
**The ERP PCA Toolkit: An Open Source Program For Advanced Statistical Analysis of
Event Related Potential Data**

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Research Article

Running Head: EP Toolkit

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ABSTRACT

This article presents an open source Matlab program, the ERP PCA (EP) Toolkit, for facilitating the multivariate decomposition and analysis of event-related potential data. This program is intended to supplement existing ERP analysis programs by providing functions for conducting artifact correction, robust averaging, rereferencing and baseline correction, data editing and visualization, principal components analysis, and robust inferential statistical analysis. This program subserves three major goals: 1) optimizing analysis of noisy data, such as clinical or developmental. 2) facilitating the multivariate decomposition of ERP data into its constituent components. 3) increasing the transparency of analysis operations by providing direct visualization of the corresponding waveforms.

Key Words

Event Related Potentials, Principal Components Analysis, Artifact Correction

While statisticians have made steady progress in devising improved methods for describing and testing data, the practice of analyzing event-related potentials (ERPs) for the most part reflects the state of the art in the 60's. The voltage data is usually summarized using simple mean measures of some sort and then tested using conventional ANOVAs. Even reports using more sophisticated approaches such as factor analysis tend to rely on procedures from this period, such as the Varimax rotation (Kaiser, 1958). While this straightforward approach is adequate for many uses (where its very simplicity can be considered a strength), in other cases it can fall short.

The EP (which stands for ERP PCA, which in turn stands for "event-related potential" and "principal components analysis") Toolkit was developed to address these difficulties. By implementing the statistical algorithms within a widely used programming environment (Matlab), it has been possible to package the procedures in a fashion that make use of current statistical advances, including some not yet available in commercial packages, and to optimize them for the special needs of ERP datasets. Distributed over the internet since 1999, it has been utilized by an increasing number of researchers (Clementz, Brahmhatt, McDowell, Brown, & Sweeney, 2007; Curran & Dien, 2003; Curran & Friedman, 2004; Curran, DeBuse, Woroch, & Hirshman, 2006; Dien, 1999; Dien, Franklin, & May, 2006; Dien, Frishkoff, Cerbone, & Tucker, 2003; Dien, Spencer, & Donchin, 2003; Dien, Spencer, & Donchin, 2004; Dien, Tucker, Potts, & Hartry, 1997; Fishman, Goldman, & Donchin, 2008; Foti & Hajcak, 2009; Foti, Hajcak, & Dien, in press; Franklin, Dien, Neely, Waterson, & Huber, 2007; Frishkoff, Perfetti, & Westbury, 2009; Frishkoff, Perfetti, & Collins-Thompson, in press; Hestvik, Maxfield, Schwartz, &

Shafer, 2007; Holroyd, Pakzad-Vaezi, & Krigolson, 2008; Krigolson & Holroyd, 2006; Krigolson & Holroyd, 2007; Krigolson, Holroyd, Van Gyn, & Heath, 2008; Lister, Maxfield, & Pitt, 2007; Luu, Tucker, & Stripling, 2007; Macnamara, Foti, & Hajcak, 2009; Matsuda, Nittono, Hirota, Ogawa, & Takasawa, 2009; Maxfield, Lyon, & Silliman, 2009; McDonald, Gabbay, Rietschel, & Duncan, in press; O'Hare & Dien, 2008; Yang, Perfetti, & Schmalhofer, 2005; Yang, Perfetti, & Schmalhofer, 2007; Yang & Perfetti, 2006).

The primary goal of this report will be to provide readers with a sense of what capabilities it makes available and what is required to use them. This report will be divided into three portions: preparing the data for ERP analysis, ERP analysis using PCA, and robust inferential statistics for testing the ERP effects.

Requirements

The EP Toolkit has the following requirements to use. The Toolkit itself is free and available via download (<https://sourceforge.net/projects/erppcatoolkit/>). Those interested can also join the mailing list (<https://lists.sourceforge.net/lists/listinfo/erppcatoolkit-support>) to be alerted when new versions are posted. It is necessary to have a license for Matlab, and it has been tested under both OS X and Windows XP using Matlab 2006 through 2009b. It is recommended that the computer have a minimum of 2GB and preferably at least 4GB. EEGlab (Delorme & Makeig, 2004) and Robert Oostenveld's FieldTrip (<http://www.ru.nl/neuroimaging/fieldtrip>) will also need to be installed, the former for the ICA function and the channel coordinates function and the latter for the file format functions. Both of these software suites are free by internet download. It can currently support the following file formats: EGI's EGIS and Simple Binary,

EEGlab's .set, Biosig's .edf, Neuroscan's .avg, tab-delimited text, and its own EP format. The author is interested in adding support for additional file formats if potential users are willing to help with testing, time permitting.

