

Running Head: SAMPLING BIAS OF TAPERING

Correcting sampling bias of tapering functions in EEG analysis

David A. Kaiser, Ph.D.¹ and M.B. Sterman, Ph.D.²

Rochester Institute of Technology, New York¹

and University of California, Los Angeles²

Abstract

Tapering functions such as Hamming or Hann functions are sources of error for spectral analysis of nonstationary signals as data at the center of an epoch are amplified relative to values elsewhere. Window overlapping corrects sampling bias, the unequal amplification and diminishment of data within an epoch, by analyzing spectra continuously across time. Window overlapping also permits rejection of artifact of any length (e.g., sub-epoch). An artifact rejection technique called seaming eliminates artifact of sub-epoch duration by connecting uncorrupted segments at the point where the artifact once was, but this approach should be avoided as it generates spurious frequencies, especially in lower bands. Clipping, a sub-epoch approach analogous to whole-epoch rejection, ignores spectral contributions of corrupted data without refashioning the time series. Clipping is recommended as it produces significantly less spectral distortion than seaming and no spurious frequencies when modest restrictions are observed. Window overlapping, also called sliding Fourier transforms, a mainstay of electroacoustics, seismology, and other fields of data analysis, improves the quality of EEG spectral analysis and reproduces the fluidity of temporal data in the frequency domain.

Keywords: Electroencephalography, data window, Hanning, nonstationary, artifact, overlapping windows

Correcting sampling bias of tapering functions in EEG analysis

EEG data has been analyzed with Fourier analysis for more than 70 years (Berger, 1932; Dietsch, 1932). Discrete Fourier transforms are commonly used to estimate spectral density but when a continuous signal is chopped into discrete segments, problems arise. Even when epochs are tailored to signal properties (Lopes da Silva, 1978), truncation of any time series (windowing) produces temporal discontinuities that cause considerable spectral rippling. This false spectral information is known as leakage, border ringing, or Gibbs' artifact, and it has been part of quantitative EEG since its inception (Grass & Gibbs, 1938, no relation). Hann, Hamming, and other data functions eliminate discontinuities by gradually tapering values to zero at an epoch's edge (Tukey, 1959), but the use of such functions presents its own set of problems. Tapering suppresses the ripples or side peaks but broadens the main peak. Spectral broadening is tolerated in order to eliminate leakage (Brigham, 1998) but more troublesome is the sampling bias inherent to tapering functions, the unequal attenuation of signal amplitudes across an epoch.

Different tapering functions have different sampling biases. For instance, more than three-quarters of Hann and Hamming cumulative weight occurs in their middle (i.e., central half) and Blackman-Harris functions are even more disproportionate (see Harris, 1978 for review). Overlapping or sliding windows eliminate sampling bias completely and although this correction is straightforward and common to seismology, acoustics, and neuroscience (e.g., Tukey, 1959; Theunissen & Doupe, 1998), it has not been widely adopted for EEG analysis. Its present lack of popularity is perplexing given its simplicity

and its advantage over non-overlapping or tiled windows in accommodating the range of stationarity of human EEG signals, from wholly stationary to virtual randomness.

Sampling bias also surfaces during artifact management in EEG analysis. Muscle movements (eye, tongue, face, neck, heart), changes in skin conductance, or equipment problems can bury cortical signals within non-cerebral potentials many times their size. Of course the solution is to exclude artifact from analysis through correction or rejection techniques. In artifact correction, non-cerebral potentials are estimated and subtracted from a signal directly, a precarious approach that involves models of regression, propagation, time delay estimations, independent components analysis, or other assumptions (Kenemans et al., 1991; Wallstrom et al., 2004; Croft et al., 2005). In artifact rejection, an entire epoch is rejected when artifact is present anywhere within its duration, or with sub-epoch rejection only contaminated data is eliminated and remaining data is left intact and can be analyzed. How we analyze this remaining data depends on whether we manage the consequences of artifact rejection in the time domain or in the frequency domain (Kenemans et al., 1991).

