Advanced Signal Processing II
(aka Acronym Day)

Ocular Artifacts (acronym free)
Latency Jitter and Woody Filters (acronym free)
Inference Problems with Scalp Topography (acronym free)
PCA
ICA
BESA
Simultaneous ERP with ICA and fMRI!

Announcements

- Papers:
  - You will received highly personal canned email acknowledgement that it was received
  - You will receive commented version via email once all papers are graded
- Take home final due May 7 at noon (hardcopy in my mailbox).
- 3x5s

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Dealing with Ocular Artifacts

Ocular Artifacts

- The problem
  - Eye movements and blinks create a potential that is propagated in volume conducted fashion
  - Manifests in recorded EEG
- Why?
  - Eye not spherical; more rounded in back
  - Potential is therefore positive in front with respect to rear of eye
  - Movements = Moving dipole
  - Blinks = sliding variable resistor

Ocular Arifacts

- Eye-blinks are ***systematic*** noise with respect to the ERP signal
  - Occur at predictable latencies (Stim-Resp-Blink)
  - John Stern: Information processing and blink latency

Ocular Artifacts

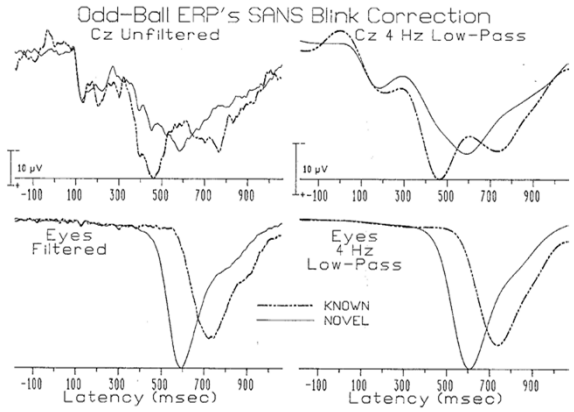
- Signal averaging will not remove this "noise" (noise wrt signal of interest)
- Average waveform a(t) is mixture of timelocked signal s(t) and randomly distributed error (noise)

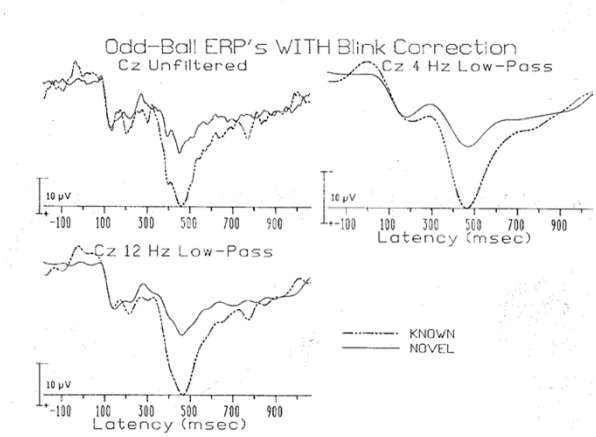
$$a(t) = s(t) + \frac{\sum_{1}^{n} e(t)}{n}$$

- If non-ERP signals are random with respect to stimulus onset, then the latter term will approach zero with sufficient trials (n)
- If not, the latter term will not sum to zero, but will include time-locked noise
- Noise will therefore average IN, not average OUT

Ocular Artifacts

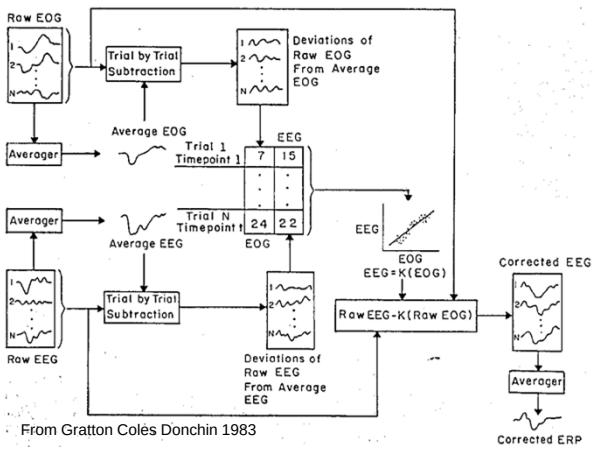
- Eye-blinks tend to occur at the cessation of processing.
  - Recall that the P300 is also a good index of cessation of processing.
- As a result, eye-blink artifact tends to appear as a late P300ish component





What to Do?!

- Reject trials during which eye-blink occurred.
  - Problems:
    - Trials which elicit blinks may not be equivalent to those which do not.
    - Large data loss, may be unable to get usable average
    - Telling subjects not to blink creates dual task
- Eye-blink correction (Gratton, Coles, & Donchin, 1983)
  - Assumes that the effect of an eye-movement or blink on the recorded EEG can be inferred from activity recorded near the source of the artifact (top and bottom of eye, e.g.)
- Model ocular potentials as a source, and remove from scalp sites (more later)



From Gratton Coles Donchin 1983

The Details

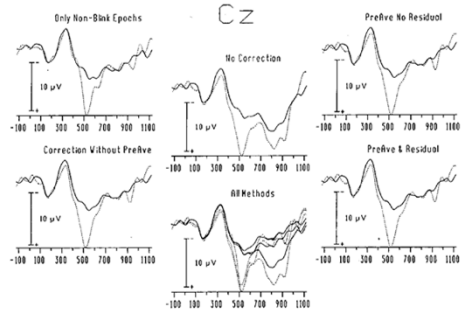
- Must determine extent to which EOG signal propagates to various scalp loci
  - Propagation factors computed only after any event-related activity is removed from both EOG & EEG channels
  - Event related activity in both channels may spuriously inflate estimate of propagation
  - Based upon correlation and relative amplitudes of EEG & EOG, a scaling factor is computed. The scaling factor is then applied on a trial by trial basis as follows:

Corrected EEG = Raw EEG - K*(Raw EOG)

- Corrected EEG epochs then averaged together to get blink-corrected ERP

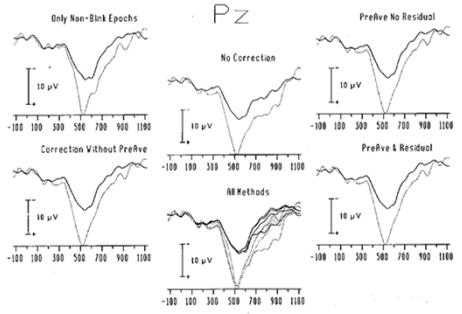
Validity of Ocular Correction

- Can produce valid results, but important to examine data to ascertain how well procedure worked.
- Variant of Gratton et al devised by Semlitsch, Anderer, Schuster, and Presslich (1986).
  - Creates blink-locked averages
  - Should reduce event-related contributions to correction estimate
  - Produces highly similar results



Four methods of undetermined validity for dealing with Blink Artifact in an Oddball Paradigm. Solid lines represent frequent novel items, and dotted lines represent rare learned items.

"Only Non-Blink Epochs" = excluding blink-contaminated epochs (28/60 Learned, 34/150 Unlearned)
"Correction without PreAve" = Gratton et al. method without the preliminary subtraction of event-related activity
"PreAve No Residual" = Gratton et al. method, event-related activity extracted prior to correction, no residual correction
"PreAve & Residual" = Gratton et al. method, event-related activity extracted prior to correction, with residual correction
For comparison, non-corrected data and all methods are presented in the center column. Abscissa is latency (msec).