Preparation of the Data

The primary goal for this first section is to provide a sense to potential users of what is required to use the EP Toolkit to prepare the data. The nature of the procedures themselves have largely been reported on elsewhere and just the appropriate citations will be provided. Data preparation in turn consists of artifact correction and robust averaging. Functions are accessed via the Start Pane:

Insert Figure 1 Here

The Toolkit can automatically eliminate both blink artifacts and movement artifacts from session files, prior to averaging. The data must already have been segmented into discrete trials. The artifact correction function reads in a session file and segments it into manageable chunks which are temporarily stored (since an ICA of an entire session file can often exceed the available RAM). The default behavior (parameters can be changed by going to the Preferences menu of the EP Toolkit) is:

- 1) Detect globally bad channels, defined as channels that correlate poorly with neighboring channels and channels that are flat.
- 2) The next step uses EEGlab's runICA

routine to decompose the data into basic scalp topography components. These components are then compared to a blink template which specifies the topography of a typical blink. The template can be formed either automatically or manually. Components which correlate highly with this blink topography are deleted from the data.

3) The next step can be to detrend the data, although the default is not to do this. Detrending can be helpful for salvaging noisy data with strong DC drifts but will also affect the final ERP waveform.

4) Using an experimental approach (publication in preparation), movement artifacts can then be removed via PCA (using the Promax rotation). Since this algorithm has not been formally evaluated yet, nothing more will be said about it at this time.

5) Bad channels are then detected on a trialwise basis and can be replaced via interpolation from the other electrodes.

During the artifact correction process, a new Artifact Correction figure will be presented illustrating the progression of the process. For each chunk, it will chart the state of the data in a butterfly plot, which consists of all the trials laid end to end, with one line corresponding to each channel. Artifacts can be easily detected as high amplitude divergences from the central mass of lines. Several such plots are provided:

- 1) the original data
- 2) the data after baseline correction
- 3) the portion of the data identified as blinks. They should be sharp spikes.
- 4) the data with the blinks subtracted.
- 5) the portion of the data identified as movement artifacts.

- 6) the data with the movement artifacts removed.
- 7) the portion of the data identified as bad channels or bad trials.
- 8) the data with bad channels interpolated and bad trials zeroed out.

Insert Figure 2 Here

In addition, a log is produced which documents how the files were processed:

```
Working on: /Volumes/LACIE/SLI/02exported/subset/SLI_3001f_45m_POA.egis.  
Bad Channels: None  
128 trials corrected for blink activity.  
159 trials corrected for movement activity.  
Detecting bad data.  
There were 37 bad trials.  
For good trials, there was an average of 7.1172 bad channels per trial.  
Detecting horizontal eye movements.  
There were 0 horizontal eye movement trials.
```

The next step is to average the data. The averaging options are:

- 1) mean - which is the conventional averaging procedure.
- 2) median - which uses the median instead of the mean.
- 3) trimmed mean - which uses the mean but first trims off the most extreme values at each time point. The default value (which can be changed under Preferences) is 25% so

the highest and lowest 25% will be dropped. This results in a more robust estimate of the central tendency of the event related potentials. The trimmed mean is recommended over the median (Leonowicz, Karvanen, & Shishkin, 2005).

An edit function allows for the data file to be inspected and, if necessary, corrected. Of particular utility are some summary statistics that help users identify bad data. Available diagnostic measures for each averaged waveform include the number of good trials, the number of trials containing blinks, the number of trials containing movement artifacts, the mean number of bad channels, the magnitude of the noise as estimated by the +/- reference (Schimmel, 1967), the root mean square (RMS), and the mean standard deviation.

Further inspection of data quality can be performed by directly viewing the waveforms. Up to four different waveforms can be overlaid and they can come from the same or different datasets.

Insert Figure 3 Here

Principal Component Analysis

The next step is to obtain a PCA of the data, typically a two-step sequential PCA (Spencer, Dien, & Donchin, 1999; Spencer, Dien, & Donchin, 2001) in which the first step is a temporal Promax rotation and the second step is a spatial Infomax (ICA) rotation (Dien, in press).

