Evaluating high-resolution frequency spectral estimation approaches to real-time frequency modulation neurofeedback

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Motivation

1. Cognitive performance may by mediated by modulation of an oscillation's peak amplitude frequency at sub-Hz scales
(Samaha, Bauer, Cimaroli, Postle, 2015)

2. Neurofeedback could target peak amplitude frequency modulation to enhance cognitive performance

3. Sub-Hz frequency spectrum estimation methods must therefore detect these frequency changes at real-time speed

Question

Which of these methods has the highest frequency resolution using the least data and runtime?

Two Peak Discrimination

Discriminate two peaks at 10.54 and 10.56 Hz

One Peak Detection with 1/f Noise

Detect single peak at 10.55 Hz embedded in noise with SNR = 1/6

One Peak Detection with 1/f Noise, filtered

Same as above, 2nd order Butterworth IIR filter 10 -11 Hz passband

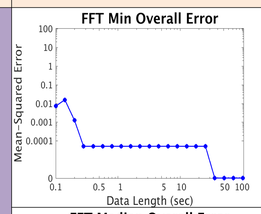
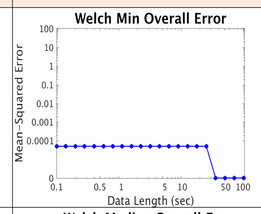
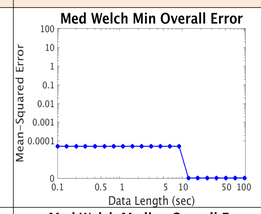
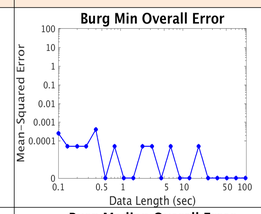
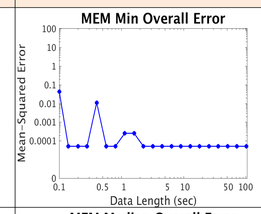
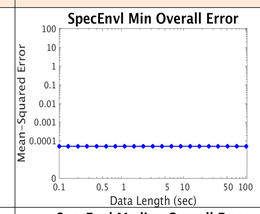
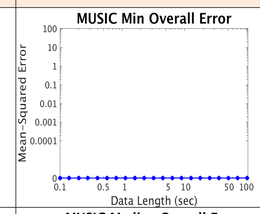
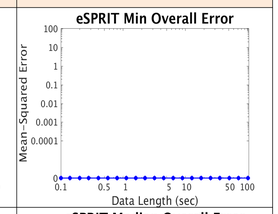
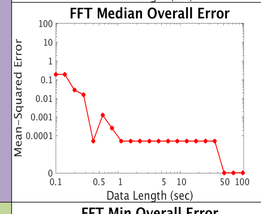
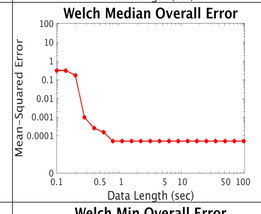
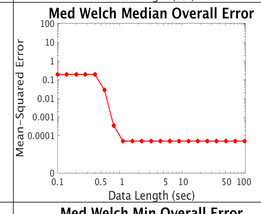
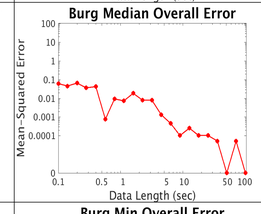
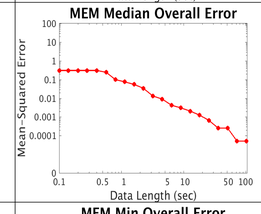
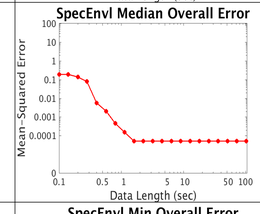
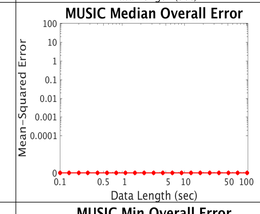
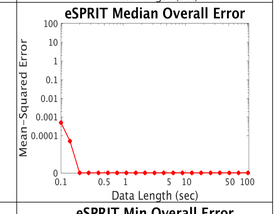
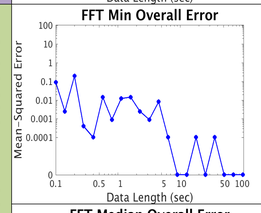
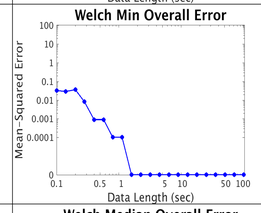
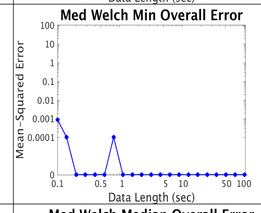
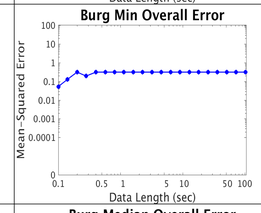
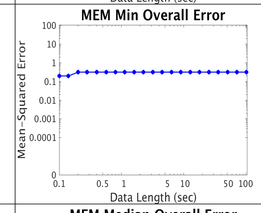
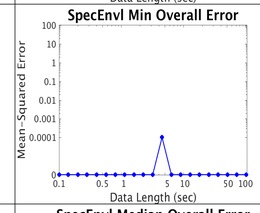
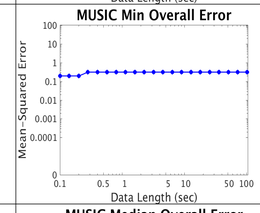
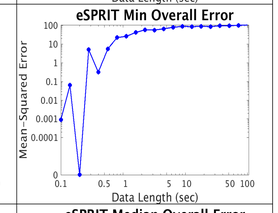
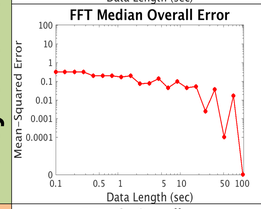
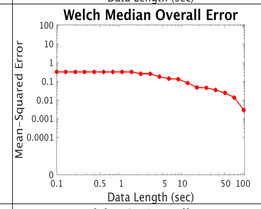
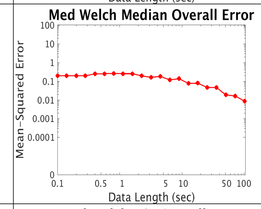
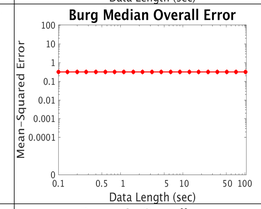
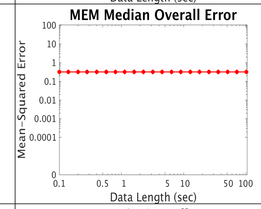
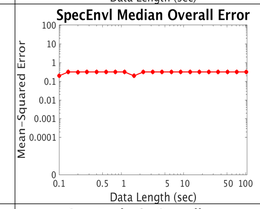
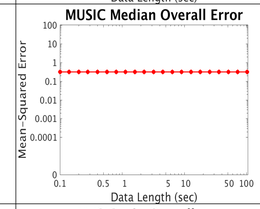
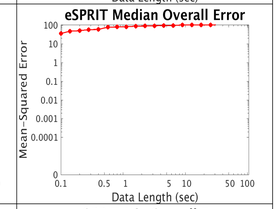
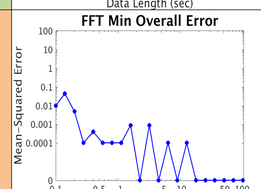
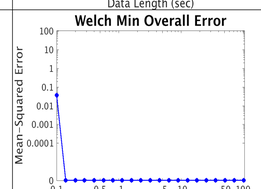
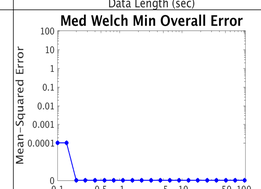
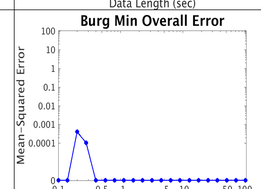
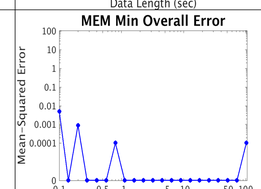
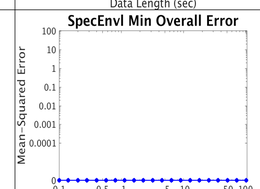
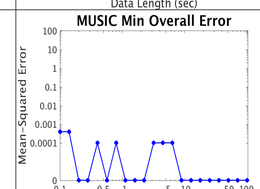
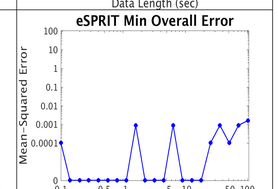
Conclusions

