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
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

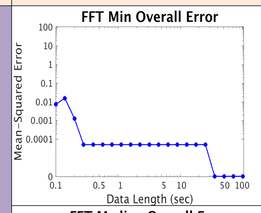
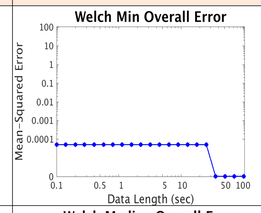
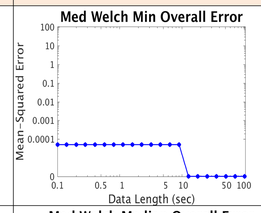
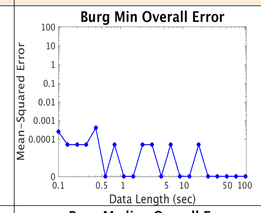
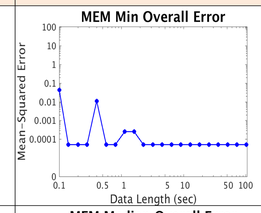
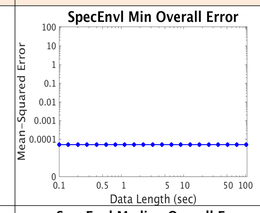
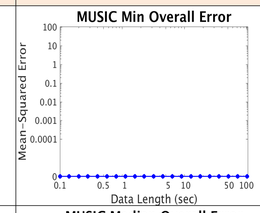
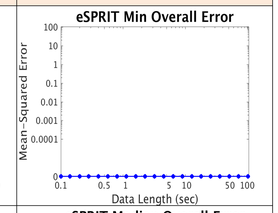
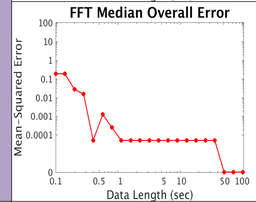
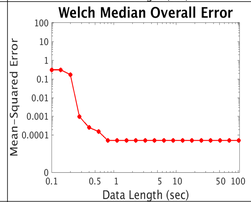
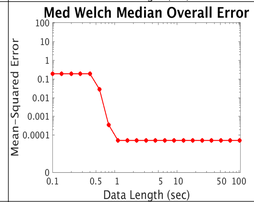
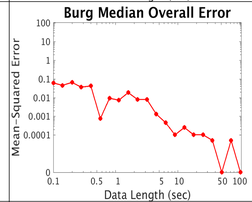
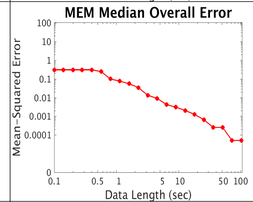
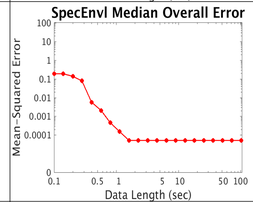
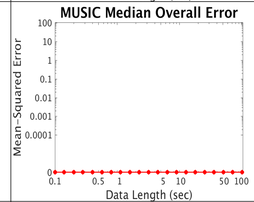
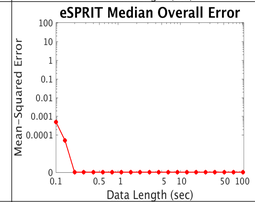
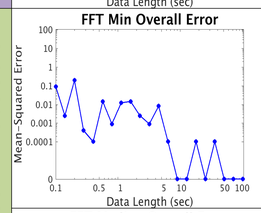
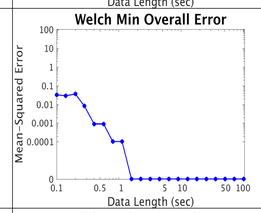
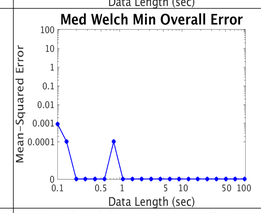
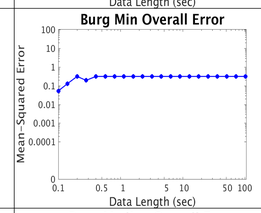
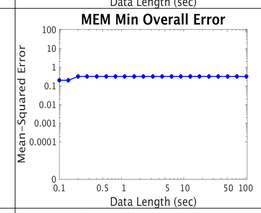
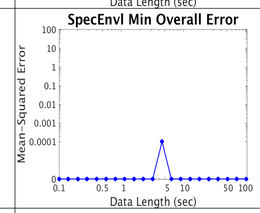
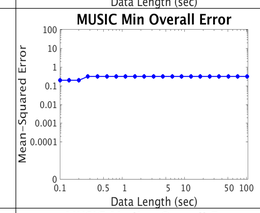
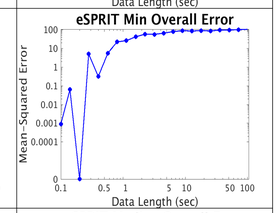
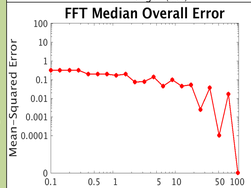
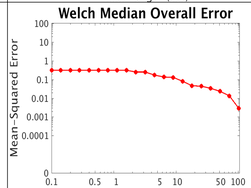
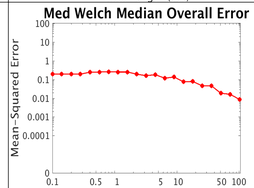
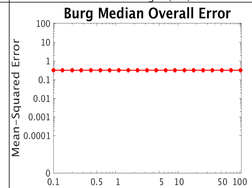
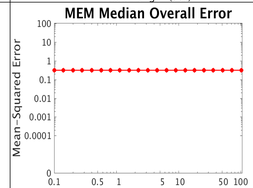
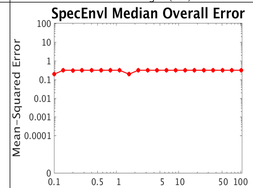
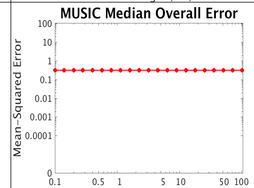
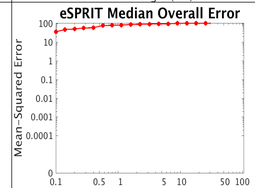
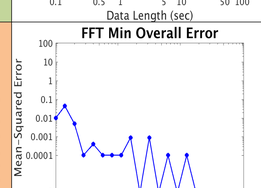
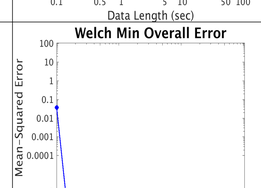
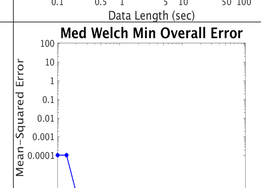
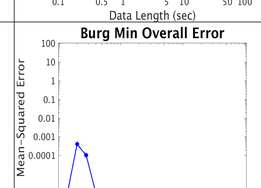
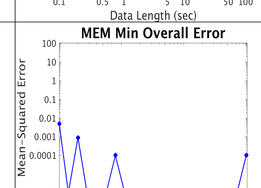
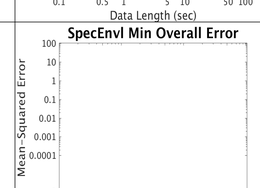
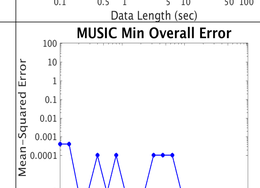
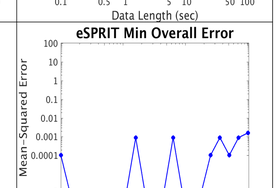
Same as above, 2nd order Butterworth IIR filter 10 -11 Hz passband

