ARTIFACT AND SIGNAL

Example artifacts caused by ultrahigh field (UHF) fMRI scanning with EPI sequence while performing neural recording are shown in Figure S1. Artifacts are much larger than local field potential signals of interest and the interference frequency depends on scanning parameters including repetition time (TR), number of slices, and number of k-space sampling shots.

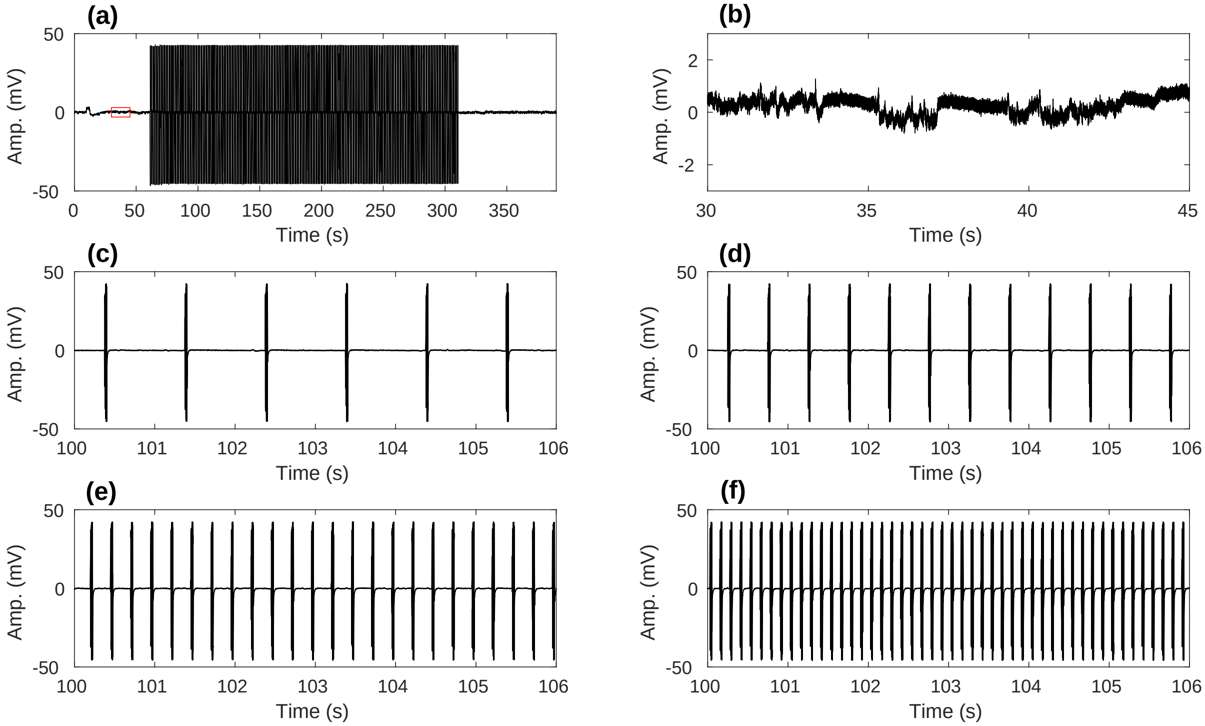

Fig. S1. Example of interferences in extracellular recording caused by fMRI scanning at UHF with differing acquisition frequencies. Scanning artifacts are tens of millivolts (a) compared to extracellular local field potential, which is hundreds of microvolts (b). Subplot (b) corresponds to small (red) boxed region in (a). Scanner interference frequency depends on number of slices, multiple k-space sampling segment shots, and repetition time (TR) for echo-planar imaging (EPI) acquired with regularly spaced slice timing. Slices × shots ÷ TR = 1 Hz (c), 2 Hz (d), 4 Hz (e), and 8 Hz (f).

