Time-frequency analysis using Hanning window, multitapers and wavelets

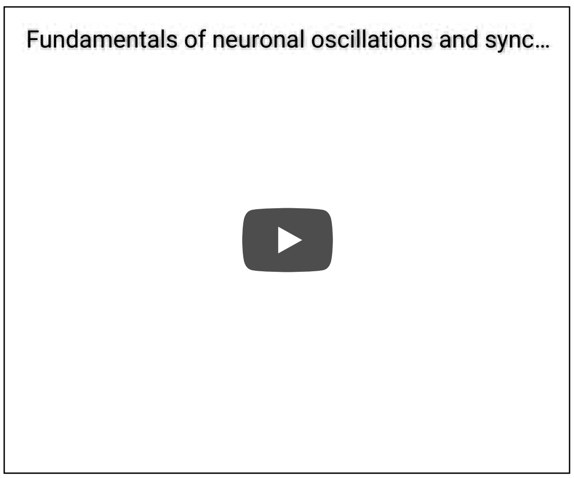
Introduction

In this tutorial you can find information about the time-frequency analysis of a single subject's MEG data using a Hanning window, multitapers and wavelets. This tutorial also shows how to visualize the results.

Here, we will work on the MEG-language-semantics dataset, you can click here for details on the dataset. This tutorial is a continuation from the preprocessing tutorials. We will begin by repeating the code used to select the trials and preprocess the data as described in the first tutorials (trigger based trial selection, artifact rejection). We assume that the reader already knows how to do the preprocessing in FieldTrip.

There is no information in this tutorial about how to compare conditions, how to grandaverage the results across subjects or how to do statistical analysis on the time-frequency data. Some of these issues are covered in other tutorials (see Summary and suggested further reading).

This tutorial contains hands-on material that we use for the MEG/EEG toolkit course and is complemented by this lecture.



Background

Oscillatory components contained in the ongoing EEG or MEG signal often show power changes relative to experimental events. These signals are not necessarily phase-locked to the event and will not be represented in event related fields and potentials [1]. The goal of this section is to compute and visualize event related changes by calculating time-frequency representations (TFRs) of power. This will be done using analysis based on Fourier analysis and wavelets. The Fourier analysis will include the application of multitapers [2][3] which allow a better control of time and frequency smoothing.

Calculating time-frequency representations of power is done using a sliding time window. This can be done according to two principles: either the time window has a fixed length independent of frequency, or the time window decreases in length with increased frequency. For each time window the power is calculated. Prior to calculating the power one or more tapers are multiplied with the data. The aim of the tapers is to reduce spectral leakage and control the frequency smoothing.

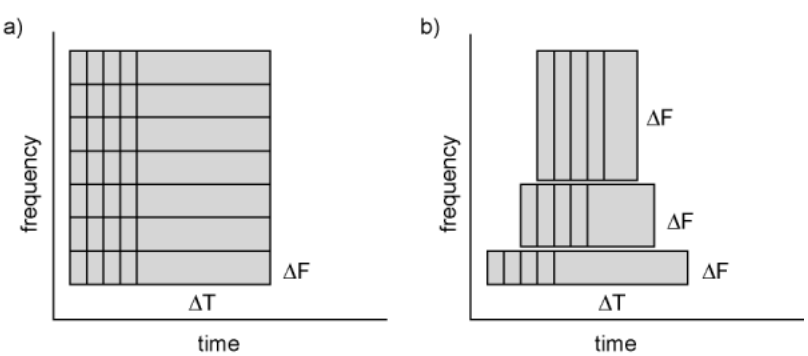


Figure 1; Time and frequency smoothing. (a) For a fixed length time window the time and frequency smoothing remains fixed. (b) For time windows that decrease with frequency, the temporal smoothing decreases and the frequency smoothing increases.