In a time domain technique called “seaming,” contaminated segments are deleted and the signal is refashioned by connecting uncorrupted data from either side of the eliminated artifact at a convenient zero-crossing as shown in Figure 1. An artifact of 300 ms, for instance, pulls remaining data forward this amount of time in the record. In “clipping,” contaminated segments are converted to zeroes (the signal is “clipped”) but the course of the time series remains intact, which is the critical difference between approaches. Data segments can be overwritten with zeroes but their positions stay put and the contiguous zeroes allow convenient identification and exclusion during analysis. In

fact any clipping or zeroing out can be performed virtually, in an auxiliary channel for instance, so that the actual EEG record remain untouched and unaltered. Zeroing out sections of an auxiliary channel consisting of ones provides a convenient means of indicating what to keep (clean data) and what to exclude (artifact) during spectral analysis. In this way clipping manages artifact in the frequency domain.

Two complementary rules are also employed for clipping: Any data window with artifact across 10 % of its length is ignored during spectral analysis AND each act of clipping (zeroing out) must capture a contiguous segment of data equal to or greater than 10 % of a window. For example, in a 128-samples-per-epoch record the smallest allowable clipping is of 13 contiguous points. The percentage in this dual-rule system is based on cumulative weight in the tail of a tapering function. As shown in Figure 2, a Blackman-Harris 4-term window distributes less than 0.1 % of its weight across its opening tenth. Likewise, Hanning coefficients accumulate to a mere 0.6 % at this point in its tail, but a Hamming window distributes 2.0% of its weight due to its pedestal. Accordingly, a 6% rule is recommended for a Hamming window, where less than 1.0% of its total weight is distributed. The dual 10% rules ensure that a corrupted data segment is either ignored entirely or else positioned at the edge of a window where tapering coefficients attenuate its impact to a negligible amount. When overlapping or sliding windows are used, clean data adjacent to an artifact will not contribute to windows peaking directly over the nearby artifact, but this data will contribute to other windows sliding past.

Finally, the seaming technique produces additional spectral distortion when disparate signals are connected. A very simple case -- seaming together pure sine waves -

- illustrates the problem. As shown in Figure 3, when sine waves of different frequencies (e.g., 5 and 9 Hz) are brought adjacent to each other *in phase*, middle frequencies are identified at and around the seam (e.g., 7 Hz). When juxtaposed *out of phase*, lower frequencies are identified at the seam (e.g., 1-4 Hz).

In this paper we evaluate sampling bias in three popular data functions and the effectiveness of overlapping windows in EEG analysis. We also compared performance of two sub-epoch artifact rejection techniques known as seaming and clipping.

Method

Participants. Twenty right-handed participants (10 men, 10 women, mean age 29.2 years old) participated in this study. Participants reported no history of neurological problems, no use of controlled substances 24 hr prior to the study, and no recent experiences which could alter normal psychophysiology (e.g., disturbed sleeping habits, atypical stress). Informed consent was obtained prior to their participation using a form approved by the Veterans' Administration Human Study Committee.

Apparatus. A Neurosearch-24 acquisition unit was used (Lexicor Medical Technologies, Inc.). Using a 12 bit A/D converter, EEG data were digitized at 512 samples per s during acquisition but analyzed at 128 samples per s. Epoch length was set at 1 s. High and low pass filters were set at 2 Hz and 38 Hz with rolloffs of 12 and 48 Db/octave, respectively. Topographic EEG was recorded from the scalp using 10-20 system elastic Electro-Caps. Fast Fourier transformation was performed on each data window (1 s length, 128 samples per s) on 19 channels for 30 s of data per file. Three data windows were used, each analyzed separately: Hann, Hamming, and 4-term Blackman-Harris (-92 db, coefficients 0.35875, 0.48829, 0.14128, 0.01168).

Procedure. Each participant was fitted with an appropriate-sized Electro-Cap. Preparation of recording sites involved cleaning the scalp at each site with gentle scraping of an uncottoned Q-tip. Electrolytic gel was injected into each electrode port using a blunt-needle syringe. Reference electrodes were attached to each ear lobe. All electrode impedances were below 5 K. Preparation instruments that came in direct physical contact with the subject were discarded after use.