SIGNAL PRE-PROCESSING

A general overview of the signal pre-processing approach is provided. The first stage involves setting parameters to prepare for artifact-based signal alignment and filtering. Artifacts are aligned by repetition time (TR), which is known from the scanning parameters. The data need to be upsampled to aid in artifact alignment because the artifacts are high frequency and the data acquisition clock is not synchronized with the MRI console [1]. Therefore, the data are upsampled by a factor of 4 using spline interpolation. Then the TR is estimated by checking the cross correlation of artifact occurrences for a maximum lag width of a few ms to account for small errors between the set TR parameter and the actual value. The average result from all artifact occurrences across the 16 channels is used as the TR. At this point the TR is an integer multiple of the sampling period, but that integer is not necessarily evenly divisible by the upsampling factor of 4, so rather than downsampling by taking every 4th sample, we resample the data using spline interpolation at the sampling rate closest to the original sampling rate that allows an integer number of samples for each TR. This allows window-based operations to be performed at approximately the original sampling frequency to improve computation speed if desired, but in general we operate on the upsampled data for improved filtering performance. Finally, we estimate the standard deviation of the first difference of the upsampled neural recording data from a baseline recording segment (1-3 minute duration) before the beginning of the fMRI scan. The standard deviation is estimated for each channel and stored for use later. Data acquired during EPI reference and dummy scans were nulled due to differences in waveform shapes compared to acquisition scans.

SIGNAL ALIGNMENT

Our artifact removal approach relies on averaging signals across time as well as performing a principal component analysis (PCA) transformation and using singular value shrinkage (SVD). These techniques are performed channel-by-channel as the artifact waveform shape varies across channels (space) but is relatively consistent for an individual channel across repetitions (time). The original channel data is a column vector. To perform averaging and PCA, the individual channel data need to be rearranged into a matrix and aligned based on the artifact timing. In the simplest implementation, nonoverlapping rectangular windows can be used to segment the data and align them based on repetition time (TR).

First, data are upsampled by a factor of 4 (we only store one upsampled channel of data in memory at a time for computational reasons, necessitating the upsampling to be performed again at this step for each channel). Then, nonoverlapping rectangular window segmentation is performed where the window length is the TR. The data are stored in matrix form where the rows are sample points in each window and the columns are different artifact occurrences (repetitions/observations). The segment means are removed so that the offset of each windowed segment is zero. Cross correlation is used to find the best alignment of each artifact occurrence to the first one, which should be small or zero because the TR was previously corrected. Artifacts are shifted by the appropriate number of samples and zeros are added to either end of the window to account for the shift. Afterwards the segment means are added back to the matrix and the data are reshaped into a column of data (un-segmented).

One may wonder why it is necessary to use cross correlation-based alignment of the windowed segments when a similar operation was performed in pre-processing. The explanation is that in pre-processing, the cross correlation was used to find the most accurate TR from the data (where most accurate means highest average linear correlation at the specified sampling frequency), but artifacts were not shifted to improve alignment. In this step, artifact waveforms are shifted by a few samples to improve the overall alignment for computing the average artifact waveform.

WINDOWING

After pre-processing and signal alignment, we begin estimation of the signal artifacts in the recorded data. The first step is to take the first difference of the data; the reason for doing so is explained in detail in the main body of the paper. At this stage the data is still upsampled from the alignment step. Subsequently, the first difference of the data is windowed using overlapping tapered windows. The use of overlapping tapered windows greatly reduces edge effects that can occur in the processing of signals with nonoverlapping windows. Selecting a window and hop size that satisfies the constant overlap add (COLA) constraint allows perfect reconstruction of the original signal [2]. Alignment is based on repetition time (TR) as depicted in Figure S2. We refer to the aligned data matrix as the observed matrix ***Y***. In our implementation, we used hamming windows approximately 250 msec in length with 75% overlap.

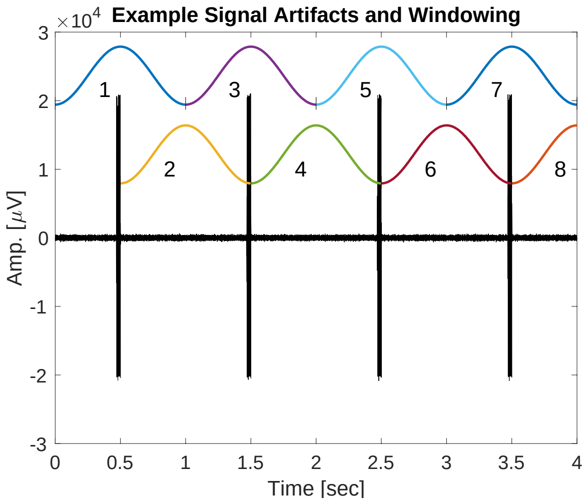

Fig. S2. Example windowing of signal contaminated by artifacts. Artifact interferences occur at 1 second intervals (TR = 1 second, interferences at 0.5, 1.5, 2.5, 3.5 s). In this simple example, the window is a 1 second long hamming window, and the overlap is 50%. The odd numbered windows (1,3,5,7) are used to form a matrix of 1 second long data segments with the artifact interferences aligned. Likewise, the even numbered windows form another matrix of 1 second long data segments with interferences aligned in the windows.