In order to determine the number of factors to retain, the Parallel Test (Horn, 1965), which compares the Scree of the dataset to that obtained from a fully random dataset, is available. The point where the blue line crosses the green line is the number of factors to retain. The red line represents the Scree plot of the noise data produced by the +/- reference (Schimmel, 1967), which provides further information about the dimensionality of the dataset. For completeness sake, the minimum %age accounted criterion is also available.

Insert Figure 4 Here

One can then generate the initial temporal PCA step. Options for rotation include: Varimax, Promax, Infomax, Quartimax, Quartimin, Oblimin, Geomin, and others. Clicking on done generates a new dataset containing the PCA results. A similar process then generates the second spatial PCA step from the initial temporal PCA results.

Insert Figure 5 Here

Aside from viewing the numeric results such as the factor loadings, one can also view the factors directly . One could, for example, examine what portion of the grand average is accounted for by TFSF1 (the first spatial factor formed from the first temporal factor) by overlaying them.

An expanded view of channel 20 reveals the following waveforms, where the red and the green lines are two of the conditions and the black and green lines (indistinguishable) are the portions of the red and green waveforms accounted for by the factor at this channel:

Insert Figure 6 Here

Robust Inferential Statistics

Obtaining Summary Measures

To test whether there are any statistically significant effects, first set channel regions of interest by clicking on the appropriate channels or by using the factor loadings produced by a spatial PCA:

Insert Figure 7 Here

Then window the data:

Insert Figure 8 Here

One can use the View facility to examine the waveforms to see how they relate to the windowed measures:

Insert Figure 9 Here

Analysis of PCA data is conducted in much the same way. The Toolkit can automatically run through all the factors, choosing the peak channel and the peak time point for each factor. It will only generate a windowed file for each factor whose size (variance accounted for) meets a minimum threshold to screen out factors that account for only small clumps of noise. This kind of selectivity is, in turn, helpful when controlling for multiple comparisons as one will not have to be as stringent as if one had included the noise factors. The output of a PCA is expressed in voltages, corresponding to the voltage accounted for at the chosen time points and channels.

Inferential Statistical Test

Next, the robust statistics function generates inferential statistical tests comparable to ANOVAs that are designed to be more robust against violations of statistical assumptions. The statistical routines were translated from the SAS/IML routines posted

by Keselman (<http://www.umanitoba.ca/faculties/arts/psychology/>). The routines were fully described in the following publication (Keselman, Wilcox, & Lix, 2003). A front-end has been added that automatically generates the necessary contrast matrices for omnibus ANOVAs and that organizes the results in an easy to read manner. Note that the routines take some time to run at present.

The editors of *Psychophysiology* at present (December, 2009) recommend the use of these robust statistics (specifically, statistical tests using non-pooled error terms) in its Guidelines to Authors. In brief, this robust statistic has the following three features: 1) trimmed means and winsorized covariances to protect against outliers; 2) bootstrapping routine to estimate the population distribution rather than making the assumption that the data is normally distributed; 3) Welch-James approximate degrees of freedom statistic (resulting sometimes in decimal degrees of freedom) that avoids the assumption that the cells have homogeneous error variances. The latter also makes it unnecessary to use epsilon correction like G-G or H-F since sphericity is not assumed. In practice, it seems to generate results that are largely comparable to normal ANOVAs but that are more robust against violations of assumptions. For a direct comparison of ERP results against univariate and multivariate ANOVAs, see (Dien et al., 2006). A very approachable treatment of this robust statistic is available (Wilcox, 2001). A description of the issues involved in using conventional ANOVAs with ERP data is also available (Dien & Santuzzi, 2005).

Insert Figure 10 Here

You can verify that your factor structure mapped correctly onto the data by clicking on the View button.

Insert Figure 11 Here

Output of Inferential Tests

Some typical output follows. First it provides the basic parameters. Then each combination of between factor effects is presented. For each between factor effect combination, the within factor effects are provided. The section titled "NO BETWEEN EFFECTS" are the effects without interactions with the between group factors. The effect labeled " NO WITHIN EFFECTS" in the "sex MAIN EFFECT" is, conversely, the main effect of the between group effect of sex (thus having no interaction with the within group factors) and the "POA MAIN EFFECT" that follows it is the interaction with the sex main effect. Each effect lists the statistical test numbers (appropriate for directly copying into a manuscript). If the test reaches one-tailed significance (normally .10) then it is listed in green. If it reaches two-tailed significance but not Bonferroni corrected significance then it is listed in orange. If it reaches two-tailed significance even with the Bonferroni correction then it is listed in red. Finally, it lists the trimmed cell means underlying each of these tests.