If you want to know more about tapers/ window functions you can have a look at this wikipedia site (http://en.wikipedia.org/wiki/Window_function). Note that Hann window is another name for Hanning window used in this tutorial. There is also a wikipedia site about multitapers, to take a look at it click here (http://en.wikipedia.org/wiki/Multitaper).

Procedure

To calculate the time-frequency analysis for the example dataset we will perform the following steps:

- Read the data into MATLAB using **ft_definetrial** and **ft_preprocessing**
- Compute the power values for each frequency bin and each time bin using the function **ft_freqanalysis**
- Visualize the results. This can be done by creating time-frequency plots for one (**ft_singleplotTFR**) or several channels (**ft_multiplotTFR**), or by creating a topographic plot for a specified time- and frequency interval (**ft_topoplotTFR**).

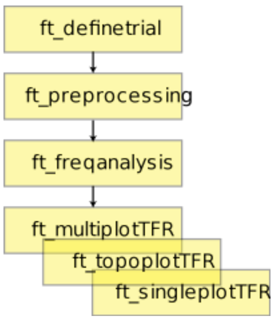


Figure 2; Schematic overview of the steps in time-frequency analysis

In this tutorial, procedures of 4 types of time-frequency analysis will be shown. You can see each of them under the titles: Time-frequency analysis I., II. ... and so on. If you are interested in a detailed description about how to visualize the results, look at the Visualization part.

Preprocessing

The first step is to read the data using the function **ft_preprocessing**. With the aim to reduce boundary effects occurring at the start and the end of the trials, it is recommended to read larger time intervals than the time period of interest. In this example, the time of interest is from -0.5 s to 1.5 s (t = 0 s defines the time of stimulus); however, the script reads the data from -1.0 s to 2.0 s.

Reading the FIC data

Ft_definetrial and **ft_preprocessing** require the original MEG dataset, which is available from ftp://ftp.fieldtriptoolbox.org/pub/fieldtrip/tutorial/Subject01.zip (ftp://ftp.fieldtriptoolbox.org/pub/fieldtrip/tutorial/Subject01.zip).

```
% find the interesting segments of data
cfg = [];                                          % empty configuration
cfg.dataset                 = 'Subject01.ds';      % name of CTF dataset
cfg.trialdef.eventtype      = 'backpanel trigger';
cfg.trialdef.prestim        = 1;
cfg.trialdef.poststim       = 2;
cfg.trialdef.eventvalue     = 3;                   % event value of FIC
cfg = ft_definetrial(cfg);

% remove the trials that have artifacts from the trl
cfg.trl([15, 36, 39, 42, 43, 49, 50, 81, 82, 84],:) = [];

% preprocess the data
cfg.channel   = {'MEG', '-MLP31', '-MLO12'};        % read all MEG channels except MLP31 and MLO12
cfg.demean    = 'yes';                              % do baseline correction with the complete trial

dataFIC = ft_preprocessing(cfg);
```

These data have been cleaned from artifacts by removing several trials and two sensors; see the visual artifact rejection tutorial.

Subsequently you can save the data to disk.

```
save dataFIC dataFIC
```

2009/03/11 13:41 (2009-03-11T13:41:12Z)

Time-frequency analysis I.

Hanning taper, fixed window length

We will here describe how to calculate time frequency representations using Hanning tapers. When choosing for a fixed window length procedure the frequency resolution is defined according to the length of the time window (delta T). The frequency resolution (delta f in figure 1) = 1/length of time window in sec (delta T in figure 1). Thus a 500 ms time window results in a 2 Hz frequency resolution (1/0.5 sec= 2 Hz) meaning that power can be calculated for 2 Hz, 4 Hz, 6 Hz etc. An integer number of cycles must fit in the time window.