- MUSIC and eSPRIT
  - Perform exceptionally without noise, but fail even when filtered under 1/f noise, likely due to white noise assumption
  - Using the derivative of the signal could reshape the 1/f noise to white, while keeping the oscillatory components, but must be tested
  - eSPRIT gets worse with more data under noise, unless filtered
- Spectral envelope and Welch
  - Good candidates for further exploration
  - Achieve minimum error across parameter spaces in filtered noise scenario, with minimal data length
  - Perhaps selecting the optimal parameters in practice would work

References

Samaha, J., Bauer, P., Cimaroli, S., & Postle, B. R. (2015). Top-down control of the phase of alpha-band oscillations as a mechanism for temporal prediction. PNAS, 112(27), 8439-8444.

Stoica, P., & Moses, R. L. (2005). Spectral analysis of signals. Upper Saddle River, NJ: Pearson Prentice Hall.

Method	Fast Fourier Transform	Welch's Method	Median Welch's Method	Burg Spectrum	Maximum Entropy	Spectral Envelope	MUSIC	eSPRIT
	Dot product of the signal and sinusoids of varying frequencies Parameter free	Sliding window FFT averaging the spectra of individual windows Has large parameter space windowLength x overLap	Sliding window FFT median of the spectra of individual windows Has large parameter space windowLength x overLap	Autoregressive model that minimizes prediction error using an optimized Levinson–Durbin algorithm One parameter for model order	Special case of Burg spectrum, that results in a spectrum with analytic maximum entropy One parameter for model order	Autoregressive model, generalizes Capon method, assumes the data are passed through an adaptive, data-dependent bandpass filter Large parameter space numOfEigVals x spectralRadius	**Multiple Signal Classification** Eigenspace decomposition of signal covariance matrix of preselected size/lag, must know the size of the signal subspace, i.e. # of eigenvalues/vectors Parameter free, assuming 1 or 2 sinusoids	**Estimation of Signal Parameters via Rotation Invariance Techniques** Similar to MUSIC, as a subspace method, exploits the eigenvalue structure between a spectrum and its representation as a rotational transformation. State of the art. One parameter for model order
Two Peak Discrimination								
								
Noisy One Peak								
								
Filtered Noisy One Peak Detection								

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