WELCH-JAMES APPROXIMATE DF SOLUTION

TRIMMED MEANS & WINSORIZED VARIANCES

PERCENTAGE OF TRIMMING: 0.05

BOOTSTRAP CRITICAL VALUE FOR SINGLE TEST STATISTIC

NUMBER OF BOOTSTRAP SAMPLES: 50000

STARTING SEED: 1000

Number of subjects in each group: 4 6

Number trimmed from each end of the groups: 0 0

Uncorrected alpha criteria: 0.05

Corrected alpha criteria: 0.0011905

#####

NO BETWEEN EFFECTS

POA MAIN EFFECT

TWJt/c(1.0,8.0)=1.36, p=0.28

Averaged Trimmed Cell Means:

D G

+1.55 +0.51

PHN MAIN EFFECT

TWJt/c(1.0,7.5)=0.25, p=0.63

Averaged Trimmed Cell Means:

Y N
+1.27 +0.79

POA * PHN INTERACTION EFFECT

TWJt/c(1.0,7.6)=0.87, p=0.37

Averaged Trimmed Cell Means:

DY DN GY GN
+1.35 +1.76 +1.19 -0.18

sex MAIN EFFECT

NO WITHIN EFFECTS

TWJt/c(1.0,5.9)=2.72, p=0.18

Averaged Trimmed Cell Means:

F -0.26
M +2.32

POA MAIN EFFECT

TWJt/c(1.0,8.0)=0.02, p=0.90

Averaged Trimmed Cell Means:

D G

F +0.20 -0.73

M +2.90 +1.74

etc. etc.

In order to further the goal of increasing transparency of the analysis, summary waveforms corresponding to the windowed measures are added to the dataset. The same subjects trimmed from the cell means are also trimmed from these added waveforms. Furthermore, if regional channels of interest are utilized, then the waveforms will also be averaged over these channels. Likewise, if the analysis involves combinations of conditions then the waveforms will also collapse across these conditions. Finally, grand average waveforms will be provided, collapsing across the subjects. If the analysis involves between-group ANOVA factors then grand average waveforms corresponding to each group will be provided. Thus, one will be able to directly compare the cell means of the ANOVAs with the corresponding waveforms. The Toolkit keeps track of which waveforms are the original data and which are the added summaries so that they do not interfere with the ongoing analyses.

Follow-up Tests

A further feature of the Toolkit's output is that when an interaction is significant (uncorrected), the Toolkit will provide all the possible follow-up tests (i.e., for a three-way interaction, it will provide all the possible two-way interactions, where one level is held constant). If any of those are significant then a the follow-up tests for that test are provided as well. In the following case, a dataset (Yoder, Molfese, Gardner, Dien, and Kressner, submitted) of auditory ERPs recorded from children was analyzed according to the between-group factor of sex and according to the within-group factors of point of articulation (D vs. G phonemes) and whether the sound parameters were within normal speech range (yes vs. no). Here, a sex by POA by PHN interaction is significant (uncorrected). It is known that this is an interaction with sex since it appears in the sex main effects section. It then follows up with all the possible two-way ANOVAs. It reports that the POA by PHN interaction is significant (uncorrected) for boys (level M of the sex factor). It then follows that up with the tests of the one-way ANOVAs for that interaction, the first of which is included below. Note that follow-up tests are in a smaller font to help set them off from the main tests. Also, follow-ups are indented deeper than the preceding level of results. Once the follow-ups to a test are completed then the results proceed to the next test. Devising a clearer format for these results tables is planned for a future release but it should suffice for now.

POA * PHN INTERACTION EFFECT

$T_{WJ/c}(1.0,6.7)=13.47, p=0.025$

Averaged Trimmed Cell Means:

DY DN GY GN

F -1.15 -1.29 -0.07 +1.61

M -1.87 +0.31 -0.81 -4.05

Holding level F of factor sex constant.

#####

NO BETWEEN EFFECTS

POA * PHN INTERACTION EFFECT

$T_{WJt}/c(1.0,3.0)=1.44, p=0.26$

Averaged Trimmed Cell Means:

DY DN GY GN

-1.15 -1.29 -0.07 +1.61

#####

Holding level M of factor sex constant.