FIRST DIFFERENCE PRESERVES ARTIFACT AUTOCORRELATION

In the body of the paper, the first difference of neural signals was shown to have an autocorrelation of approximately a delta function, indicating that averaging across time reduces the neural signal first difference – similar to noise averaging. However, the autocorrelation of artifacts caused by fMRI scanning is preserved under the first difference operation, as shown in Figure S3.

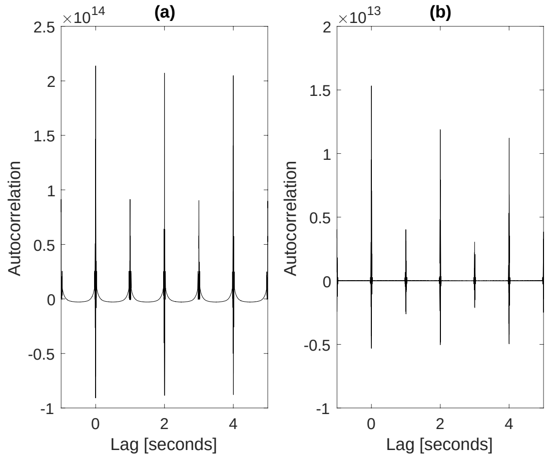

Fig. S3. Autocorrelation of neural signal with artifacts (a), and first difference of neural signal with artifacts (b). The autocorrelation of artifacts is preserved under the first difference operation. Large correlation at lags of 2n (for integer n) correspond to TR, smaller correlations at 2n-1 are due to the use of 2 shots in scanning in this example.

HARDWARE COMPARISON

A comparison of EPI artifacts recorded on the two sets of hardware mentioned in the methods section is presented in Figure S4. The left-hand and center subplots correspond to recordings made on our older hardware at 9.4T during 8 Hz EPI acquisition and at 16.4T during 10 Hz EPI acquisition. The right-hand subplots correspond to newer hardware recording during 8 Hz EPI at 16.4T. The newer hardware shows that recovery time is much shorter even in the case of larger artifact occurrences.

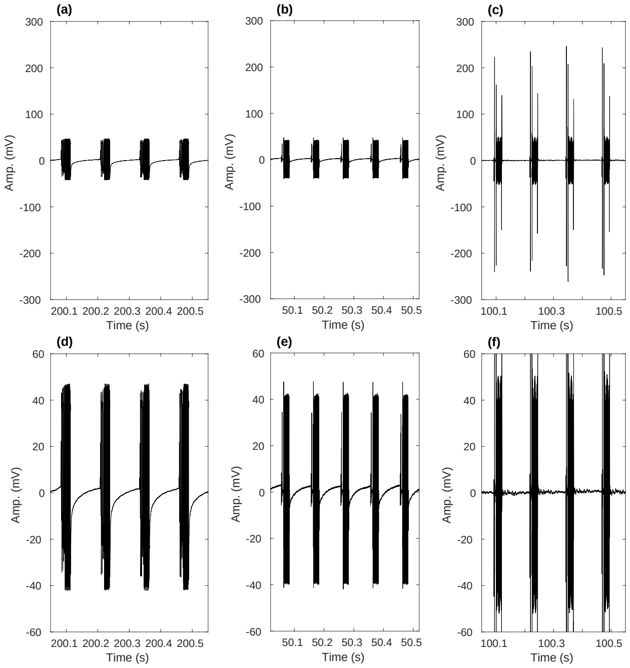

Figure S4. Comparing artifacts and amplifier recovery for older hardware during 8 Hz EPI at 9.4T (a) and (d), 10 Hz EPI at 16.4T (b) and (e), and newer hardware during 8 Hz EPI at 16.4T (c) and (f). The newer hardware recovers much more quickly than the older hardware, even when the artifact maximum amplitudes are larger.

Supporting Information

REFERENCES CITED IN SUPPORTING INFORMATION

[1] R. K. Niazy, C. F. Beckmann, G. D. Iannetti, J. M. Brady, and S. M. Smith, “Removal of FMRI environment artifacts from EEG data using optimal basis sets,” *Neuroimage*, vol. 28, no. 3, pp. 720–737, 2005.

[2] A. V. Oppenheim and R. W. Schafer, *Discrete-Time Signal Processing*, 3rd ed. Upper Saddle River, NJ: Pearson, 2009.