EEG was acquired at the Sepulveda Veterans Administration Medical Center Neuropsychology Laboratory in a dimly lit, electrically- shielded and sound-attenuated room approximately 2.5 by 3.5 m in size. Participants were seated in a padded lounge chair which could be positioned for maximum comfort. A closed-circuit video and two-way intercom system allowed monitoring during the study. A single 3-min eyes closed resting condition was recorded from each participant.

In addition to conventional data records, two additional record types were created. To evaluate sampling bias in tiled windows, every EEG record was wrapped: the first epoch was added to the last. This addition allows for a sequence of data so that analysis for every possible window starting position will be of identical data. Although this artificial juxtaposition of epoch 1 to the file's end likely creates some discontinuities at the point of wrapping (not unlike seaming), it allows analysis of the *exact same data* where only position within each window varies. Other approaches require stationary signals or alter the data (e.g., eliminate discontinuities at the point of the wrap artificially) or involve analysis of slightly different data sets (e.g., a point halfway into the first or last epoch will register in only half of the possible window assemblies). For 128 digitized samples per epoch, 128 different starting points are possible. Also, artificially corrupted

data files were created to allow comparison of artifact rejection techniques. Four eye blinks of either 250 ms or 1 s in length were inserted into each record every 2 s to produce modest (3.3% contamination, or four 250 ms segments in 30 s), mild (6.7 % contamination, four 250 ms segments in 15 s), moderate (13.3 %) and severe (26.7 %) artifact conditions for each record.

Results

Sampling bias was examined for 30 s of eyes closed data from 20 participants using wrapped data files. Spectral magnitude of six frequency bands (1-4, 4-8, 8-12, 12-15, 15-18, and 18-25 Hz) were computed for 19 sites for each 30-epoch assembly as well as a global average (i.e., mean of all 128 assemblies). Sampling bias was analyzed for the entire spectrum of interest (1-25 Hz), and for six bands independently. Results were similar for all three data functions so only Blackman-Harris results are described and topographic differences were not analyzed (i.e., site means were averaged) order to minimize Type I and II error.

Total spectral magnitude for each assembly (labeled by their starting point in the first epoch) was statistically compared to a global mean. Mean absolute error rate was 4.96% for all 128 comparisons. Nearly half (61 of 128) differed significantly from the global mean (dependent t-tests, $df=19$, $p<.05$). Because this is a risk analysis, correction for multiple comparisons were not applied as it would undermine the risk. Each analysis on its own reflects the sole pass a researcher using tiled windows would make for this data set. When frequency bands were analyzed separately, alpha and high beta were most sensitive to epoch segmentation. Alpha activity differed significantly from its global

mean in 36 and high beta in 82 of 128 comparisons. Figure 4 illustrates spectral distortion as a function of epoch position in a data window.

Seaming and clipping techniques were evaluated in the four artifact severity conditions for each of the 20 recordings. Spectral means were compared to the original uncorrupted file (i.e., pre-blink-insertion), with Bonferroni corrections for all comparisons. Using a two-way within-subject analysis of variance, rejection technique interacted significantly with artifact severity, $F(3,57)= 4.9, p<.05$. For modest artifact, clipping outperformed seaming, 1.1 % to 1.4 % error compared to the original file, $t(19)=-3.14, p =.005$. For mild, moderate, and severe artifact, clipping produced significantly less spectral distortion than seaming, 2.0 % to 2.7 %, 2.2 % to 3.6 %, and 4.2 % to 5.7 %, $t(19)=-3.70, p<.005$; $t(19)=-4.13, p<.005$; $t(19)=-4.77, p<.005$, respectively. To limit multiple comparisons, only the mild artifact condition was analyzed for frequency effects, and the three high frequency bands were combined into a single beta band. It was found that rejection technique interacted with frequency band, $F(3,57)= 3.79, p<.05$. Seaming distorted delta band activity the most, 72% more distortion than clipping, 4.3% compared to 2.5%, $t(19)=-2.91, p<.01$. Seaming also produced more distortion in alpha, 2.3 % to 1.9 %, $t(19)=-3.11, p<.01$; but similar distortion in theta and beta bands, $p>.01$.