#####

NO BETWEEN EFFECTS

POA * PHN INTERACTION EFFECT

$T_{WJt}/c(1.0,5.0)=18.36, p=0.0089$

Averaged Trimmed Cell Means:

DY	DN	GY	GN
-1.87	+0.31	-0.81	-4.05
Holding level D of factor POA constant.			
#####			
NO BETWEEN EFFECTS			

PHN MAIN EFFECT			
$T_{WJ/c}(1.0,5.0)=2.55, p=0.34$			
Averaged Trimmed Cell Means:			
Y	N		
-1.87	+0.31		

Another feature of the Toolkit is that when an effect involves an electrode factor, it will provide the McCarthy and Wood (1985) vector test (McCarthy & Wood, 1985) to determine if it does indeed indicate a change in the scalp topography rather than being an artifact of the ANOVA model. For an explanation of this issue, see (Dien & Santuzzi, 2005). Such vector tests are set off from the rest of the results tables with italics.

POA * SIT INTERACTION EFFECT			
$T_{WJ/c}(1.0,6.9)=224.44, p=0.0055$			
Averaged Trimmed Cell Means:			
DF	DP	GF	GP

+4.96 +4.22 +2.54 +4.45

Vector Scaling Test (is the scalp topography effect genuine?):

$T_{WJ/c}(1.0,7.8)=295.24, p=0.00012$

If needed, one can also perform follow-up contrasts.

Insert Figure 12 Here

The results are rather barebones but functional:

SLIfac-TF1SF2

Contrast: 1

Within: 1 -1 0 0

Between: 1 1

$T_{WJ/c}(1.0,5.3)=2.17, p=0.34$

Conclusion

In conclusion, the EP Toolkit is designed to optimize analysis of noisy data by providing automatic artifact correction, robust averaging, and robust inferential statistics. The Toolkit facilitates multivariate decomposition of ERP data by providing simple functions for applying PCA and ICA for both one-step and two-step procedures, visualizing the results by reconstructing the factor waveforms, and applying inferential statistics. Finally, the Toolkit increases the transparency of analysis by providing direct visualization of the waveforms corresponding to the PCA results and to the windowed measures.

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FIGURE LEGENDS

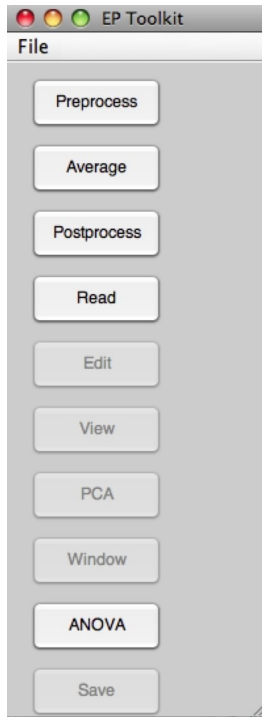


Figure 1. Start Pane.

