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Electrical Distance as a Reference-Free Measure for Identifying Artifacts in Multichannel Electroencephalogram (EEG) Recordings

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Abstract

Multichannel EEG, with hundreds of scalp placements now common, has increased the likelihood of recording artifacts in one or more channels within any given time epoch. Reliable artifact detection is mandatory because of distortion in signal topography. This becomes increasingly difficult as the number of sites and epochs increases. A systematic statistical approach for dense electrode arrays uses threshold criteria (amplitude, etc.) and their observed distributions to identify artifacts as median-based deviations (Junghöfer et al., 2000). Whereas this elegant approach eliminates the subjectivity of visual artifact screening, it is based on criteria requiring the choice of a particular recording or offline reference. Moreover, if the reference is contaminated, an artifact will be "detected" in all other channels. These problems can be circumvented and simplified with a reference-free electrical distance measure, which quantifies signal similarity through variances of waveform differences for all pairwise combinations within a given montage. Because spatial (recording sites) and temporal (sample points) proximity warrants highly intercorrelated surface potentials due to volume conduction, a low signal similarity at nearby electrodes strongly implies an unrealistic deviance (i.e., artifact). Electrical distance frequency distributions, both within and across individuals, thereby provide an easy, objective, and reference-free approach to identify recording artifacts, including those affecting the reference site. Implementations are shown for 31-, 67- and 129-channel montages.

The Problem

EEG recording artifacts, which can result from a variety of sources (e.g., body or eye movements, EKG, alpha rhythms, amplifier drift or reset, electrical fields in the recording environment, digitizing noise, electrolyte bridges), distort the time course and the topography of the EEG signal. The now common use of *dense electrode array (DEA)* EEG montages, which can include hundreds of scalp sensors, has increased the occurrence of one or more artifacts within any given time interval. Whereas routine artifact screening (e.g., by visual inspection or amplitude thresholds) is commonly applied before data processing and analysis, this task becomes disproportionately difficult with increases in sites and epochs. The subjectivity of visual artifact screening has been addressed by a systematic statistical approach, which identifies DEA artifacts (e.g., large amplitudes, drifts, alpha) as median-based deviations from the observed artifact distributions within or across subjects (Junghöfer et al., 2000). All of these artifact procedures, however, are based on criteria that require the choice of a particular reference (recording or offline). Of course, if the reference channel is contaminated (but referenced to zero), all other channels will contain an "artifact."