Clipping was also compared to traditional whole-epoch rejection on data loss and spectral distortion. In the modest and mild conditions 1 s of data was lost to eliminate four eye blinks compared to 4 s lost with whole-epoch rejection. Total spectral magnitude distortion (difference from original uncorrupted mean) was significantly less for the sub-epoch rejection technique compared to the whole epoch rejection for both the modest

artifact condition, 1.1 % versus 2.2 % error, $t(19)=-10.48$, $p < .005$; and the mild artifact condition, 2.0 % versus 4.2 % error, $t(19)=-12.63$, $p < .005$.

Finally, incidence of simultaneous multi-channel zero-crossing, a prerequisite of seaming, was evaluated in all 76,000 digitized samples from this study. It was found that a total of three zero-crossing co-occurred simultaneously in all 19 channels in this moderately large data set, but without uniform phase in any instance (all in or all out across 19 channels).

Discussion

Tapering functions are a necessary ingredient of discrete Fourier analysis but also a potential source of spectral distortion due to sampling bias. Temporal distortion is spectral distortion and tapering distorts the temporal signal, as shown in Figure 5. Alpha and high beta bands were most distorted by tapering, but any frequency may be susceptible to distortion. Total spectral distortion was modest but entirely unnecessary (4.96 % for current data). Half a century ago Tukey (1959) introduced moving windows, a variant of overlapping windows (Bly & Rosenberg, 1986), to counter spectral distortion in nonstationary signal analysis as part of an attempt to identify underground nuclear explosions in seismic data. The concept of a data window was also introduced in this work.

Window overlapping counters sampling bias perfectly. For many data windows 50% overlap acts as a unity function while others such as a 4-term Blackman-Harris require 75% overlap for unity (Kaiser & Serman, 2001). Given the current state of computers, however, maximum overlap is recommended (c.f. the global mean of Figure 4).

Sub-epoch rejection is superior to whole-epoch rejection in data loss in theory and practice, and spectral magnitude distortion was twice as large for whole-epoch rejection for identical data.

In comparing sub-epoch rejection techniques, clipping was more accurate than seaming in lower and higher frequency bands; spectral means associated with clipping were nearer to pre-insertion spectral means. The difference between seaming and clipping was small, as expected, because both techniques analyzed identical data. Nevertheless clipping provided better spectral estimates than seaming for every level of artifact severity. Poor performance by seaming was likely due to abrupt juxtaposition of disparate signals. Seaming has an additional nearly impossible burden of matching phase between signals in all channels. Figure 3 shows the results of seaming pure sine waves of different frequencies. When seamed in phase, middle frequencies were identified; when seamed out of phase, adjacent waveforms are treated as a single waveform of combined duration and a lower frequency (e.g., delta range) was identified. This latter effect is especially disturbing because it indicates that identical signals seamed out of phase will generate spurious frequencies.

Clipping is whole-epoch rejection revised for temporally continuous spectra. As with whole-epoch rejection, any window with significant artifact is eliminated in its entirety, but each data point will contribute to the spectral mean by registering in neighboring windows. Clipping will not win over scientists pursuing artifact correction techniques for EEG analysis, but it is a worthwhile approach for conventional Fourier analysis.

The point of this study was to examine the impact of tapering functions on analysis and artifact rejection, and not the effect of artifact in EEG analysis *per se*. None of the results in this paper are surprising. What is surprising is how few EEG software designers incorporate sliding windows in their applications. In terms of artifact management, clipping is recommended for continuous spectra. Clipping does have a single disadvantage compared to seaming in that it requires a minimum length of uncorrupted contiguous data (90% of an epoch due to the 10 % rule). But this prerequisite wisely limits data manipulation when only short segments are available. Although we might want to merge multiple short segments into a workable epoch length, which seaming allows, clipping forces us to ignore short isolated signals in this form of analysis.