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

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

Method	**Fast Fourier Transform** Dot product of the signal and sinusoids of varying frequencies Parameter free	**Welch's Method** Sliding window FFT averaging the spectra of individual windows Has large parameter space: windowLength x overLap	**Median Welch's Method** Sliding window FFT median of the spectra of individual windows Has large parameter space: windowLength x overLap	**Burg Spectrum** Autoregressive model that minimizes prediction error using an optimized Levinson–Durbin algorithm One parameter for model order	**Maximum Entropy** Special case of Burg spectrum, that results in a spectrum with analytic maximum entropy One parameter for model order	**Spectral Envelope** Autoregressive model, generalizes Capon method, assumes the data are passed through an adaptive, data-dependent bandpass filter Large parameter space numOfEigVals x spectralRadius	**MUSIC** **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	eSPRIT **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	 FFT Min Overall Error	 Welch Min Overall Error	 Med Welch Min Overall Error	 Burg Min Overall Error	 MEM Min Overall Error	 SpecEnvl Min Overall Error	 MUSIC Min Overall Error	 eSPRIT Min Overall Error
	 FFT Median Overall Error	 Welch Median Overall Error	 Med Welch Median Overall Error	 Burg Median Overall Error	 MEM Median Overall Error	 SpecEnvl Median Overall Error	 MUSIC Median Overall Error	 eSPRIT Median Overall Error
Noisy One Peak Detection	 FFT Min Overall Error	 Welch Min Overall Error	 Med Welch Min Overall Error	 Burg Min Overall Error	 MEM Min Overall Error	 SpecEnvl Min Overall Error	 MUSIC Min Overall Error	 eSPRIT Min Overall Error
	 FFT Median Overall Error	 Welch Median Overall Error	 Med Welch Median Overall Error	 Burg Median Overall Error	 MEM Median Overall Error	 SpecEnvl Median Overall Error	 MUSIC Median Overall Error	 eSPRIT Median Overall Error
Filtered Noisy One Peak Detection	 FFT Min Overall Error	 Welch Min Overall Error	 Med Welch Min Overall Error	 Burg Min Overall Error	 MEM Min Overall Error	 SpecEnvl Min Overall Error	 MUSIC Min Overall Error	 eSPRIT Min Overall Error
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