Ft_freqanalysis requires preprocessed data (see above), which is available from ftp://ftp.fieldtriptoolbox.org/pub/fieldtrip/tutorial/timefrequencyanalysis/dataFIC.mat (ftp://ftp.fieldtriptoolbox.org/pub/fieldtrip/tutorial/timefrequencyanalysis/dataFIC.mat).

```
load dataFIC
```

In the following example a time window with length 500 ms is applied.

```
cfg              = [];
cfg.output       = 'pow';
cfg.channel      = 'MEG';
cfg.method       = 'mtmconvol';
cfg.taper        = 'hanning';
cfg.foi          = 2:2:30;                         % analysis 2 to 30 Hz in steps of 2 Hz
cfg.t_ftimwin    = ones(length(cfg.foi),1).*0.5;   % length of time window = 0.5 sec
cfg.toi          = -0.5:0.05:1.5;                  % time window "slides" from -0.5 to 1.5 sec in steps of 0.05 sec (50 ms)
TFRhann = ft_freqanalysis(cfg, dataFIC);
```

Regardless of the method used for calculating the TFR, the output format is identical. It is a structure with the following elements:

```
TFRhann =

        label: {149x1 cell}                % Channel names
       dimord: 'chan_freq_time'            % Dimensions contained in powspctrm, channels X frequencies X time
         freq: [2 4 6 8 10 12 14 16 18 20 22 24 26 28 30]  % Array of frequencies of interest (the elements of freq may be differen
t from your cfg.foi input depending on your trial length)
         time: [1x41 double]               % Array of time points considered
    powspctrm: [149x15x41 double]          % 3-D matrix containing the power values
         grad: [1x1 struct]                % Gradiometer positions etc
          cfg: [1x1 struct]                % Settings used in computing this frequency decomposition
```

The element TFRhann.powspctrm contains the temporal evolution of the raw power values for each specified frequency.

Visualization

This part of the tutorial shows how to visualize the results of any type of time-frequency analysis.

To visualize the event-related power changes, a normalization with respect to a baseline interval will be performed. There are two possibilities for normalizing: (a) subtracting, for each frequency, the average power in a baseline interval from all other power values. This gives, for each frequency, the absolute change in power with respect to the baseline interval. (b) expressing, for each frequency, the raw power values as the relative increase or decrease with respect to the power in the baseline interval. This means active period/baseline. Note that the relative baseline is expressed as a ratio; i.e. no change is represented by 1.

There are three ways of graphically representing the data: 1) time-frequency plots of all channels, in a quasi-topographical layout, 2) time-frequency plot of an individual channel (or average of several channels), 3) topographical 2-D map of the power changes in a specified time-frequency interval.

To plot the TFRs from all the sensors use the function **ft_multiplotTFR**. Settings can be adjusted in the cfg structure. For example:

```
cfg = [];
cfg.baseline     = [-0.5 -0.1];
cfg.baselinetype = 'absolute';
cfg.zlim         = [-3e-27 3e-27];
cfg.showlabels   = 'yes';
cfg.layout       = 'CTF151.lay';
figure
ft_multiplotTFR(cfg, TFRhann);
```

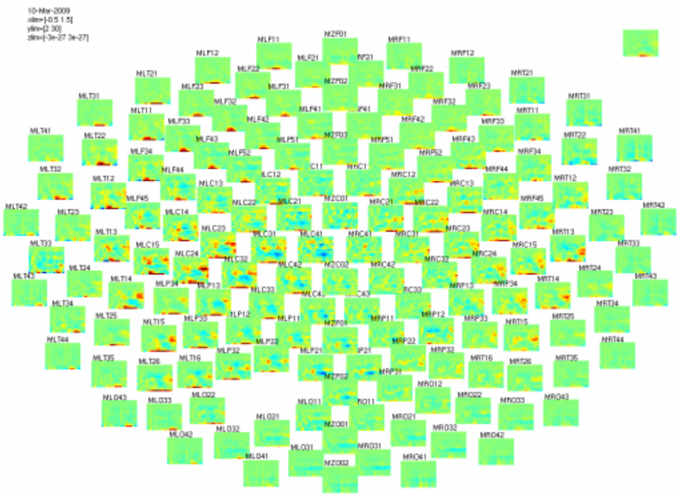


*Figure 3; Time-frequency representations calculated using **ft_freqanalysis**. Plotting was done with **ft_multiplotTFR***