References

- Berger, H. (1932). Über das Elektren-kephalogramm des Menschen. Fünfte Mitteilung. (On the Electroencephalogram of Man. Fifth Report.) *Archiv für Psychiatrie und Nervenkrankheiten*, 98, 231-254.
- Bly, S., & Rosenberg, J. (1986). A comparison of tiled and overlapping windows, *Proc. CHI '86 Conference - Human Factors in Computing Systems*, ACM, New York, NY, pp. 101-106.
- Brigham, E.O. (1998). *The Fast Fourier Transform and its Application*. Prentice Hall: Englewood Cliffs, NJ.
- Croft RJ, Chandler JS, Barry RJ, Cooper NR, & Clarke AR (2005). EOG correction: A comparison of four methods. *Psychophysiology*, 42, 16-24.
- Dietsch, G. (1932). Fourier-analyse von elektrencephalogrammen des menschen. *Pfluger Archiv Physiologie*, 230, 106-12

- Grass, A.M. & Gibbs, F.A. (1938). A Fourier transform of the electroencephalogram. *Journal of Neurophysiology*, 1, 521-526.
- Harris FJ (1978). On the use of windows for harmonic analysis with the discrete fourier transform. *Proceedings of the IEEE*, 66, 51-83.
- Kaiser, D.A. & Serman, M.B. (2001). Automatic artifact detection, overlapping windows, and state transitions. *Journal of Neurotherapy*, 4, 85-92.
- Kenemans, J.L., Molenaar, P.C., Verbaten, M.N. & Slangen, J. (1991). Removal of the ocular artifact from the EEG: A comparison of time and frequency domain methods with simulated and real data. *Psychophysiology*, 28, 114-121.
- Lopes da Silva, F.H. (1978). Analysis of EEG non-stationarities. In W.A. Cobb & H. Van Duijn (Eds.), *Contemporary Clinical Neurophysiology* (EEG Suppl 34). Elsevier, Amsterdam, 163-179.
- MacCrimmon, D.J., Durocher, G.J., Chan, R.W.Y., Hay, D.R. & Saxena, B.M. (1993). Computerized pattern recognition of EEG artifact. *Brain Topography*, 6, 21-25.
- Theunissen F.E. & Doupe A.J. (1998). Temporal and spectral sensitivity of complex auditory neurons in the nucleus HVC of male zebra finches. *Journal of Neuroscience*, 18, 3786-3802
- Tukey, J.W. (1959). Equalization and pulse shaping techniques applied to the determination of initial sense of Rayleigh waves. In *The Need for Fundamental Research in Seismology* 60- 129. Appendix 9. Report of the Panel on Seismic Improvement, Washington, DC: U.S. State Department.
- Wallstrom GL, Kass RE, Miller A, Cohn JF, & Fox NA. (2004). Automatic correction of

ocular artifacts in the EEG: a comparison of regression-based and component-based methods. *International Journal of Psychophysiology*, 53, 105-19.

Figure Captions

Figure 1. Examples of clipping and seaming rejection techniques. Segment B is present but zeroed out with clipping but eliminated entirely with seaming.