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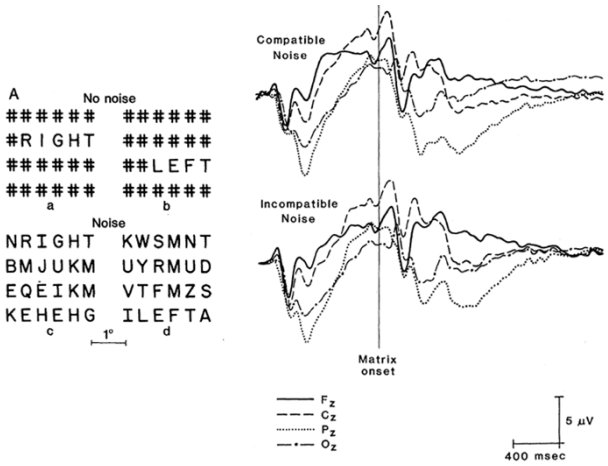
Other Methods (in brief)

- Most other methods also depend upon subtraction of a proportion of the EOG signal or some transformation of the EOG signal
  - Frequency-domain methods recognize that not all frequencies in the EOG channel propagate equally to scalp sites
  - Source localization methods attempt to derive a source that represents the equivalent of the origin of the eye potentials, and then compute the extent to which these sources would project onto scalp
    - BESA
    - ICA

The Problem of Latency Jitter

- The averaging assumption of invariance in signal is not always warranted
  - Especially for the later endogenous components
  - To the extent that the signal varies from trial to trial, the average will produce potentially misleading results
- Two common possibilities:
  - Smearing of components;
    - will underestimate amplitude of component (especially a problem if comparing groups, one group with more latency jitter)
  - Bimodal or multi-bumped components



The Solution

- The Woody Adaptive Filter (Woody, 1967)
- Based on Cross-correlation
  - Assumptions less restrictive than averaging methods
    - Waveform (morphology) must be constant across trials
    - Latency need not be constant

Details

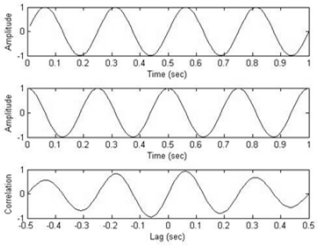
- Cross-correlational series
  - For two waveforms the correlation between each of them is computed
    - first with no lag in time
      a1, a2, ..., an
      b1, b2, ... bn
    - then with one lagged with respect to the other
      a1, a2, ..., an-1
      b2, b3, ... bn
  - A series of correlation values is obtained by progressively increasing the size of the lag

The Basic Idea

Sine

Cosine

Cross-Correlation



See … CrossCorr_Sin_Cos.m

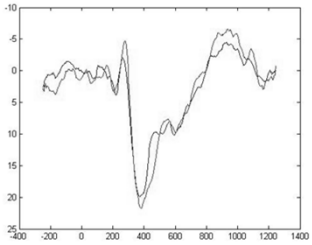
More Details

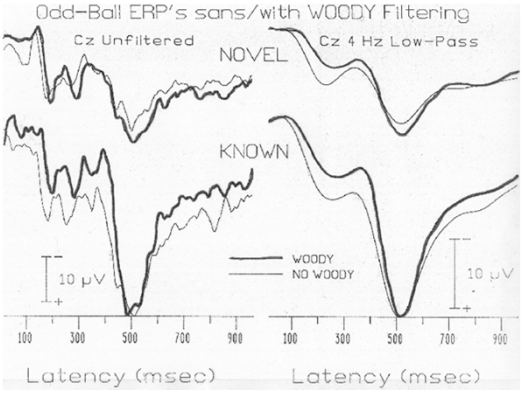
- Can be used as a "template matching" procedure
- Compare running average with raw EEG epochs
- This is a method of single-trial signal detection:
  - First create a template: either predetermined (e.g., sine wave) or empirically determined (e.g., average)
  - Then calculate cross-correlational series between each raw EEG epoch and the template
  - If some maximum correlation achieved, conclude signal is present
  - If correlation not achieved conclude absent
  - This can also be used as a method of determining the latency of a component (by examining the trial-by-trial shifts), or of determining the variability in response for a given individual (again by examining the trial-by-trail shifts)

Woody's Instantiation

- The Woody Adaptive Filter (Charles Woody, 1967) is a special case and application of cross correlational technique
- The term "adaptive" refers to the fact that the template is not established a priori, but generated and updated by an iterative procedure from the data themselves
- Procedure
  - Initial template is usually either a half cycle of a sine or triangle wave, or the unfiltered average of single trials
  - Cross-lagged correlations (or sometimes covariances) are then computed between each trial and this template typically over a limited range of samples (e.g., region of P300, not over "invariant" components)
  - Each trial is then shifted to align it with the template at the value which yields the maximum cross correlation (or covariance)
  - A new template is then generated by averaging together these time-shifted epochs
  - Procedure is repeated using this new average as the template
  - repeated until the maximal values of the cross correlation become stable
  - often, average cross-correlation value increment monitored; if r increases < .005 or .001, then stability achieved
- Some implementations, trials which do not reach a minimum criterion (e.g., .30-.50) are discarded from subsequent template construction and perhaps from subsequent analysis altogether

Woody Filtering Demo!





Validity

- Seems to do a fair job of improving signal extraction if a few iterations are used and if the original signal itself is singly peaked
- Wastell(1977) reports a decline in the validity of the procedure if numerous iterations are used
- Therefore, unlike averaging, Woody filtering can only improve signal-to-noise ratio over a definite limit
- Suggests also that Woody may not be the solution under conditions of very low signal-to-noise ratio

Dimensionality explosions!

32, 64, 128, 256!!!

Principal Components Analysis

- A method for reducing massive data sets
- See Handout for gory details

PCA (1): The Data matrix

$$D_{Nxn} = \begin{matrix} \text{Subject \#1} \\ \text{Subject \#2} \\ \text{Subject \#3} \\ \dots \\ \dots \\ \text{Subject \#N} \end{matrix} \begin{bmatrix} t_0, t_1, t_2, \dots, t_{n-1} \\ t_0, t_1, t_2, \dots, t_{n-1} \\ t_0, t_1, t_2, \dots, t_{n-1} \\ \dots \\ \dots \\ t_0, t_1, t_2, \dots, t_{n-1} \end{bmatrix}$$

Where N = Number subjects
n = Number sample points per average
t = voltage at time point 0, 1, ...

