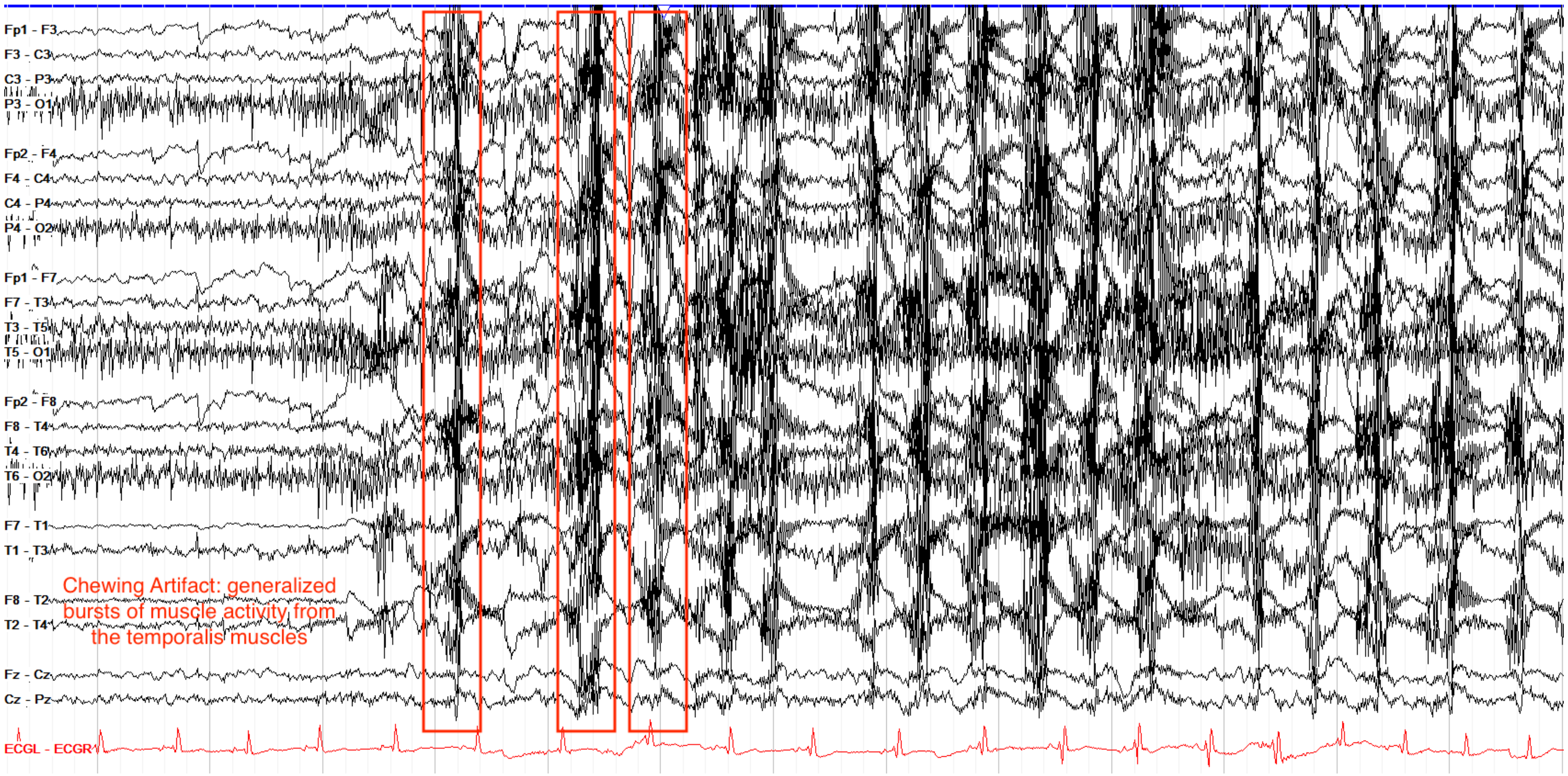
- Significant challenge due to diverse sources and spatial distribution.
- Spectral properties vary across sources, affecting both high and low-frequency EEG components.
- Temporal patterns associated with natural movements pose challenges in removal.

Example



Fp1-F3
F3-C3
C3-P3
P3-O1
Fp2-F4
F4-C4
C4-P4
P4-O2
Fp1-F7
F7-T3
T3-T5
T5-O1
Fp2-F8
F8-T4
T4-T6
T6-O2
Fz-Cz
Cz-Pz
LUC
RLC
EKG
50 uV 1 sec

Example


Fp1 - F3
F3 - C3
C3 - P3
P3 - O1
Fp2 - F4
F4 - C4
C4 - P4
P4 - O2
Fp1 - F7
F7 - T3
T3 - T5
T5 - O1
Fp2 - F8
F8 - T4
T4 - T6
T6 - O2
F7 - T1
T1 - T3
F8 - T2
T2 - T4
Fz - Cz
Cz - Pz
ECGL - ECGR
Chewing Artifact: generalized bursts of muscle activity from the temporalis muscles