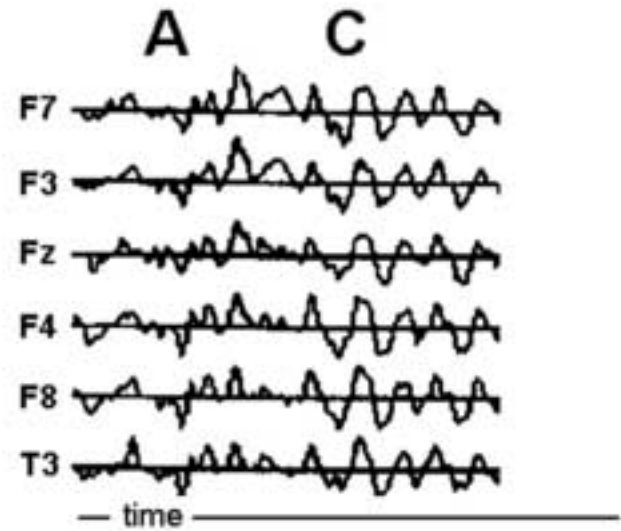
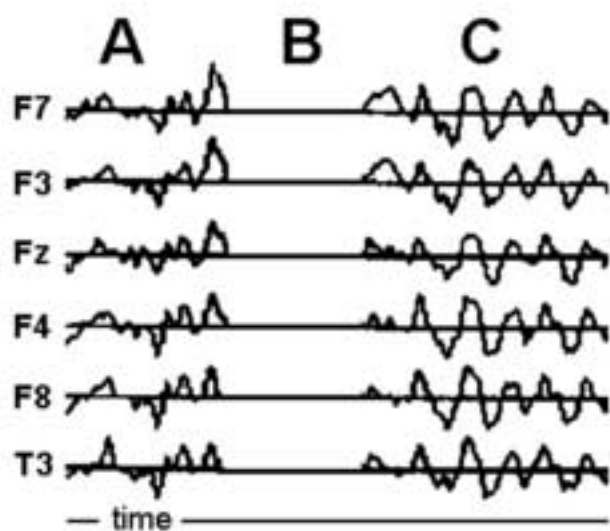
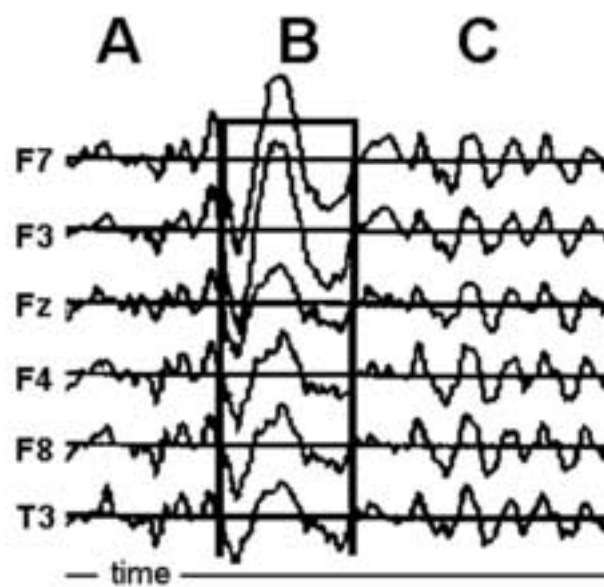
Figure 2. Weighting coefficients of Hanning, Hamming, and Blackman-Harris functions across an epoch. Note the negligible cumulative weight (area under the curve) from the origin to the vertical line, 10% into the epoch, for Blackman-Harris in particular.

Figure 3. Spectral magnitudes when 5 Hz and 10 Hz signals are seamed. Darkened areas show spurious frequency information generated at the juxtaposition or seam.

Figure 4. Mid-parietal beta activity for 30 s of eyes closed rest as a function of epoch starting point when only windows are tiled instead of overlapped.

Figure 5. Effect of Hanning tapering in the time domain. Only the bold approximation of the signal is subjected to spectral analysis.

Figure 1
[Click here to download high resolution image](#)



CLIP

SEAM

Figure 2
[Click here to download high resolution image](#)