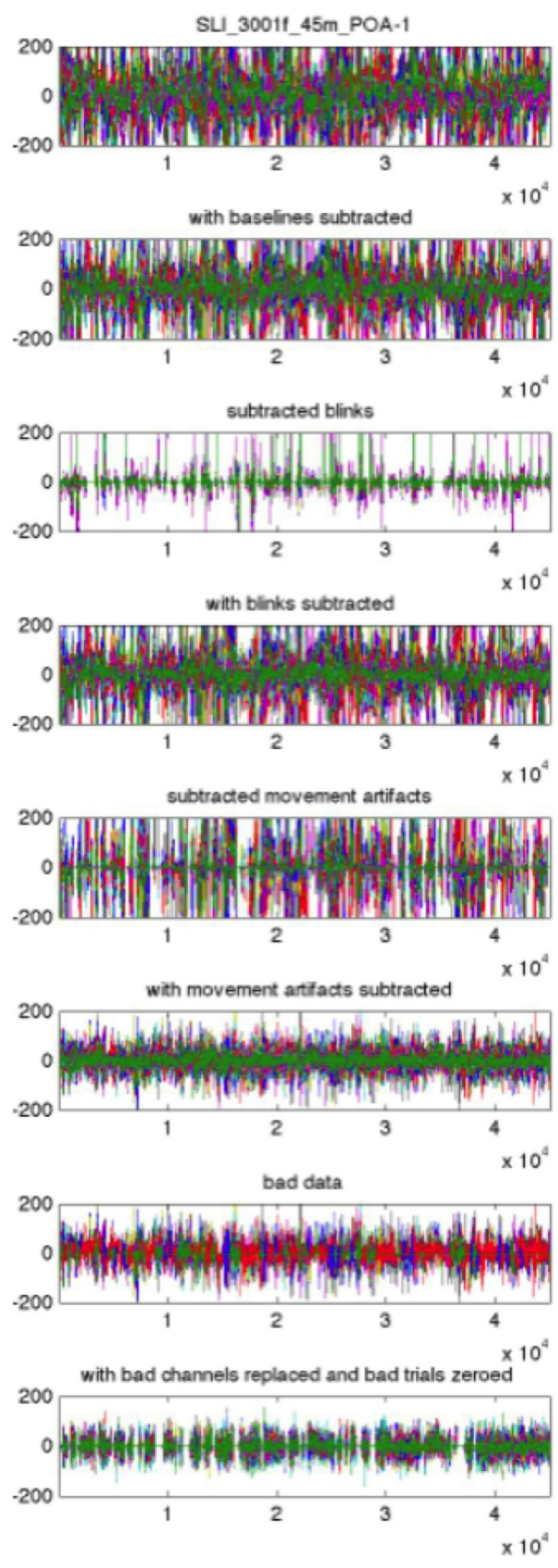


Figure 2. Artifact Correction Summary Plot.

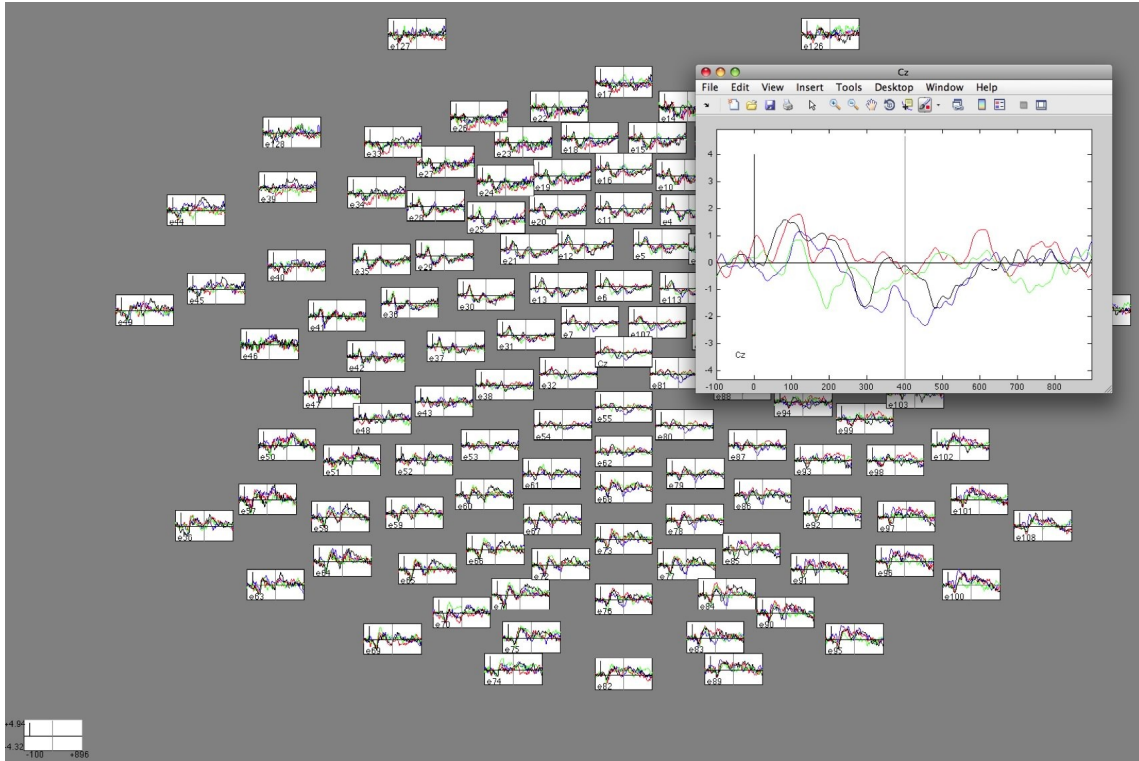


Figure 3. Waveform Plot With Zoom for One Channel.

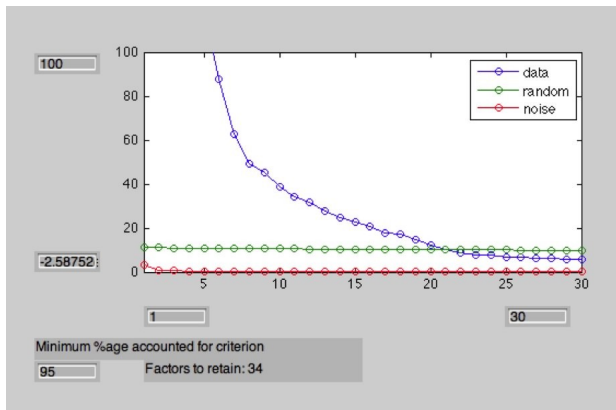


Figure 4. Scree Plot.