Note that by using the options cfg.baseline and cfg.baselinetype when calling plotting functions, baseline correction can be applied to the data. Baseline correction can also be applied directly by calling **ft_freqbaseline**. You can combine the various visualisation options/functions interactively to explore your data. Currently, this is the default ploting behavior because the configuration option cfg.interactive='yes' is activated unless you explicitly select cfg.interactive='no' before calling **ft_multiplotTFR** to deactivate it. See also the plotting tutorial for more details.

An interesting effect seems to be present in the TFR of sensor MRC15. To make a plot of a single channel use the function **ft_singleplotTFR**:

```
cfg = [];
cfg.baseline     = [-0.5 -0.1];
cfg.baselinetype = 'absolute';
cfg.maskstyle    = 'saturation';
cfg.zlim         = [-3e-27 3e-27];
cfg.channel      = 'MRC15';
figure
ft_singleplotTFR(cfg, TFRhann);
```

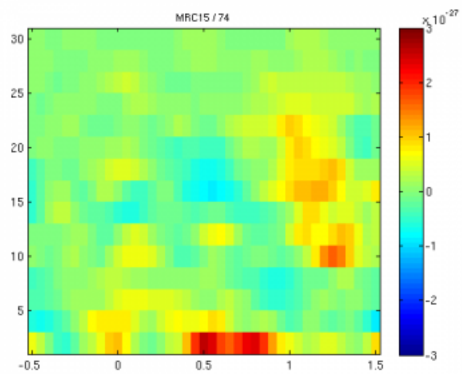


*Figure 4; The time-frequency representation with respect to single sensor obtained using **ft_singleplotTFR**.*
(if you see artifacts in your figure, see I am getting strange artifacts in figures that use opacity)

From Figure 4 one can see that there is an increase in power around 15-20 Hz in the time interval 0.9 to 1.3 s after stimulus onset. To show the topography of the beta increase use the function **ft_topoplotTFR**:

```
cfg = [];
cfg.baseline     = [-0.5 -0.1];
cfg.baselinetype = 'absolute';
cfg.xlim         = [0.9 1.3];
cfg.zlim         = [-1.5e-27 1.5e-27];
cfg.ylim         = [15 20];
cfg.marker       = 'on';
figure
ft_topoplotTFR(cfg, TFRhann);
```

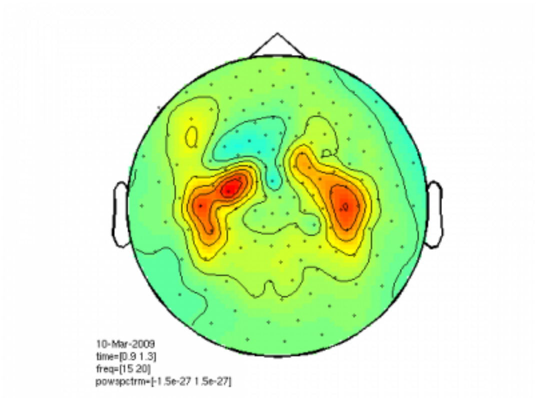


*Figure 5; A topographic representation of the time-frequency representations (15 - 20 Hz, 0.9 - 1.3 s post stimulus) obtained using **ft_topoplotTFR***

Exercise 1

- Plot the power with respect to a relative baseline (hint: use cfg.zlim = [0 2.0] and use the cfg.baselinetype option)
- How are the responses different? Discuss the assumptions behind choosing a relative or absolute baseline

Exercise 2

- Plot the TFR of sensor MLC24. How do you account for the increased power at ~300 ms (hint: compare to ERFs)?

Time-frequency analysis II.