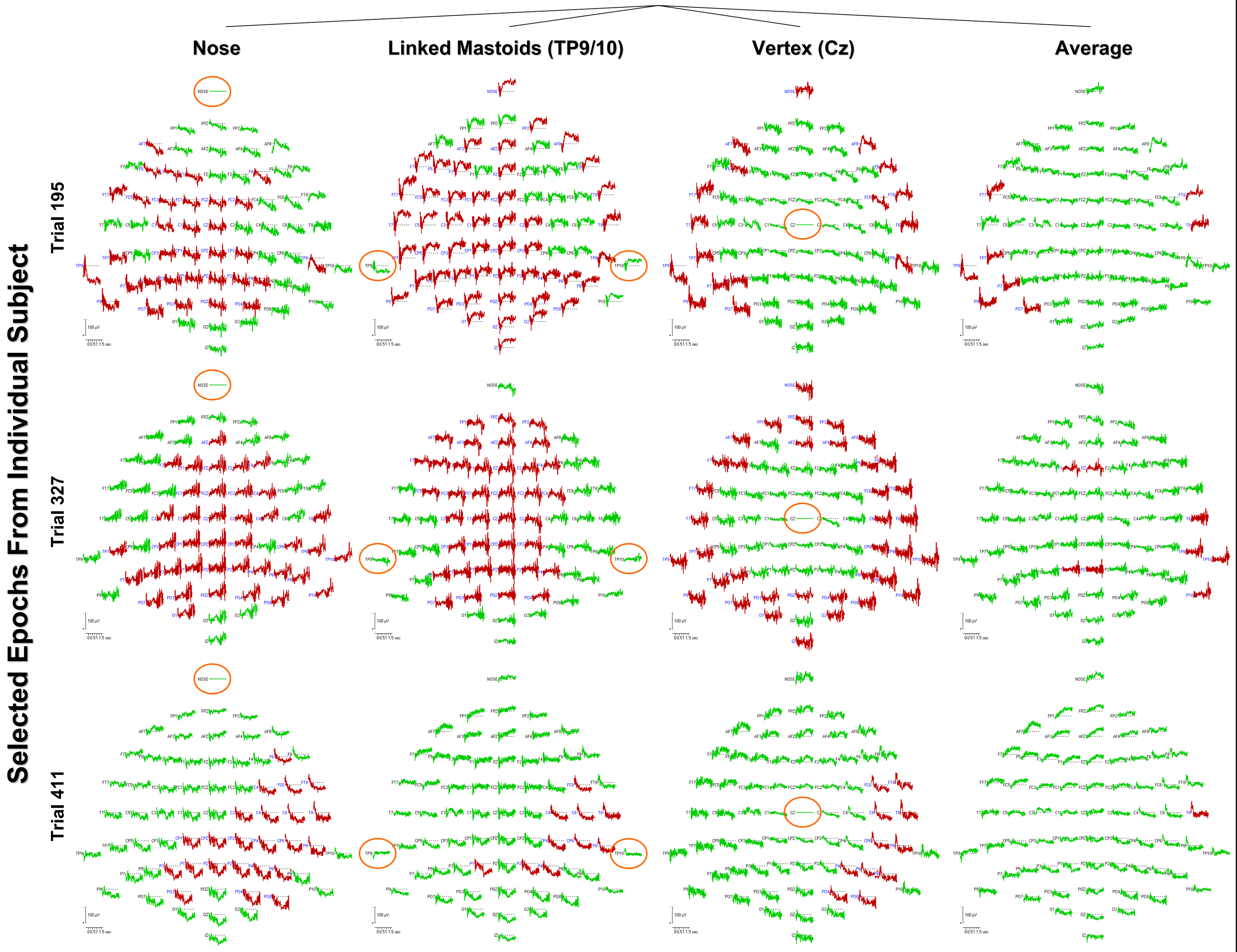


Fig. 1. Reference-dependent identification of artifacts in three single 2-s epochs (rows: #195, #327, #411) of one participant (67-channel EEG montage). Shown are clean and artifact channels based on a 100-µV range criterion (max - min > 100 µV) for four typical reference schemes (columns: nose, linked mastoids, vertex, average). Despite the same criterion, artifacts appear in different channels over scalp regions displaced from the reference, whereas the reference channels themselves are never flagged. Note the polarity inversion at sites TP9/10 (mastoids) for and caused by the linked mastoid reference.

Electrical Distance

The similarity of two surface potentials recorded from any pair of electrodes i and j of a given EEG montage consisting of M recording sites can be expressed for a fixed time interval T (e.g., a recording epoch) by a continuous, nonspatial 'electrical distance' measure D_{ij} defined as the temporal variance of a difference potential waveform (Tenke & Kayser, 2001):

$$D_{ij} = \frac{1}{T}\sum_{t=1}^{T} P_{i-j}(t)^2 \quad \text{, with} \quad P_{i-j}(t) = P_i(t) - P_j(t)$$

Pairwise-comparisons are by definition *reference-free*. After computing an $M \times M$ matrix of pairwise electrical distances D_{ij}, the electrical distances to each other electrode are ranked for each electrode to determine the N single nearest electrical neighbors ($N = M$). After deciding on an appropriate threshold, this approach can be used to determine whether any given electrode is bridged to another electrode or not, because nearly identical surface potentials will tend to have D_{ij} values close to zero (Tenke & Kayser, 2001). Conversely, an extremely large D_{ij} value for the nearest neighbor will indicate high signal dissimilarity.

Given the volume conduction of electrical current, spatial and temporal proximity of the recorded surface potentials in a multichannel EEG montage results in similar signals for any recording site and time interval. Thus, an unrealistic low signal similarity, as indicated by large *nearest neigbor* electrical distances, strongly implies an artifact.

Objective: Can the continuous and reference-free nature of the electrical distance measure be exploited to detect EEG recording artifacts?