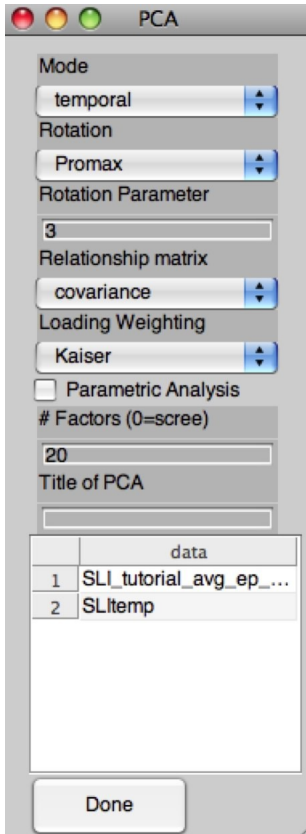


Figure 5. PCA Pane.

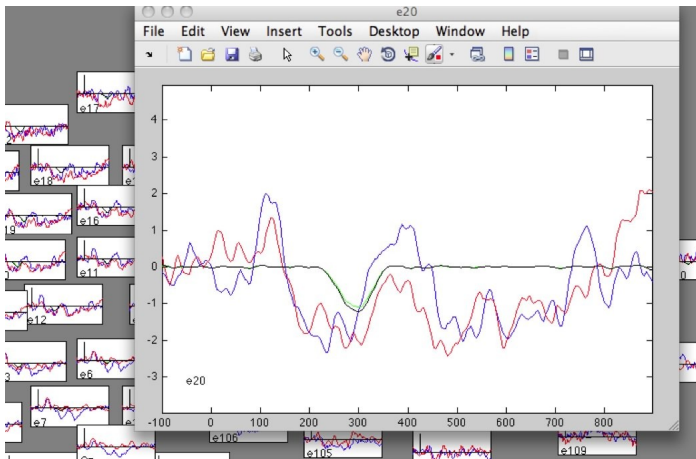


Figure 6. Overplot of Factor Waveform and Grand Average Waveform.

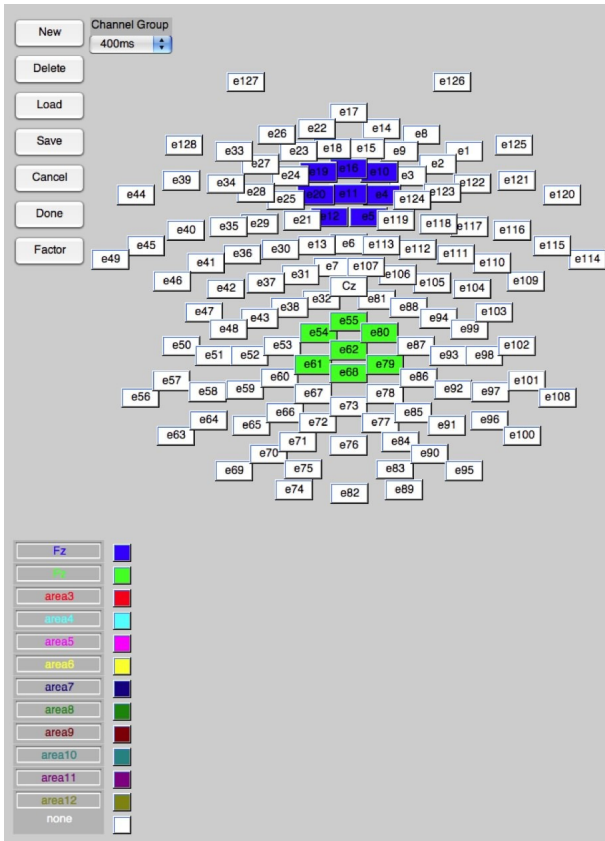


Figure 7. Selecting Channel Region of Interest.

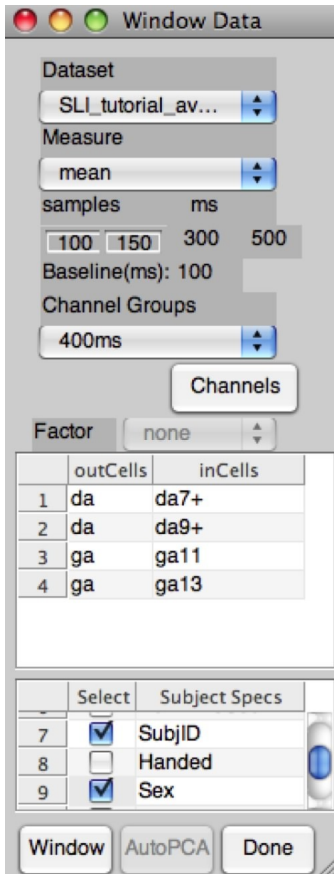


Figure 8. Window Data Pane.