Hanning taper, frequency dependent window length

It is also possible to calculate the TFRs with respect to a time window that varies with frequency. Typically the time window gets shorter with an increase in frequency. The main advantage of this approach is that the temporal smoothing decreases with higher frequencies; however, this is on the expense of frequency smoothing. We will here show how to perform this analysis with a Hanning window. The approach is very similar to wavelet analysis. A wavelet analysis performed with a Morlet wavelet mainly differs by applying a Gaussian shaped taper.

The analysis is best done by first selecting the numbers of cycles per time window which will be the same for all frequencies. For instance if the number of cycles per window is 7, the time window is 1000 ms for 7 Hz (1/7 x 7 cycles); 700 ms for 10 Hz (1/10 x 7 cycles) and 350 ms for 20 Hz (1/20 x 7 cycles). The frequency can be chosen arbitrarily - however; too fine a frequency resolution is just going to increase the redundancy rather than providing new information.

Below is the cfg for a 7 cycle time window. The calculation is only done for one sensor (MRC15) but it can of course be extended to all sensors.

```
cfg              = [];
cfg.output       = 'pow';
cfg.channel      = 'MRC15';
cfg.method       = 'mtmconvol';
cfg.taper        = 'hanning';
cfg.foi          = 2:1:30;
cfg.t_ftimwin    = 7./cfg.foi;  % 7 cycles per time window
cfg.toi          = -0.5:0.05:1.5;
TFRhann7 = ft_freqanalysis(cfg, dataFIC);
```

To plot the result use **ft_singleplotTFR**:

```
cfg              = [];
cfg.baseline     = [-0.5 -0.1];
cfg.baselinetype = 'absolute';
cfg.maskstyle    = 'saturation';
cfg.zlim         = [-3e-27 3e-27];
cfg.channel      = 'MRC15';
cfg.interactive  = 'no';
figure
ft_singleplotTFR(cfg, TFRhann7);
```

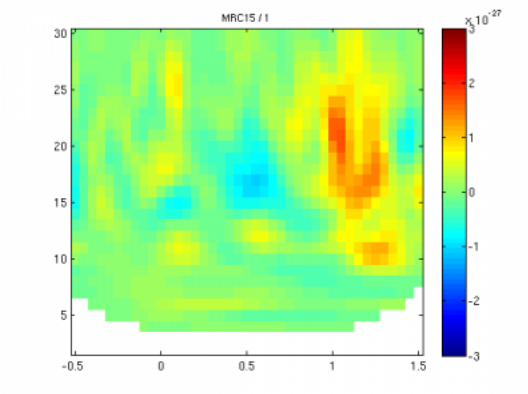


*Figure 6; A time-frequency representation of channel MRC15 obtained using **ft_singleplotTFR***
(if you see artifacts in your figure, see I am getting strange artifacts in figures that use opacity)

Note the boundary effects for lower frequencies (the white time frequency points in the plot). There is no power value calculated for these time frequency points. The power value is assigned to the middle time point in the time window. For example for 2 Hz the time window has a length of 3.5 sec (1/2 * 7 cycles = 3.5 sec), this does not fit in the 3 sec window that is preprocessed and therefore there is no data point here. For 5 Hz the window has a length of 1.4 sec (1/5 * 7 cycles = 1.4 sec). We preprocessed data between t = -1 sec and t = 2 sec so the first power value is assigned to t= -0.3 (since -1 + (0.5 * 1.4) = -0.3). Because of these boundary effects it is important to apply **ft_freqanalysis** to a larger time window to get all the time frequency points for your time window of interest.

If you would like to learn more about plotting of time-frequency representations, please see the Visualization section.