- Data Matrix above shows only one site – could have multiple sites by adding rows for each subject
- This data matrix is for "temporal PCA" but one could transpose for "spatial PCA"

PCA (2): The Score matrix

S_{Nxm} =

Subject #1	$[s_1, s_2, s_3, \ldots, s_m$	Where N = Number subjects
Subject #2	$s_1, s_2, s_3, \ldots, s_m$	m = Number of components
Subject #3	$s_1, s_2, s_3, \ldots, s_m$	s = score on component 1, 2, ...
...	...	
...	...	
Subject #N	$s_1, s_2, s_3, \ldots, s_m]$	

- These scores for each subject are optimally weighted composites of the original data, designed to capture as much variance as possible with as few scores as possible.
- But for conceptual ease, imagine 5 scores: P1, N1, P2, N2, P3 amplitude

PCA (3): The Loading matrix (to guess what components mean)

L_{mxn} =

Component #1	$[l_0, l_1, l_2, \ldots, l_{n-1}$	Where m = Number of components
Component #2	$l_0, l_1, l_2, \ldots, l_{n-1}$	n = Number sample points per average
Component #3	$l_0, l_1, l_2, \ldots, l_{n-1}$	l = component loading for time point 0, 1, ...
...	...	
Component #m	$l_0, l_1, l_2, \ldots, l_{n-1}]$	

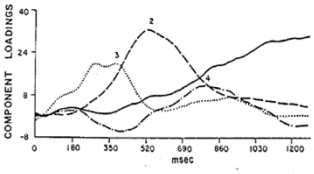
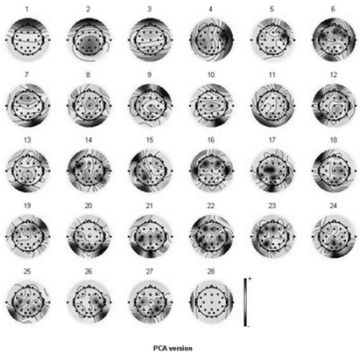
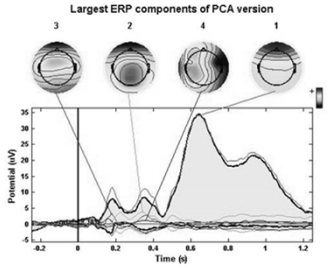


Figure 10-4. Plot of four sets of component loadings derived from a principal-components analysis (PCA) of an ERP data set. Each of the component loading vectors is composed of 128 points corresponding to 128 time points (100-Hz digitizing rate) in the waveforms.

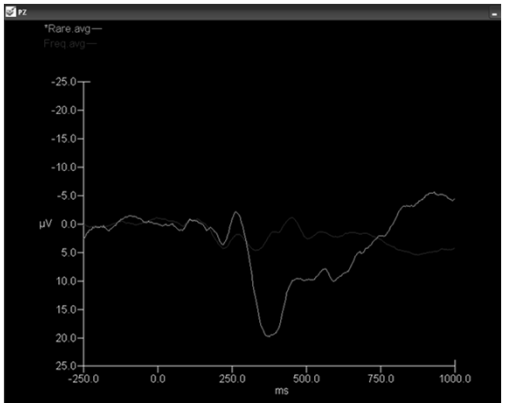
PCA on Sample Data



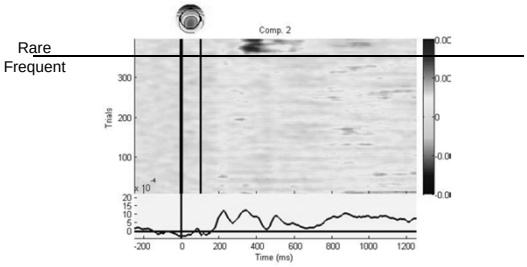
PCA (3b): The Loading Map (for Spatial PCA)



Reminder: The ERP from which it derives



PCA Component 2



PCA (4): Reconstructing Data Matrix

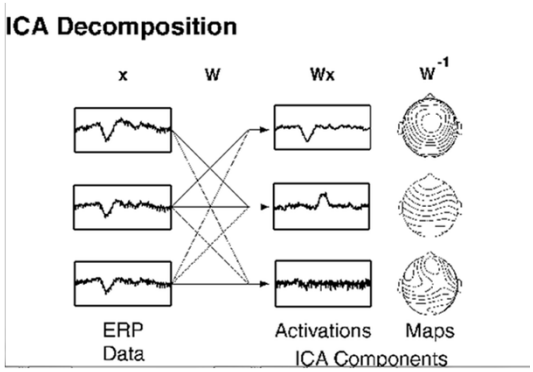
- $\mathbf{D}_{Nxn} \sim= \mathbf{S}_{Nxm} * \mathbf{L}_{mxn}$
- This reconstructed Data matrix will differ slightly from the original Data matrix because not all n components are used.
- To the extent that the m components account for most of the variance in the original data set, the reconstructed data matrix will closely approximate the original data matrix.

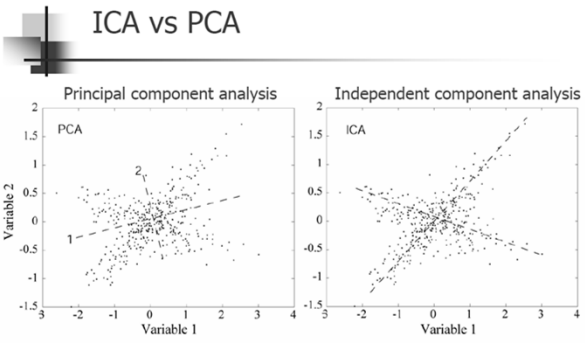
PCA (4): Caveat Emptor

- PCA is a linear model; assumes the components sum together without interaction to produce the actual waveform
- Sources of variance are orthogonal; if two sources are highly correlated, may result in a composite PCA component reflecting both
- Component invariability in terms of latency jitter across subjects
  - PCA does not distinguish between variations in amplitude vs variations in latency
  - Especially a problem in comparing control vs pathological groups; pathological groups will typically be more variable
  - Allen & Collins unpublished simulation study:
    - Two groups: Control & Pathological
    - Identical waveforms for each group differed only in latency
    - The two groups differed significantly on three of four principal component scores
    - In other words, if one indiscriminately interprets these as amplitude or morphology differences, one would be WRONG!!!

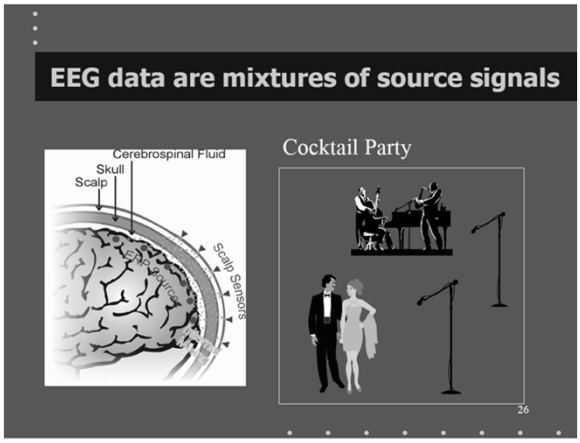
ICA … a "better" PCA?

- PCA finds orthogonal components
  - First PC accounts for most variance
  - Next PC accounts for most remaining variance
  - Components will have orthogonal scalp distributions
- ICA separates temporally independent components
  - Also known as blind source separation
  - May or may not correspond to brain "hotspots" but do represent functional brain networks
- See:
  http://www.sccn.ucsd.edu/~scott/tutorial/icafaq.html
  http://sccn.ucsd.edu/~arno/ (ICA for Dummies!)