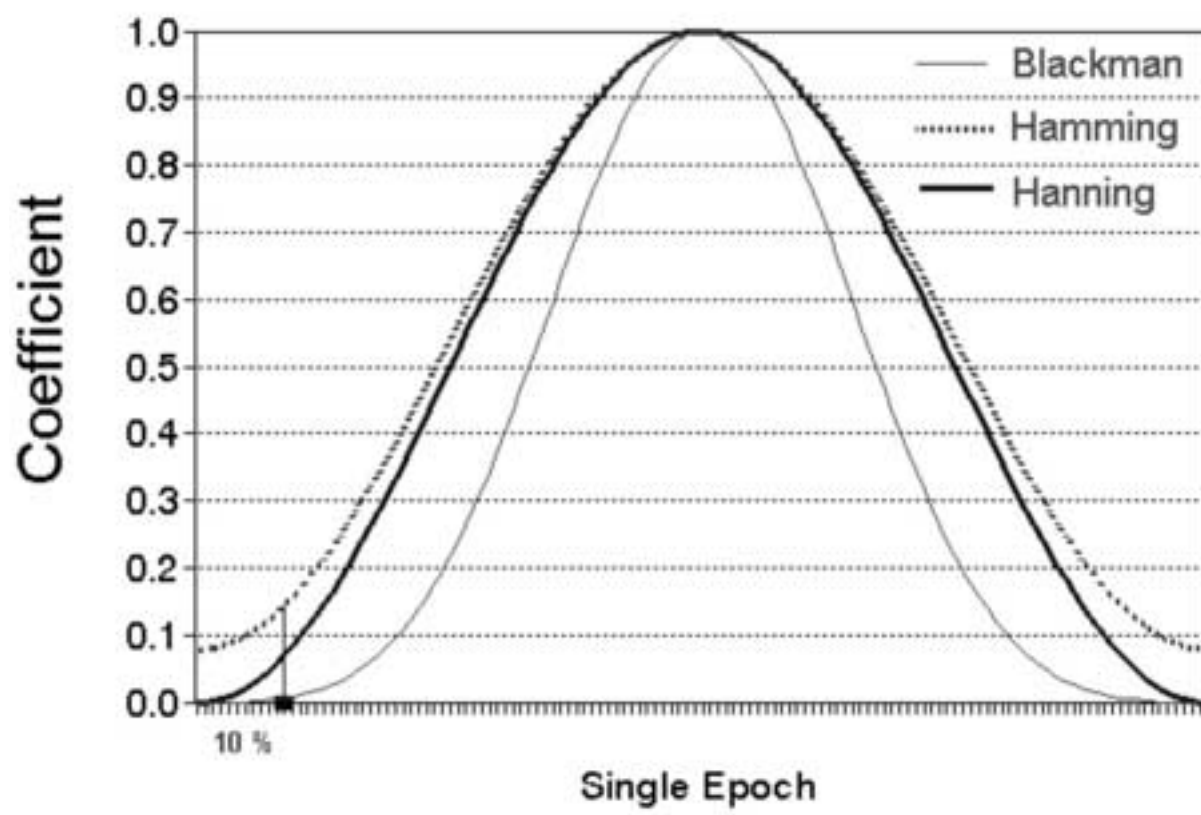


Figure 3
[Click here to download high resolution image](#)

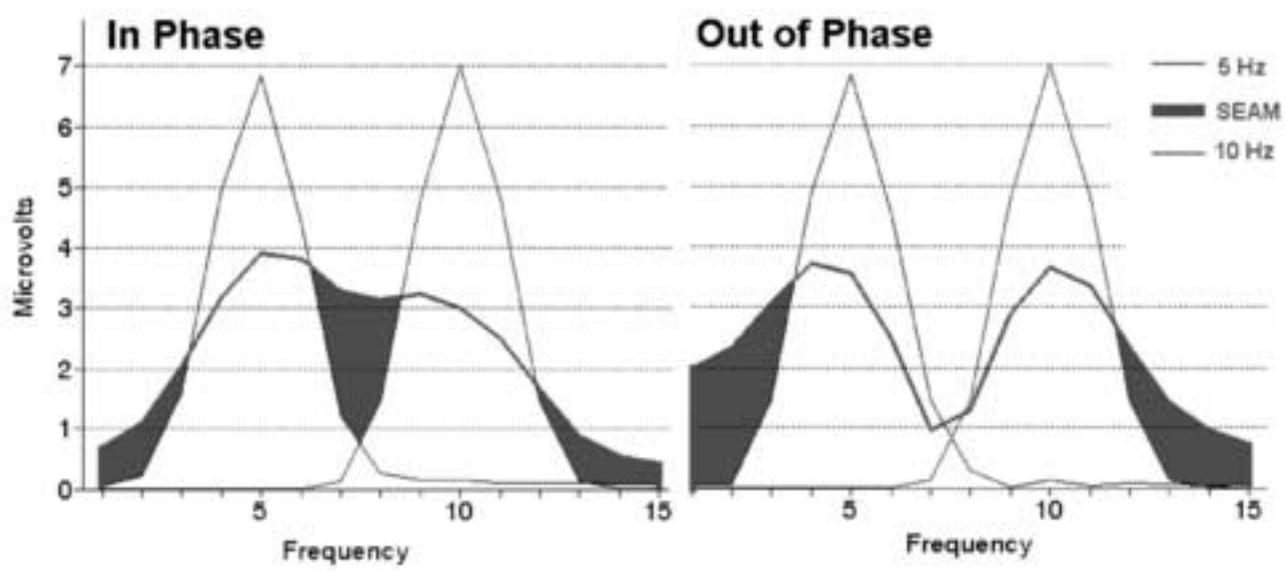


Figure 4

[Click here to download high resolution image](#)