Exercise 3

Adjust the length of the time-window and thereby degree of smoothing. Use **ft_singleplotTFR** to show the results. Discuss the consequences of changing these settings:
4 cycles per time window:

```
cfg              = [];
cfg.output       = 'pow';
cfg.channel      = 'MRC15';
cfg.method       = 'mtmconvol';
cfg.taper        = 'hanning';
cfg.foi          = 2:1:30;
cfg.t_ftimwin    = 4./cfg.foi;
cfg.toi          = -0.5:0.05:1.5;
TFRhann4 = ft_freqanalysis(cfg, dataFIC);
```

5 cycles per time window:

```
cfg.t_ftimwin    = 5./cfg.foi;
TFRhann5 = ft_freqanalysis(cfg, dataFIC);
```

10 cycles per time window:

```
cfg.t_ftimwin    = 10./cfg.foi;
TFRhann10 = ft_freqanalysis(cfg, dataFIC);
```

Time-frequency analysis III.

Multitapers

Multitapers are typically used in order to achieve better control over the frequency smoothing. More tapers for a given time window will result in greater smoothing. High frequency smoothing has been shown to be particularly advantageous when dealing with electrophysiological brain signals above 30 Hz. Oscillatory gamma activity (30-100 Hz) is quite broad band and thus analysis of such signals benefit from multitapering. For signals lower than 30 Hz it is recommend to use only a single taper, e.g. a Hanning taper as shown above (beware that in the example below multitapers are used to analyze low frequencies because there are no effects in the gamma band in this dataset).

Time-frequency analysis based on multitapers can be performed by the function **ft_freqanalysis**. The function uses a sliding time window for which the power is calculated for a given frequency. Prior to calculating the power by discrete Fourier transformations the data are 'tapered'. Several orthogonal tapers might be used for each time window. The power is calculated for each tapered data segment and then combined. In the example below we apply a time window which gradually becomes shorter for higher frequencies (similar to wavelet techniques). The arguments for the chosen parameters are as follows

- cfg.foi , the frequencies of interest, here from 1 Hz to 30 Hz in steps of 2 Hz. The step size could be decreased at the expense of computation time and redundancy.
- cfg.toi, the time-interval of interest. This vector determines the center times for the time windows for which the power values should be calculated. The setting cfg.toi = -0.5:0.05:1.5 results in power values from -0.5 to 1.5 s in steps of 50 ms. A finer time resolution will give redundant information and longer computation times, but a smoother graphical output.
- cfg.t_ftimwin is the length of the sliding time-window in seconds (= tw). We have chosen cfg.t_ftimwin = 5./cfg.foi, i.e. 5 cycles per time-window. When choosing this parameter it is important that a full number of cycles fit within the time-window for a given frequency.

- cfg.tapsmofrq determines the width of frequency smoothing in Hz (= fw). We have chosen cfg.tapsmofrq = cfg.foi*0.4, i.e. the smoothing will increase with frequency. Specifying larger values will result in more frequency smoothing. For less smoothing you can specify smaller values, however, the following relation (determined by the Shannon number) must hold (see Percival and Walden, 1993):

```
K = 2*tw*fw-1,  where K is required to be larger than 0.
```

K is the number of multitapers applied; the more tapers the greater the smoothing.

These settings result in the following characteristics as a function of the frequencies of interest:

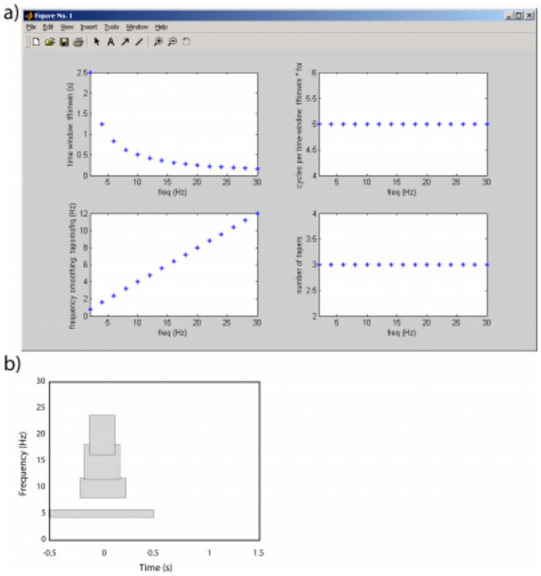


Figure 7; a) The characteristics of the TFRs settings using multitapers in terms of time and frequency resolution of the settings applied in the example. b) Examples of the time-frequency tiles resulting from the settings.

```
cfg = [];
cfg.output     = 'pow';
cfg.channel    = 'MEG';
cfg.method     = 'mtmconvol';
cfg.foi        = 1:2:30;
cfg.t_ftimwin  = 5./cfg.foi;
cfg.tapsmofrq  = 0.4 *cfg.foi;
cfg.toi        = -0.5:0.05:1.5;
TFRmult = ft_freqanalysis(cfg, dataFIC);
```

Plot the results:

```
cfg = [];
cfg.baseline     = [-0.5 -0.1];
cfg.baselinetype = 'absolute';
cfg.zlim         = [-3e-27 3e-27];
cfg.showlabels   = 'yes';
cfg.layout       = 'CTF151.lay';
figure
ft_multiplotTFR(cfg, TFRmult)
```

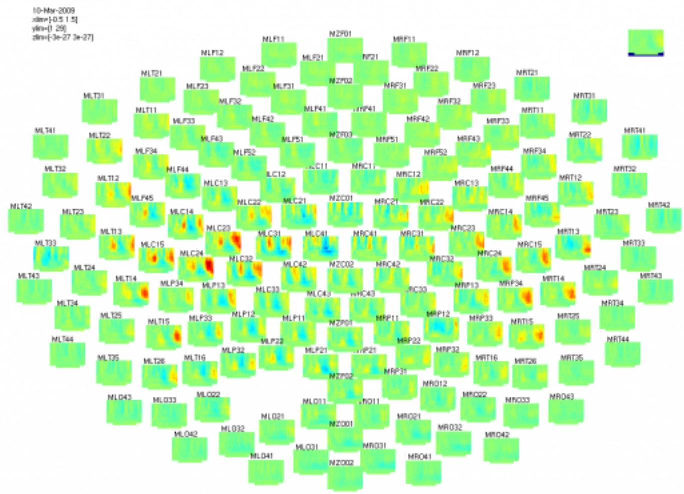


Figure 8; Time-frequency representations of power calculated using multitapers.

If you would like to learn more about plotting of time-frequency representations, please see the Visualization section.

Time-frequency analysis IV.

Morlet wavelets

An alternative to calculating TFRs with the multitaper method is to use Morlet wavelets. The approach is equivalent to calculating TFRs with time windows that depend on frequency using a taper with a Gaussian shape. The commands below illustrate how to do this. One crucial parameter to set is cfg.width. It determines the width of the wavelets in number of cycles. Making the value smaller will increase the temporal resolution at the expense of frequency resolution and vice versa. The spectral bandwidth at a given frequency F is equal to F/width*2 (so, at 30 Hz and a width of 7, the spectral bandwidth is 30/7*2 = 8.6 Hz) while the wavelet duration is equal to width/F/pi (in this case, 7/30/pi = 0.074s = 74ms) [4].

Calculate TFRs using Morlet wavelets:

```
cfg = [];
cfg.channel    = 'MEG';
cfg.method     = 'wavelet';
cfg.width      = 7;
cfg.output     = 'pow';
cfg.foi        = 1:2:30;
cfg.toi        = -0.5:0.05:1.5;
TFRwave = ft_freqanalysis(cfg, dataFIC);
```

Plot the results:

```
cfg = [];
cfg.baseline     = [-0.5 -0.1];
cfg.baselinetype = 'absolute';
cfg.zlim         = [-3e-25 3e-25];
cfg.showlabels   = 'yes';
cfg.layout       = 'CTF151.lay';
figure
ft_multiplotTFR(cfg, TFRwave)
```