From Tzyy-Ping Jung , presented at EEGLab Workshop, Nov 8,2007



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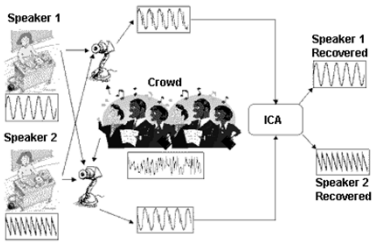


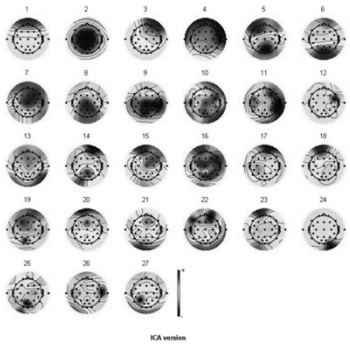
ICA/EEG Assumptions

- Mixing is linear at electrodes
- Propagation delays are negligible
- Component time courses are independent
- Number of components ≤ number of channels.

27

From Tzyy-Ping Jung , presented at EEGLab Workshop, Nov 8,2007

ICA: The Projection Map



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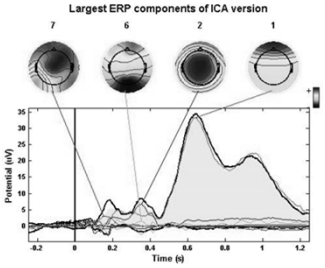
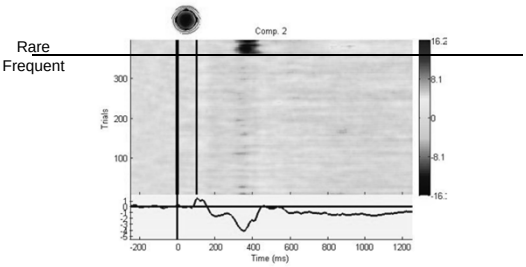
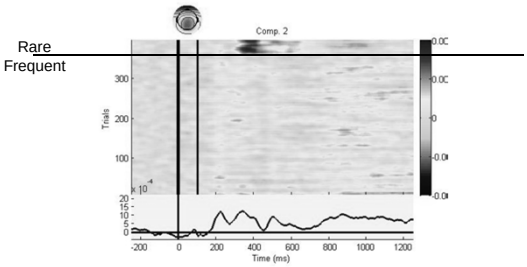


ICA: Trial by Trial IC Projection to Pz



PCA Component 2

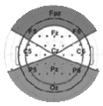


ICs as Artifacts!

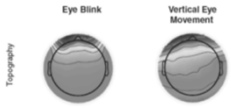
ADJUST:
An automatic EEG artifact detector based on the joint use of spatial and temporal features

Mognon, Jovicich, Bruzzone, & Buiatti, 2010

Features



- Spatial Average Difference (SAD)
  - Spatial topography of blink ICs
  - Looks for higher amplitude in frontal vs. posterior areas

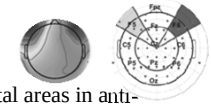


- Temporal Kurtosis (TK)
  - Kurtosis over the IC time course
    - Kurtosis is "peakedness" of the distribution (i.e. distribution of timepoints in the epoch)
  - Looks for outliers in amplitude distribution typical of blinks

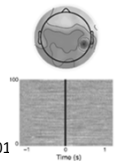
Mognon, Jovicich, Bruzzone, & Buiatti, 2010

Features

- Maximum Epoch Variance (MEV)
  - Is a ratio of variance in epoch with most variance compared to mean variance over all epochs
  - Looks for slower fluctuations typical of vertical eye movement



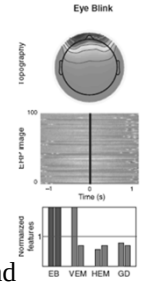
- Spatial Eye Difference (SED)
  - Looks for large amplitudes in frontal areas in anti-phase typical of horizontal eye movement



- Generic Discontinuities Spatial Feature (GDSF)
  - Looks for local spatial discontinuities

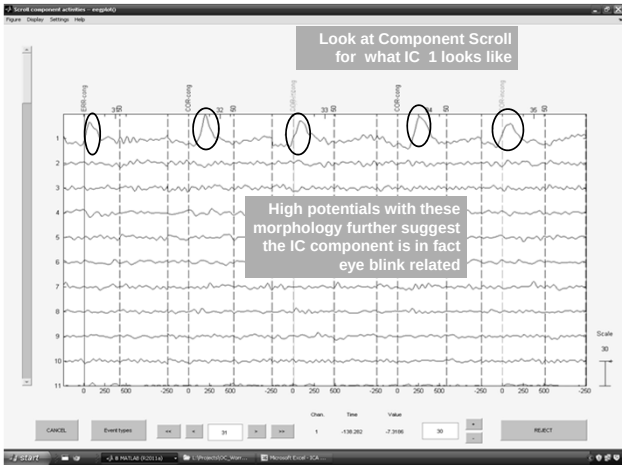
Mognon, Jovicich, Bruzzone, & Buiatti, 201

Eye blinks

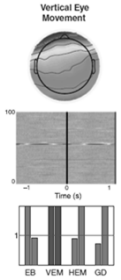


- Features used
  - Spatial Average Difference (SAD)
  - Temporal Kurtosis (TK)
- Frontal distribution
- High power in delta frequency band

Mognon, Jovicich, Bruzzone, & Buiatti, 2010



Vertical Eye Movement

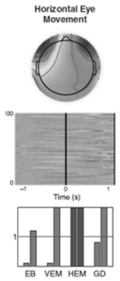


- Features used
  - Spatial Average Difference (SAD)
  - Maximum Epoch Variance (MEV)
- Frontal distribution similar to that of an eye blink

Mognon, Jovicich, Bruzzone, & Buiatti, 2010

Horizontal Eye Movement

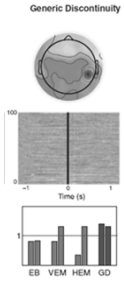
- Features used
  - Spatial Eye Difference (SED)
  - Maximum Epoch Variance (MEV)
- Frontal distribution in anti-phase (one positive and one negative)

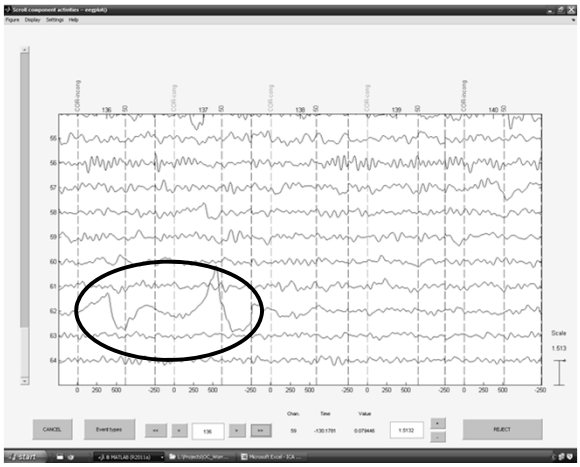


Mognon, Jovicich, Bruzzone, & Buiatti, 2010

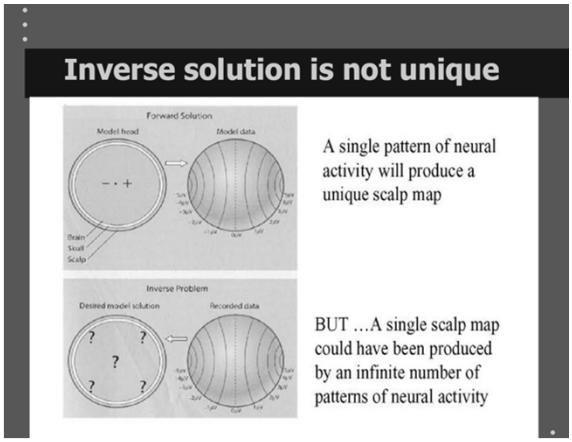
Generic Discontinuities

- Features used
  - Generic Discontinuities Spatial Feature (GDSF)
  - Maximum Epoch Variance (MEV)
- Variable distribution
- Sudden amplitude fluctuations with no spatial preference
  - Could be present in as little as one or 2 trials, and limited to 1 channel
- In component data scroll weird activity in the trial plotted on the IC activity