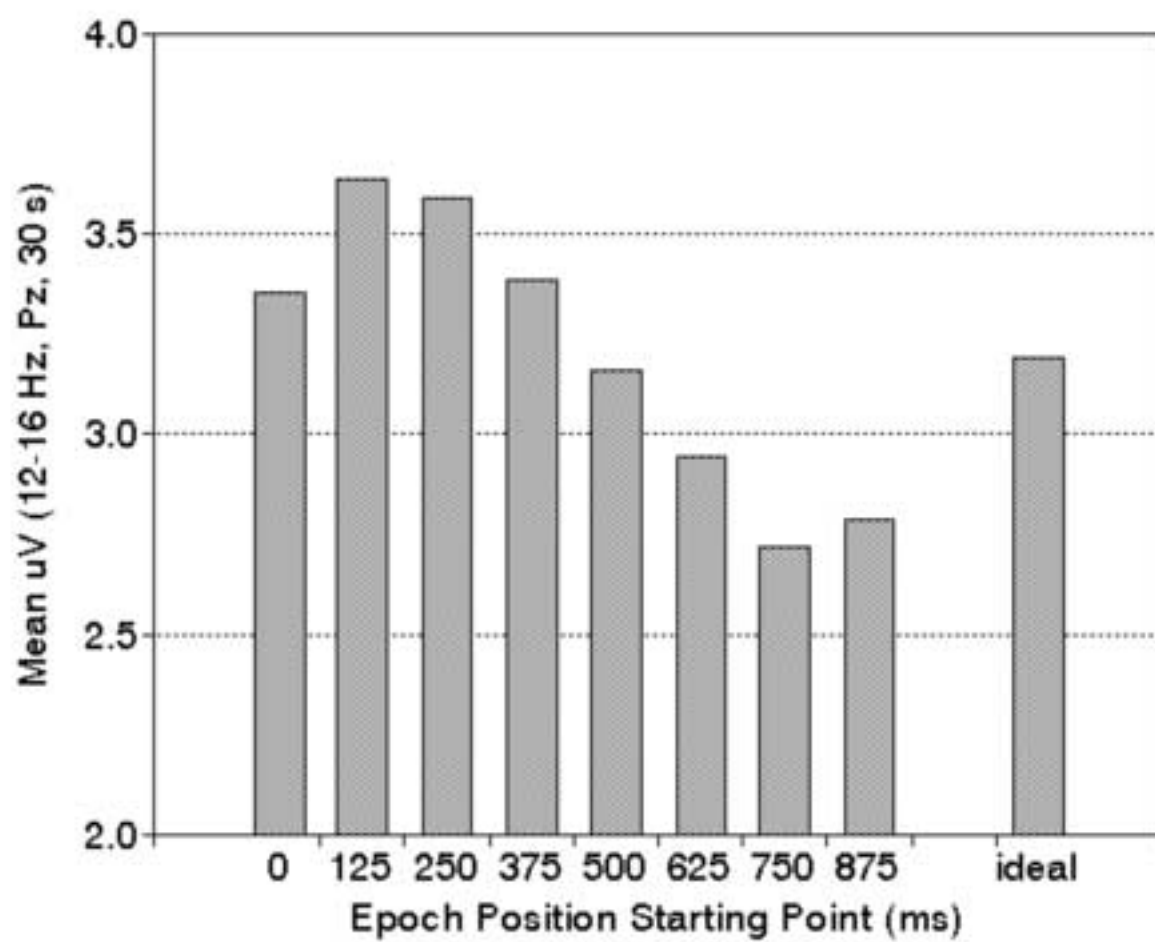


Figure 5
[Click here to download high resolution image](#)