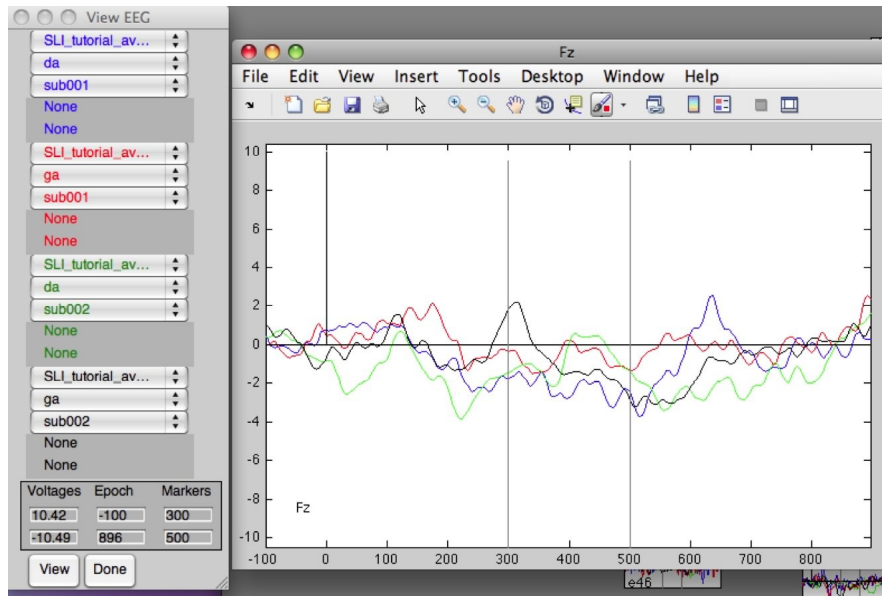


Figure 9. Displaying the Windowed Epoch in the Waveform Plot.

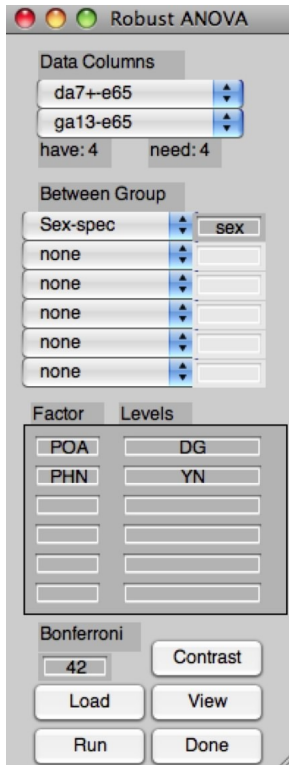


Figure 10. Robust ANOVA Pane.

	D Y da7+-e65	D N da9+-e65	G Y ga11-e65	G N ga13-e65	Sex-spec
1	2.6173	2.6293	-1.5068	0.4842	F
2	-0.1643	1.8684	2.2455	-5.2501	F
3	-0.6412	-0.8659	-0.5475	-0.6545	M
4	2.9261	4.2162	2.8295	-0.7088	F
5	-4.1796	0.3537	0.3777	-0.9644	M
6	-1.0015	-0.2631	0.3102	1.9439	M
7	3.4788	5.2024	7.2824	1.2119	F
8	-1.5257	-1.6124	-1.1385	3.1496	M
9	8.8995	-4.3484	-3.2288	-6.3214	M
10	6.9293	11.9082	7.3319	8.1829	M

Figure 11. Verifying Assignment of Columns to ANOVA Factors.

	Cells	POA	PHN	Con1	Con2	Con3	Con4	Con5
1	da7+e7	D	Y	1	0	0	0	0
2	da9+e7	G	Y	-1	0	0	0	0
3	ga11-e7	D	N	0	0	0	0	0
4	ga13-e7	G	N	0	0	0	0	0

	sex	Con1	Con2	Con3	Con4	Con5
1	F	0	0	0	0	0
2	M	0	0	0	0	0

Figure 12. Performing Contrast.