Neural Sources of EEG



From Tzyy-Ping Jung , presented at EEGLab Workshop, Nov 8,2007

Source Analysis

- BESA -- Brain Electrical Source Analysis
- This is a model-fitting procedure for estimating intracranial sources underlying ERPs
  - Estimate -- if model fits, then data are consistent with these sources; yet there is no unique solution
  - Not for ongoing EEG -- too many sources

BESA

- Imagine a data matrix of ERPs:

$\mathbf{V_{Cxn}}$ (# Channels by # timepoints)

- Note that this is really the result of the subtraction of the activity at the reference from the activity at the these sites; i.e.,

$\mathbf{V_{Cxn}} = \mathbf{U_{Cxn}} - \mathbf{R_{Cxn}}$

- Note: the reference matrix has identical rows! Thus BESA Presumes that all channels referenced to the same reference!

BESA

- Reconstruct a data matrix that includes not only the original channels, but the implicit channel (reference) as well:

$\mathbf{U_{Exn}}$ (# electrodes = # channels+1),

which represents the activity at each electrode with respect to an average reference (i.e., the average of all channels)

BESA

- Now this matrix $\mathbf{U_{Exn}}$ can be decomposed into
  - a set of sources: $\mathbf{S_{Sxn}}$ (# Sources by # timepoints)
  - a set of attenuation coefficients $\mathbf{C_{ExS}}$
  - so that $\mathbf{U_{Exn}} = \mathbf{C_{ExS}}\ \mathbf{S_{Sxn}}$

BESA

- The attenuation matrix is determined by:
  - the geometry between the source and the electrodes
  - the nature of the conductance of the three-layer head model (Brain, Skull, Scalp);
    - the skull is less conductive than the layers on either side
    - this results in a spatial smearing of potentials as they cross the skull
    - the skull produces the equivalent of a brain that is 60% of the radius of the outer scalp (rather than the "true" figure of ~84%)

Next

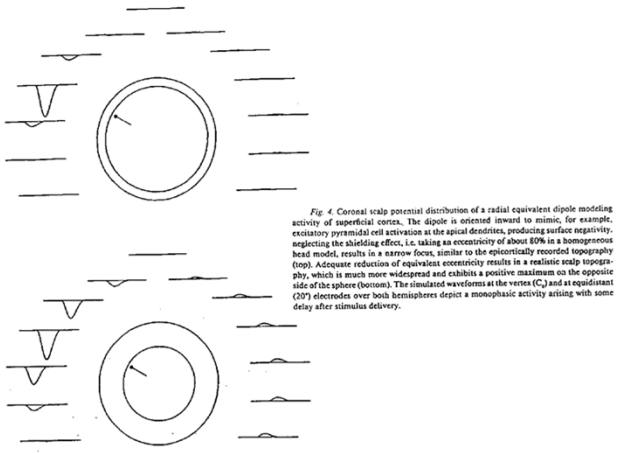


Fig. 4. Coronal scalp potential distribution of a radial equivalent dipole modeling activity of superficial cortex. The dipole is oriented inward to mimic, for example, excitatory pyramidal cell activation at the apical dendrites, producing surface negativity, neglecting the shielding effect, i.e. taking an eccentricity of about 80% in a homogeneous head model, results in a narrow focus, similar to the epicortically recorded topography (top). Adequate reduction of equivalent eccentricity results in a realistic scalp topography, which is much more widespread and exhibits a positive maximum on the opposite side of the sphere (bottom). The simulated waveforms at the vertex (C_z) and at equidistant (20°) electrodes over both hemispheres depict a monophasic activity arising with some delay after stimulus delivery.

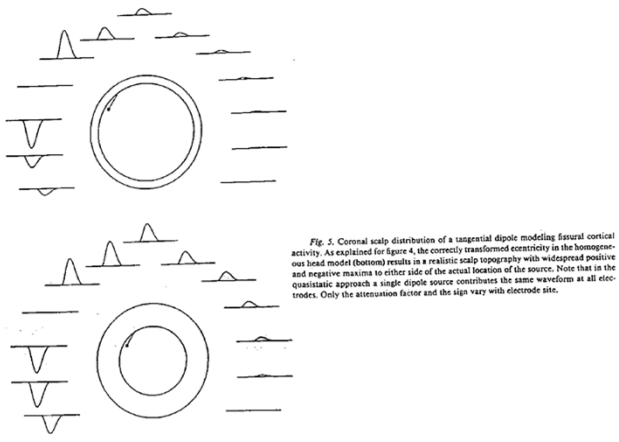
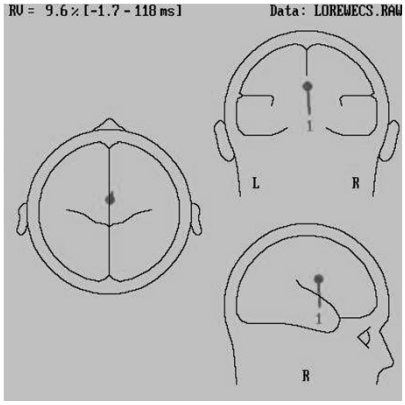


Fig. 5. Coronal scalp distribution of a tangential dipole modeling fissural cortical activity. As explained for figure 4, the correctly transformed eccentricity in the homogeneous head model (bottom) results in a realistic scalp topography with widespread positive and negative maxima to either side of the actual location of the source. Note that in the quasistatic approach a single dipole source contributes the same waveform at all electrodes. Only the attenuation factor and the sign vary with electrode site.

BESA

- Note that the decomposition of **U** into **C** and **S** results in
  - an electroanatomical time-independent matrix (**C**) that reflects that anatomical substrates do not move around in the head
  - a time-variant dipole source potential matrix that represents the change in activity of each source over time



BESA Vs PCA Vs ICA (a battle of acronyms)

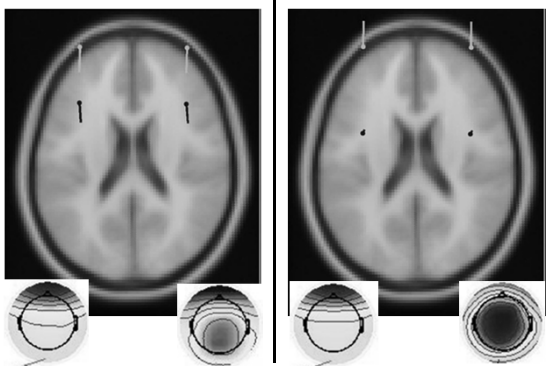
- This decomposition is akin to PCA/ICA
  - PCA and ICA have sources and propagation coefficients
  - PCA solutions are constrained by orthogonality of components, and by those that account for greatest common variance
  - ICA constrained to find temporally independent components
  - BESA solutions are constrained by the geometry of the head, the volume conduction of the dipoles, and the anatomical constraints dictated by the user (e.g., inside the head, symmetrical, not in the ventricles, must not be in the brainstem after a certain point in time, etc...)

BESA Vs PCA Vs ICA continued

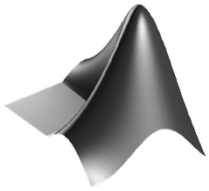
- Like PCA/ICA, the reconstruction of the original data set will be imperfect
  - With all methods. better chance of reconstructing the original matrix if data are reliable
  - If you capture the important sources, the reconstruction should be very good (i.e., small residual variance)
  - It is useful to attempt to upset a solution by inserting another source and seeing if:
    - the original solution is stable
    - the new source accounts for any substantial variance
- Can do dipole localization (BESA) on an IC!

Dipole Fitting

PCA | ICA



You can try it!



Implementations

- BESA can be used:
  - in a strict hypothesis-testing manner by designating sources a priori and testing the fit
  - in an exploratory/optimizing manner by allowing the program to iteratively minimize the residual variance (between observed and reconstructed waveforms) by:
    - moving dipoles
    - changing the orientation of dipoles
    - altering the time-by-activity function of the dipoles

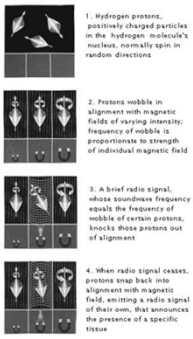
BESA – Did it work?

- In the end, the adequacy of your solution will be judged by
  - stability of your solution:
    - against insertion of additional dipoles
    - across multiple subjects
  - anatomical feasibility
  - follow-up tests with patients with lesions
  - your reviewers!

Recording EEG in fMRI environments: Oodles of Issues

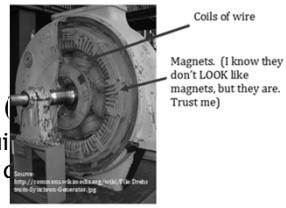
- EEG can be bad for fMRI
  - Wires and electrodes can be ferromagnetic = TROUBLE
  - Wires and electrodes can be paramagnetic = less trouble
- MRI and fMRI can be bad for EEG
  - Gradient switching creates huge artifact for EEG
  - Movement in Magnetic fields creates current in any conductive medium (e.g. wires!)
  - High frequency current can make wires HOT and RF is 127.68 MHz at 3T – that's fast, and can create mega-hurts!
    - Thus in-line 10K resistor

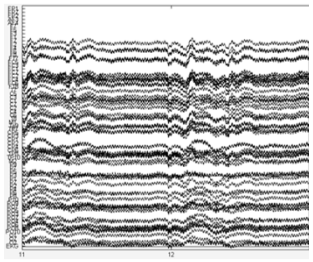
Whence EEG Artifacts in fMRI?

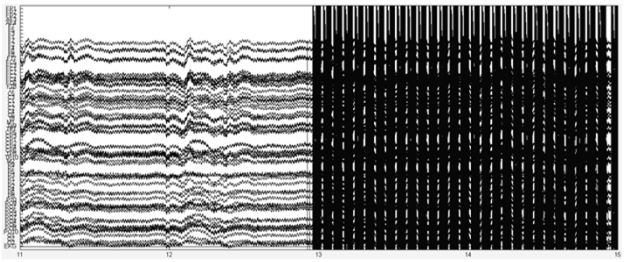


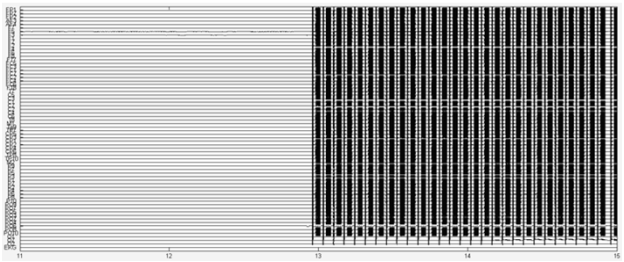
Whence EEG Artifacts in fMRI?

- Faraday's law of induction…
  - induced electromotive force is proportional to the time derivative of the magnetic flux
  - Flux = summation of the magnetic field perpendicular to the circuit plane over the area circuit
  - $\varepsilon = d\Phi/dt$
- Can reflect:
  - changes in the field (
  - Changes in the circui
    relative to the field







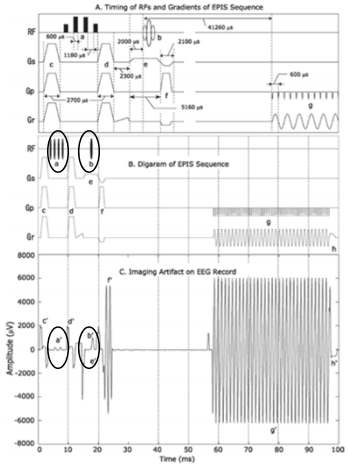


Whence EEG Artifacts in fMRI?

- RF pulses
  - For 3T = 127.6 MHz
  - Brain oscillations ≈ 0.5-50 Hz
  - Amplifier frequency range = DC-3.0 KHz
- Artifacts thus attenuated, but still range from 10-100 μV
- EEG in range from 1-75 μV

Whence EEG Artifacts in fMRI?

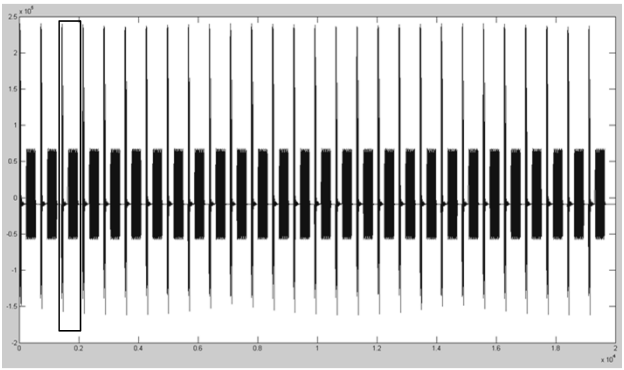
- Gradient Switching
  - Artifact approximates differential waveform of the gradient pulse
  - Polarity and amplitude varies across channels
  - Frequency ≈ 500-900 Hz
- EEG dominated by
  - harmonics of slice repetition frequency (≈10-25 Hz)
  - convolved with harmonics of volume repetition frequency (≈0.2-2 Hz)
- Artifacts in range from 1000-10,000 μV!



