Theory of a Spatial Filter for Removing Ocular Artifacts With Preservation of EEG

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This technical note supplements the workshop demonstration by providing (a) pointers to issues in the literature regarding the correction of EEG (or MEG) recordings for blink and eye movement artifacts, and (b) a theoretical description of a spatial filter for removing ocular artifacts, with special attention to the problem of preserving frontal EEG (which is vulnerable to "overcorrection").

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Principal Issues

Are ocular artifacts frequency-dependent? References [4]. [7], [9], and [14] discuss this issue. The current consensus is that ocular artifact propagation occurs via instantaneous volume conduction, and therefore, that instantaneous time domain methods are adequate.

Is an EOG regression/subtraction method adequate? Most “traditional” ocular correction methods, such as [5]-[11], [14], [21], [25], [26], [28], and [30], work (i) by estimating transmission coefficients from EOG channels to EEG channels, followed (ii) by subtracting a fraction of the instantaneous EOG from each EEG channel. However, as discussed in [20], [19], [27], and [31], this approach assumes that EOG channels contain only artifact. Volume conduction is a two-way street: Just as a fraction of ocular artifact propagates from the eyes to scalp EEG channels, so does a fraction of brain activity propagate from (mainly frontal) EEG generators to EOG channels. Consequently, regression/subtraction methods tend to distort the EEG/ERP topographies by removing a portion of activity generated by bona fide brain sources.

How, then, to avoid the problem of spatial overlap between topographies produced by ocular artifacts and topographies produced by brain generators? Berg and Scherg [20] devised a multiple source components approach that integrates empirical characterization of the signal space spanned by ocular artifacts with the modeling of brain sources. The latter aspect of the approach requires the use of a head model in order to distinguish brain activity from ocular artifacts. On the other hand, blind source separation, or independent component analysis (ICA), is a completely empirical solution, which does not require a biophysical model ([22], [31], [32]). This powerful approach nevertheless requires (at present) the user to select, perhaps somewhat subjectively after the analysis, which components should be discarded as artifacts. These selections might be obvious in some cases, but less so in others.

Like ICA, the spatial filter described in the next section is a completely empirical solution, which does not require a head model in order to distinguish brain activity from ocular artifacts. However, like the Berg-Scherg approach, the method described here is not blind. Rather, it depends on representative samples of both artifacts and “clean” brain activity.

Theory

In brief, we design a spatial filter (including all EEG channels and optional EOG channels) that projects the data into the orthogonal complement of an identified artifact subspace *after* spatially whitening the data with respect to the covariance statistics of artifact-free EEG. The latter step attenuates components that “look like” ordinary EEG, while accentuating components (such as artifacts) that “look different”. This feature permits the method to distinguish artifact topographies from brain activity topographies.

The spatial filter for ocular correction has the form

$$\mathbf{F} = \mathbf{C}^{+1/2}(\mathbf{I} - \mathbf{U}_r \mathbf{U}_r^{\mathrm{T}})\mathbf{C}^{-1/2}$$

where $\mathbf{C}$ is a covariance matrix (N-by-N, where N = number of channels) for artifact-free EEG (estimated from a sample), and the r columns of matrix $\mathbf{U}_r$ (N-by-r) span the artifact subspace. $\mathbf{C}^{+1/2}$ is the symmetric square root of $\mathbf{C}$, and $\mathbf{C}^{-1/2}$ is the inverse symmetric square root of $\mathbf{C}$ (both obtained via singular value decomposition). Note that $\mathbf{C}^{-1/2}$ spatially whitens the input data with respect to clean EEG, and $\mathbf{C}^{+1/2}$ spatially unwhitens the resulting output. The matrix $\mathbf{U}_r$ equals the first r columns of a matrix $\mathbf{U}$, which is obtained as follows. Let

$$\bar{\mathbf{A}} \equiv \mathbf{C}^{-1/2}\mathbf{A}\mathbf{C}^{-1/2}$$

where $\mathbf{A}$ is the covariance matrix for artifact-containing EEG (estimated from a sample). Then $\mathbf{U}$ comes from the singular value decomposition of $\bar{\mathbf{A}}$:

$$\bar{\mathbf{A}} = \mathbf{U}\mathbf{W}\mathbf{U}^{\mathrm{T}}$$

Some Practical Considerations

In practice, it is necessary to obtain “sufficiently large and representative” samples of both “clean EEG” and artifacts-to-be-removed, for an “adequate” number *N* of channels. In addition, the number *r* of artifact components must be determined, based on either prior experience or examination of the singular values of the matrix $\bar{\mathbf{A}}$ (which are contained in the diagonal matrix $\mathbf{W}$).

Generally, as the number of artifact components (*r*) to be removed increases, the sample sizes must also increase. Sample size should also increase with the number of channels (*N*). One way to assure adequate sample sizes is to obtain “calibration data” in the forms of both clean EEG (typically eyes-open and fixated) and artifact-containing EEG (obtained along the lines of reference [20]).

Ocular Artifact Literature (chronological)

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