Frequency Distributions of Nearest Neighbor Electrical Distance

Complete data sets of three ERP studies using a different multichannel EEG montage are shown for illustration. Nose-referenced ERP data were recorded during tonal and phonetic oddball tasks from 30 schizophrenia patients and 36 healthy adults (31 sites; Fig. 2) and from 17 healthy adults (129 sites; Fig. 4), and during a continuous recognition memory task from 30 depressed patients and 17 healthy adults (67 sites; Fig. 3). As can be seen for each data set, the *nearest neighbor electrical distance* measure shows across all trials an unimodal, positively-skewed distribution (similar distributions are observed for the data of individual subjects). Although the distributions of this measure may vary across sessions, it seems reasonable to define a threshold across all sites or for each site and flag all instances (*channel x epoch x subject*) exceeding this threshold as artifacts.

As an example, values equal to 95% of the distribution are *marked* for the three data sets. Accordingly, these data can be treated as artifacts. On any given trial, for instance, the data of channels containing artifacts can be interpolated from all other sites if only a few sensors are affected (i.e., less than 20%). Trials with too many artifacts can be excluded otherwise.

As can be seen from the *scatterplot ranges*, there is a tendency for larger values at sites in the periphery of the EEG montage, which can be attributed to the polar effect (Junghöfer et al., 1999). By comparison, sensors in the periphery of the EEG montage will also have a reduced probability for *near neighbors* in terms of electrical distance because their surrounding sensors tend to have a greater spatial distance. Following suggestions of Junghöfer et al. (1999), a *2nd degree polynomial* could be used to adjust the electrical distance measure for this bias.

Median-based criteria may be used to determine consistently contaminated sensors (i.e., distribution outliers). Sensors having a median nearest neighbor electrical distance outside a given confidence range (e.g., $Median \pm 3 * SD_{Median}$), may be globally interpolated or rejected (cf. site Nose in Figs. 2 and 3, and site 26 in Fig. 4)

31 Sites, N=66, 960 Epochs/Subject, 2000 ms/Epoch, 200 samples/s

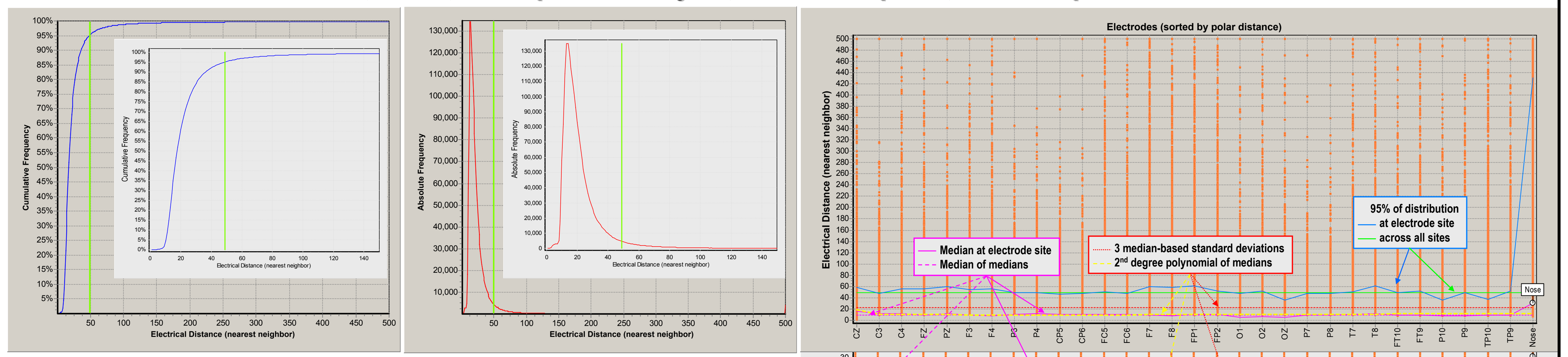


Fig. 2. Cumulative and absolute frequency across all trials (31 sites * 66 subjects * 960 epochs = 1,964,160 values) as a function of nearest neighbor electrical distance, and scatterplot ranges of nearest neighbor electrical distance as a function of recording site (electrode location sorted by distance to vertex). The 95% distribution threshold equals 50 (detail enlargements in light gray).

67 Sites, N=47, 456 Epochs/Subject, 2000 ms/Epoch, 256 samples/s

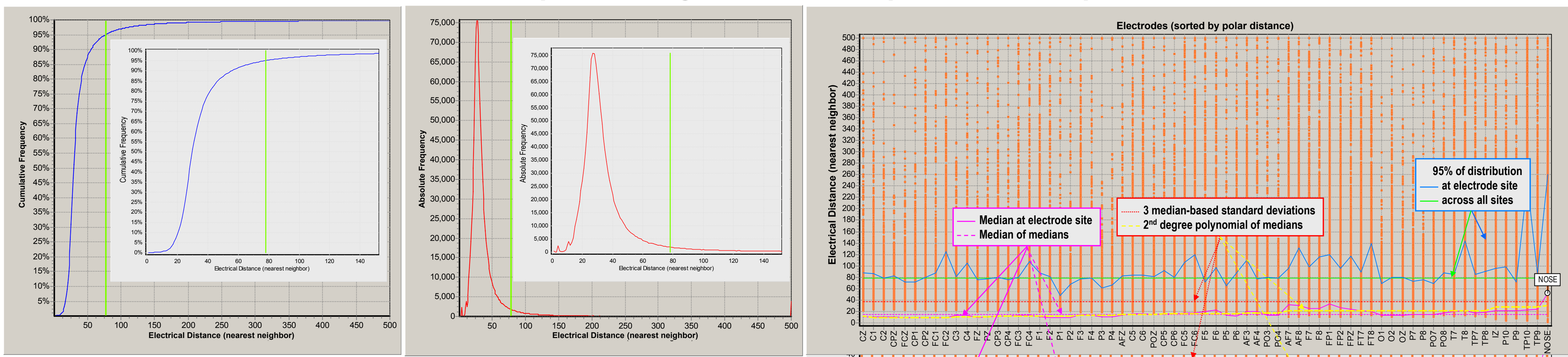
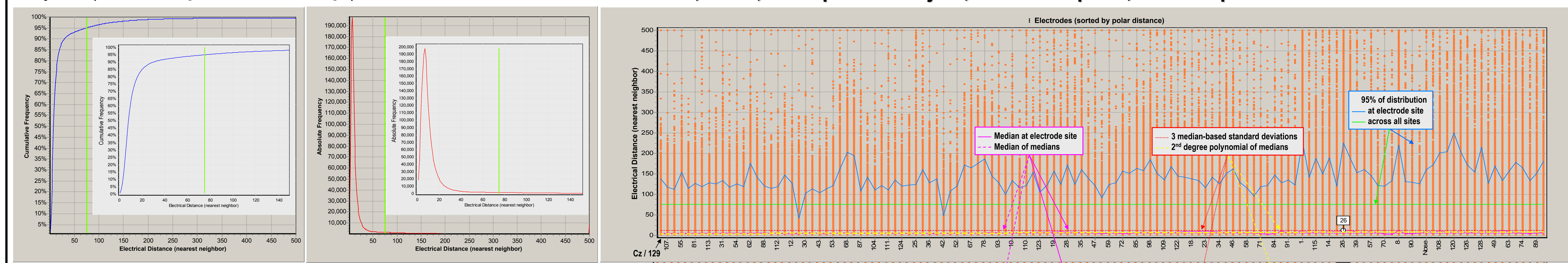


Fig. 3. Cumulative and absolute frequency across all trials (67 sites * 47 subjects * 456 epochs = 1,335,944 values) as a function of nearest neighbor electrical distance, and scatterplot ranges of nearest neighbor electrical distance as a function of recording site (electrode location sorted by distance to vertex). The 95% distribution threshold equals 78 (detail enlargements in light gray).

129 Sites, N=17, 960 Epochs/Subject, 1280 ms/Epoch, 200 samples/s



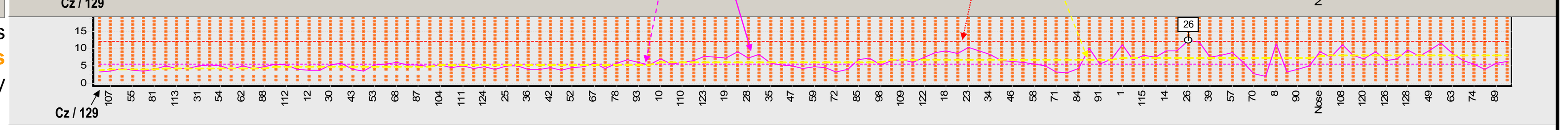


Fig. 4. Cumulative and absolute frequency across all trials (129 sites * 17 subjects * 950 epochs = 2,105,280 values) as a function of nearest neighbor electrical distance, and scatterplot ranges of nearest neighbor electrical distance as a function of recording site (electrode location sorted by distance to vertex). The 95% distribution threshold equals 75 (detail enlargements in light gray).

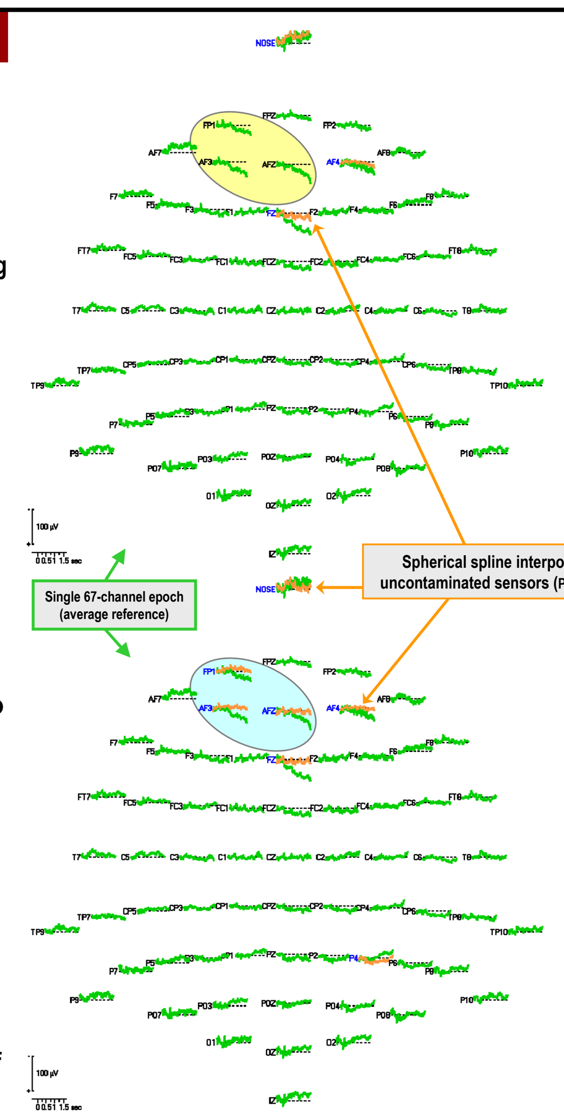
Issues and Solutions

Two or more sensors may contain a similar artifact. In this case, artifact channels may mutually serve a their nearest electrical distance neighbor (cf. Fp1, AF3 and AFz being below the applied threshold of 50).

This problem can be addressed by defining additional threshold criteria derived from the electrical distance distribution.

For example, for each sensor and epoch, *mean* and *median* of *all* electrical distances resulting from all pairwise difference waveforms (or a *representative* subrange) also show unimodal, positively-skewed distributions, allowing to define measure-specific thresholds (cf. Fp1, AF3 and AFz being detected as artifacts after applying these additional criteria).

All electrical distance values and their distributions will depend on the data features (e.g., epoch length, montage, number of subject, noise level).



Sensor pairs of *nearest neighbor electrical distance* (sorted in descending order)

#:	Ch#=	Label-	nLab	ED
1:	38=	FZ-	AFZ	127.611 *
2:	69=	NOSE-	IZ	78.267 *
3:	36=	AF4-	FP1	55.171 *
4:	47=	FCZ-	CPZ	40.798
5:	41=	F6-	AF7	39.022
6:	31=	PZ-	CPZ	38.633
7:	58=	P4-	P1	38.304
8:	37=	AFZ-	AF3	37.946
		:		
19:	3=	AF3-	FP1	33.321
		:		
35:	1=	FP1-	AF3	28.533
		:		

Additional *electrical distance* criteria (sensors sorted in descending order by criterion *mean*)

#	Ch#	Label	mean	median
1:	38	FZ	490.7*	479.1*
2:	37	AFZ	264.7*	254.1*
3:	3	AF3	236.9*	223.9*
4:	36	AF4	185.2*	174.2*
5:	69	NOSE	175.4*	165.3*
6:	1	FP1	168.5*	154.0*
7:	58	P4	166.7*	164.3*
8:	26	PO3	145.3	141.5
9:	64	O2	145.0	139.9
10:	47	FCZ	143.3	137.8
11:	20	P1	142.5	140.4
12:	2	AF7	132.5	125.4
		:		

Applications

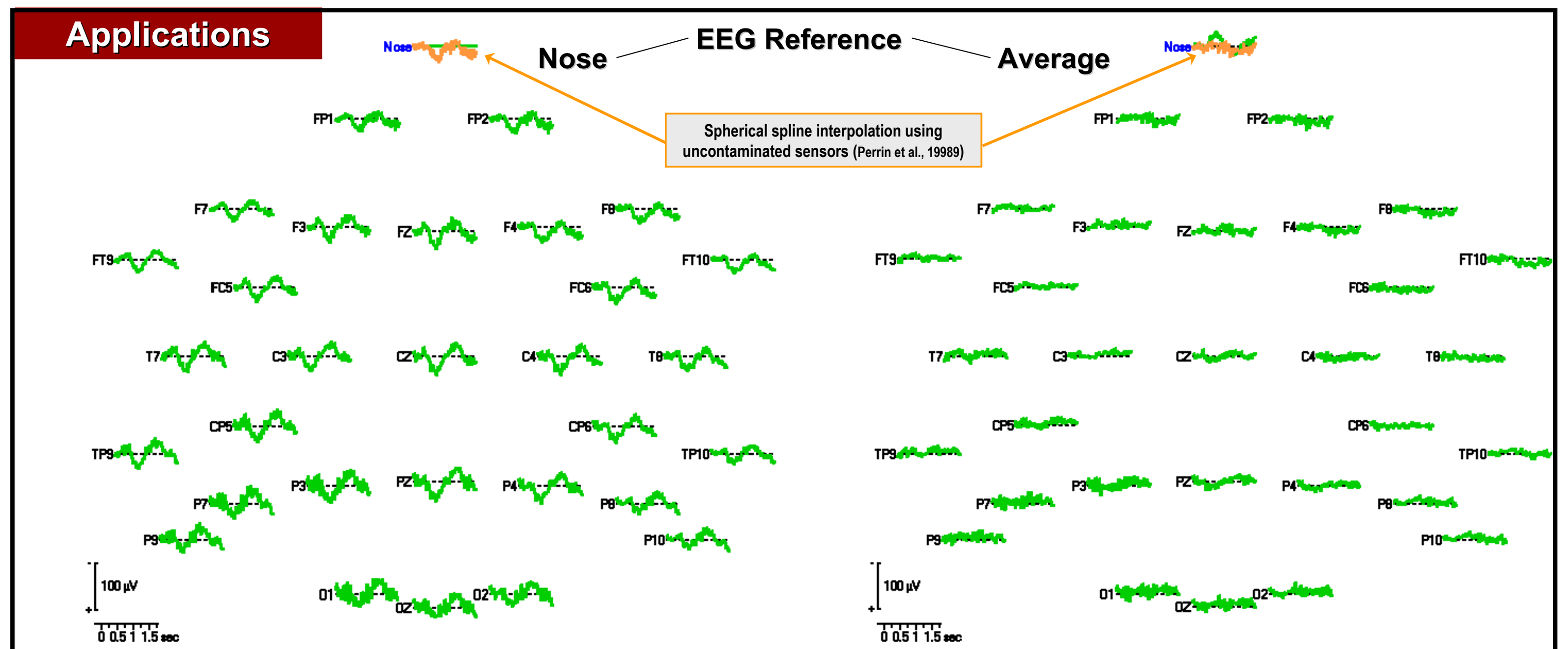


Fig. 4. If the reference is contaminated, the data of *all* sensors will appear contaminated when displayed using this reference (cf. above nose reference example). The proposed *reference-free* electrical distance measure detects artifacts independent of the recording re

Several EEG/ERP data sets have been (or are currently) processed in our laboratory using this reference-free artifact identification approach (e.g., see Poster Session 1 Poster #29, #31 and #120). This includes data from a study comparing schizophrenic patients and healthy adults in a working memory task employing very long (> 10 s) EEG epochs (Kayser et al., 2006).

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