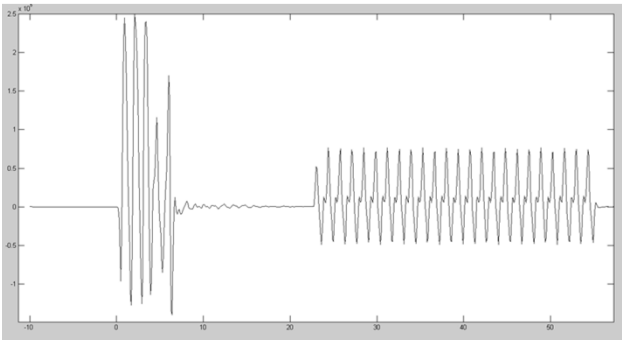
RF = radiofrequency wave;
Gs = slice selection gradient
Gp = phase encoding gradient
Gr = readout gradient
a = Fat suppression pulses (1-3-3-1 pulses)
b = slice selection RF
c, d, h = spoilers
e = slice selection gradient
f = dephasing and rephasing gradient
g = readout gradient
' = EEG artifact corresponding to letter

Ritter et al., 2009

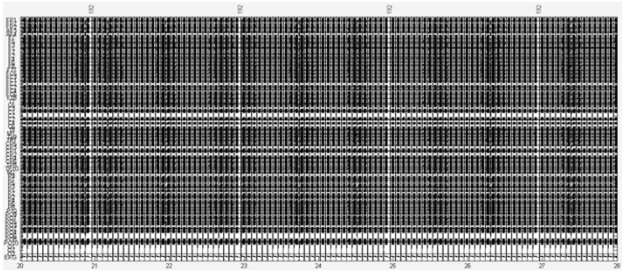
Average Artifact (across 1 TR)



Average Artifact (0-60 msec)



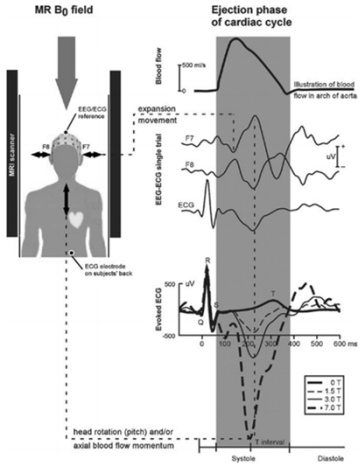
Artifact (across several TRs)



NOTE THE CODE!!!!!

Whence EEG Artifacts in fMRI?

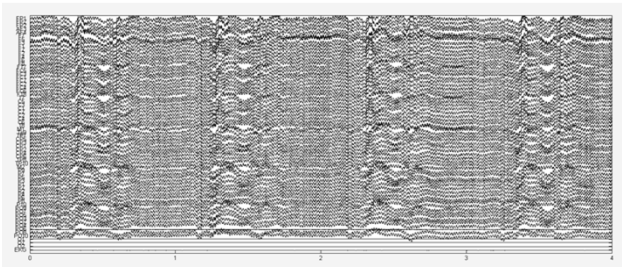
- Faraday's law of induction…
  - induced electromotive force is proportional to the time derivative of the magnetic flux
  - Flux = summation of the magnetic field perpendicular to the circuit plane over the area circuit
  - $\varepsilon = d\Phi/dt$
- Can reflect:
  - changes in the field (gradient switching, RF)
  - Changes in the circuit geometry or position relative to the field due to body motion



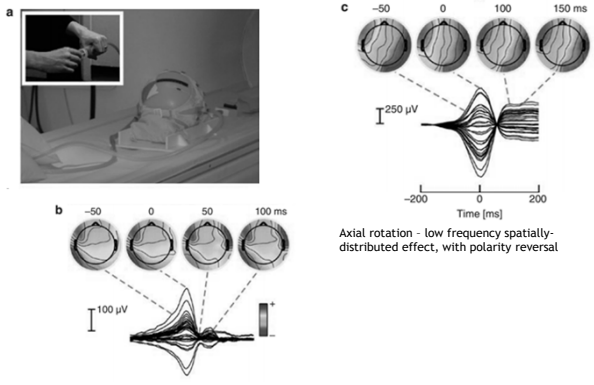
- Two types of movement:
  - Axial nodding
  - Expansion at lateral sites
- Motion of blood (flow) can lead to "Hall effect"
  - Voltage difference on opposite sides of a moving conductor through which current is flowing, when within a strong magnetic field
- Note field-strength dependent nature of the artifact

Debener et al., 2008

EEG in Magnet (no scanning)



Simulated EKG Artifact



Axial rotation – low frequency spatially-distributed effect, with polarity reversal

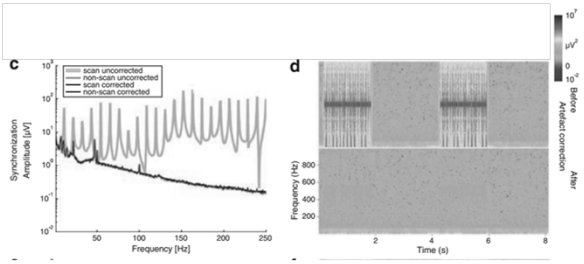
Lateral balloon expansion – locally circumscribed artifact

Debener et al., 2009

Ohmagawd… Help me in

REMOVING THOSE PESKY ARTIFACTS!

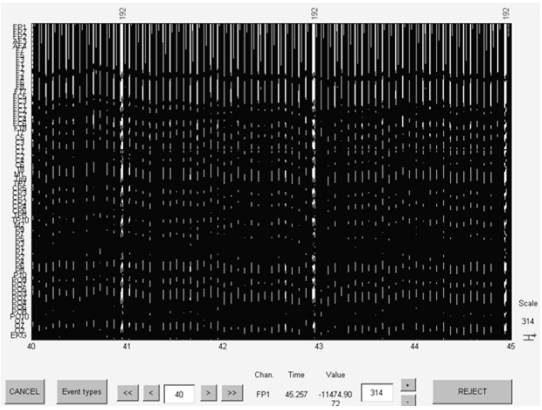
Gradiant/RF removal via moving average subtraction



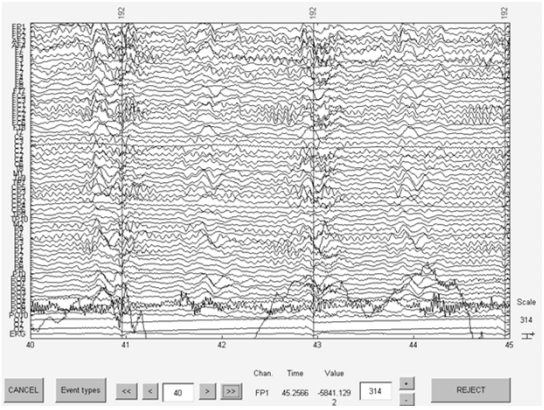
FASTR: FMRI Artifact Slice Template Removal

- Part of FMRIB Plug-in for EEGLAB
- Upsample to at least 20K Hz
- Align slices for slight jitter in timing
- Moving Window approach with subtraction
- PCA on artifact residuals form Optimum Basis Set (OBS) to reduce residual artifacts by 90%
- Downsample to original rate
- Sample Results…….

Before



After



ECG-related removal via moving average subtraction (Allen et al. 1998)

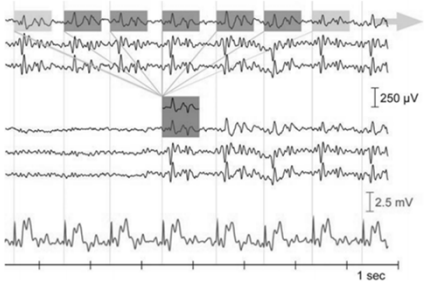
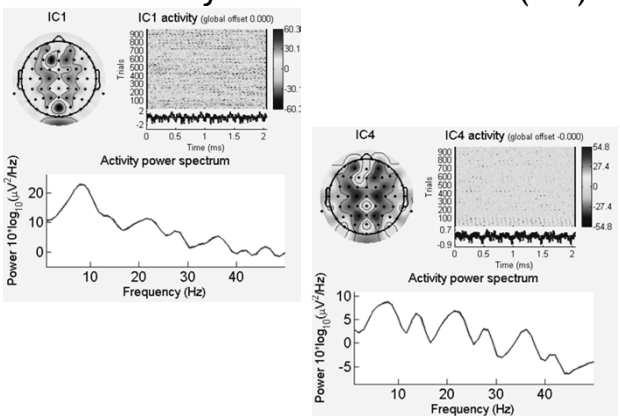
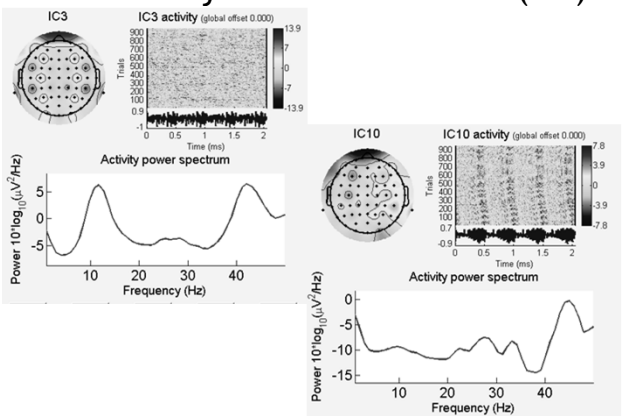


Fig. 5 Schematic of the average artefact subtraction procedure. For each channel, a waveform template is generated by averaging EEG epochs over adjacent cardiac cycles, with the time- locking event being derived from the ECG. The template generation is combined with a moving average procedure, and new templates are generated for each cardiac cycle. The procedure is repeated for each EEG channel

There may be residual crud (RC)



There may be residual crud (RC)

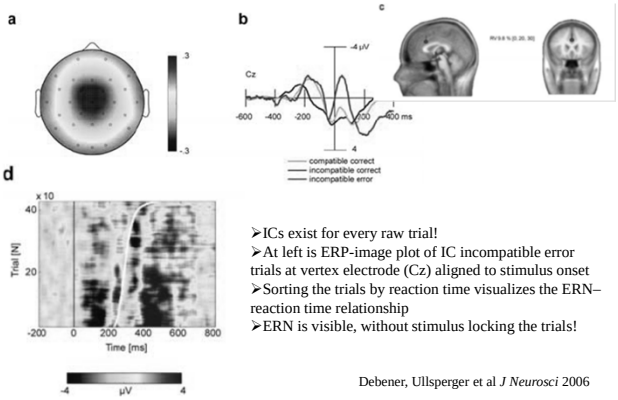


Recording EEG in fMRI environments: Really making use of the two technologies

- Could easily correlate ERP amplitude with fMRI (BOLD) signal
- This is potentially suboptimal:
  - If done on average, this neglects trial-to-trial fluctuations
  - Confounds between versus within-subject effects
  - Correlation addresses whether *people* with bigger ERP component amplitudes have larger BOLD signal
  - We wish to know whether *variations within people* from trial to trial underlie both ERP and BOLD changes within subjects

ICA of ERN Data:

The IC corresponding to the ERN for three conditions, with dipole model fit



- ICs exist for every raw trial!
- At left is ERP-image plot of IC incompatible error trials at vertex electrode (Cz) aligned to stimulus onset
- Sorting the trials by reaction time visualizes the ERN–reaction time relationship
- ERN is visible, without stimulus locking the trials!

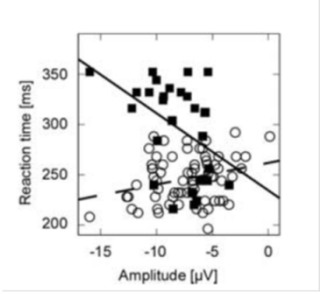
Debener, Ullsperger et al *J Neurosci* 2006

ICA on ERP with fRMI!

- Single-trial error-related negativity of the EEG is systematically related to behavior in the subsequent trial
- This trial-by-trial EEG measure of performance monitoring predicted the fMRI activity in the rostral cingulate zone (aka ACC!)

Debener, Ullsperger et al *J Neurosci* 2006

Single Trial ERN IC related to trial-to-trial variations in behavior!



- Single-subject example
- Incompatible error condition
- Relationship between single-trial IC amplitude and reaction time, separately for the current trial (open circles; dashed regression curve) and for the reaction time of the following trial (filled squares; solid regression curve).

Debener, Ullsperger et al *J Neurosci* 2006

fMRI activations to Errors

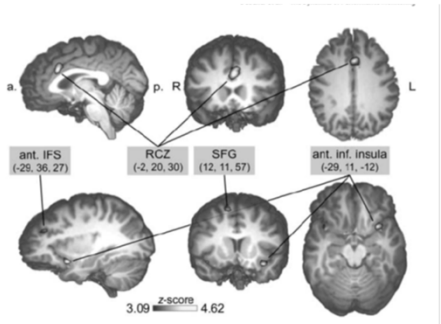


Figure 5. Significant error-related fMRI activations revealed by the conventional random effects analysis contrasting conditions incompatible error versus incompatible correct. a., Anterior; p., posterior; R, right; L, left; ant., anterior; inf., inferior; SFG, superior frontal gyrus; IFS, inferior frontal sulcus.

Debener, Ullsperger et al *J Neurosci* 2006

Regions related to ERN IC activity

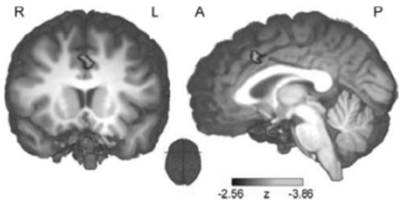


Figure 4. Result of the EEG-informed parametric fMRI analysis based on IC single-trial amplitudes, plotted on an individual brain. fMRI signals correlated with single-trial amplitudes solely in the RCZ along the banks of the cingulate sulcus [center of gravity at coordinates (x, y, z) = 0, 17, 42; $z = -3.86$]. The left part shows coronal view; the right part shows the sagittal view on the right hemisphere. The red lines on the middle top view inset indicate slice sections. R, Right; L, left; A, anterior; P, posterior.

Debener, Ullsperger et al *J Neurosci* 2006

Psychophysiology -- Synopsis

- Psychophysiology is inherently interdisciplinary, and systemic
- Psychophysiology based on dual assumptions (Cacioppo, Tassinary, & Berntson, 2007)
  - Human behavior and experience are embodied and embedded phenomena
  - Physiological responses of brain and body – when studied within the context of an appropriate experimental design – can illuminate aspects of behavior and experience.

Psychophysiology -- Synopsis

- Ultimately we obtain correlates of behavior and experience
  - Psychophysiological Correlates are not privileged; they are no better, no worse, than any other correlate of behavior and experience
- The utility of these correlates – like any correlates in science – hinges upon:
  - good experimental design
  - strong theoretically driven hypothesis testing
  - the development of a nomological net, a set of inter-relationships among tangible measures and constructs that place the findings in a larger theoretical context, and lend construct validity to the measures and findings