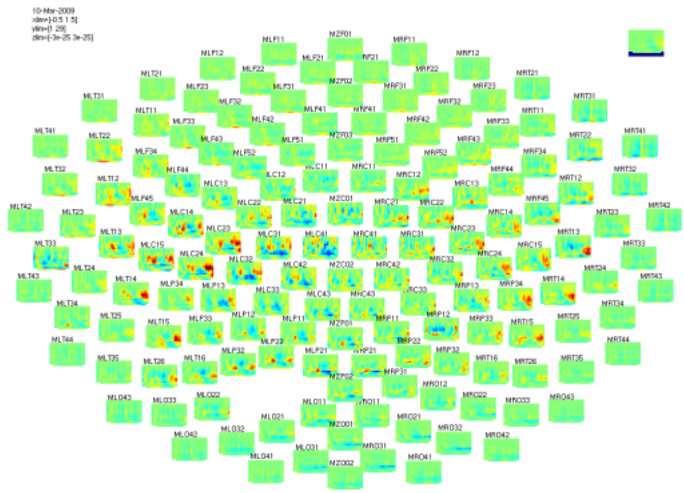


Figure 9; Time-frequency representations of power calculated using Morlet wavelets.

Exercise 4
Adjust cfg.width and see how the TFRs change.

If you would like to learn more about plotting of time-frequency representations, please see Visualization.

Summary and suggested further reading

This tutorial showed how to do time-frequency analysis on a single's subject MEG data and how to plot the time-frequency representations. There were 4 methods shown for calculating time-frequency representations and three functions for plotting the results.

After having finished this tutorial on time-frequency analysis, you can continue with the beamformer source reconstruction tutorial if you are interested in the source-localization of the power changes or the cluster-based permutation tests on time-frequency data tutorial if you are interested how to do statistics on the time-frequency representations.

Frequently asked questions:

• How can I compute inter-trial coherence?	2015/07/15 22:31	Robert Oostenveld
• How can I do time-frequency analysis on continuous data?	2014/09/18 08:26	
• How does MTMCONVOL work?	2016/09/07 11:48	Robert Oostenveld
• In what way can frequency domain data be represented in FieldTrip?	2011/06/08 09:49	Jan-Mathijs Schoffelen
• What are the differences between the old and the new implementation of 'mtmconvol' in ft_freqanalyis?	2010/11/19 12:06	Roemer van der Meij
• What are the differences between the old and the new implementation of 'mtmfft' in ft_freqanalyis?	2010/11/19 12:09	Roemer van der Meij
• What are the differences between the old and the new implementation of 'wavelet' (formerly 'wltconvol') in ft_freqanalyis?	2011/01/06 13:42	Roemer van der Meij
• What convention is used to define absolute phase in 'mtmconvol', 'wavelet' and 'mtmfft'?	2013/05/22 12:07	Roemer van der Meij
• What kind of filters can I apply to my data?	2015/03/28 14:16	
• Why am I not getting integer frequencies?	2015/02/18 15:36	Robert Oostenveld
• Why does my output.freq not match my cfg.foi when using 'mtmconvol' in ft_freqanalyis?	2010/11/24 15:04	Roemer van der Meij
• Why does my output.freq not match my cfg.foi when using 'mtmfft' in ft_freqanalyis	2013/11/26 18:49	Robert Oostenveld
• Why does my output.freq not match my cfg.foi when using 'wavelet' (formerly 'wltconvol') in ft_freqanalyis?	2011/01/06 13:38	Roemer van der Meij
• Why does my TFR contain NaNs?	2009/02/17 15:19	Robert Oostenveld
• Why does my TFR look strange (part I, demeaning)?	2010/07/27 10:27	Jan-Mathijs Schoffelen
• Why does my TFR look strange (part II, detrending)?	2010/12/21 21:50	Jan-Mathijs Schoffelen

Example scripts: