BESA Connectivity
User Manual

BESA®

Connectivity 2.0

User Manual

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Table of Contents

1. Notes

This user manual is a guide to the research product BESA Connectivity – a stand-alone software program.

The manual introduces the features, workflows, and the Main Windows and dialogs of the BESA Connectivity software. A help function is provided within the software. Press **F1** on the keyboard or select menu item **Help → BESA Connectivity Help** for help.

Before starting to work with BESA Connectivity, please read this user manual carefully.

Please report any suggestions and errors found in this manual via email to **feedback@besa.de**.

BESA GmbH provides support to all customers who have purchased BESA Connectivity directly from our sales office (**sales@besa.de**) or through our distributors.

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In case of support requests, please visit our support portal at https://besa-support.de.

2. Intended Use and Intended User, Product Classification and Certification, Installation Instructions, and System Requirements

Available in the BESA Connectivity 2.0 documents provided at https://www.besa.de/products/besa-connectivity/downloads/.

2.1. Before Setup

BESA Connectivity is available as 64-bit program. Please make sure your Windows system supports it prior to the installation. The installation and initial setup of BESA Connectivity must be carried out by an administrator or experienced technical staff.

2.2. Installation Instructions and Settings for BESA License Key

Available in the BESA License Key documents provided at https://www.besa.de/home/downloads/besa-license-key/

2.3. Start the Program

Start BESA Connectivity using the shortcut created on the desktop or run **BESA Connectivty.exe** from the **BESA → BESA Connectivity 2.0** folder in the Start menu.

First, the Welcome Screen appears. Press **Accept** to start BESA Connectivity.

2.3.1. Specify the BESA Connectivity Data Folder

As initial configuration step, the BESA Connectivity Data Folder must be specified. This is the folder where BESA Connectivity stores all project and result data to and reads from.

When starting the program for the first time, the following dialog box appears:
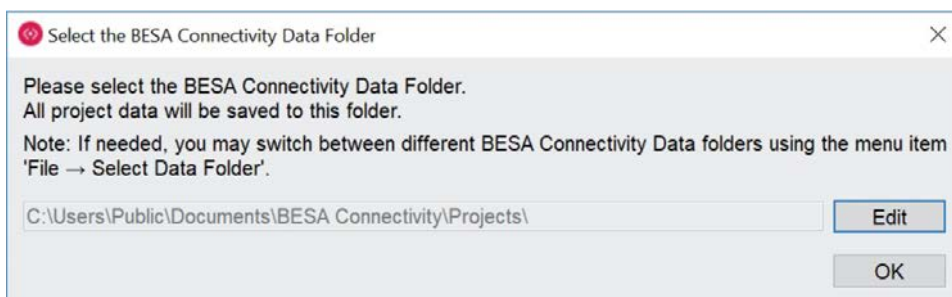
The BESA Connectivity Data Folder is pre-selected to **Public Users** on the local PC (shown above for Windows 10).

Press the **OK** button if you want to use the pre-selected local folder in Public Users.

Press the **Edit** button to create your BESA Connectivity Data Folder elsewhere, e.g. on a server.

When the selection is accepted, the following confirmation dialog appears:
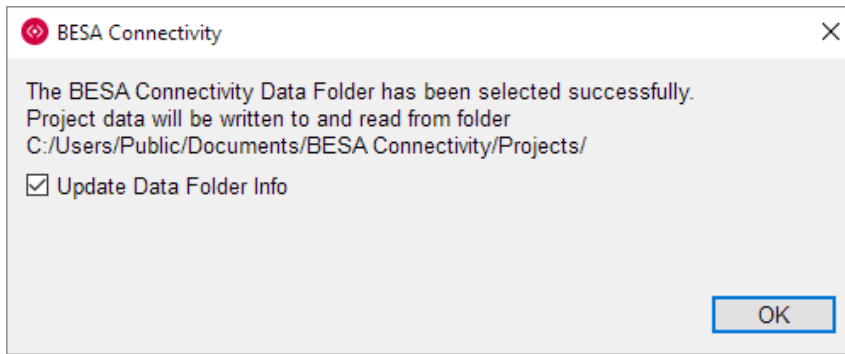
Press the **OK** button.

BESA Connectivity is now configured to start projects.

Notes

1. The procedure to define the shared BESA Connectivity Data folder on the server needs to be carried out only once at each PC where you install BESA Connectivity, i.e. when starting the program for the first time.

2. When switching between BESA Connectivity Data folders, it is recommended to leave the tick mark on to update all existing projects in the new BESA Connectivity Data folder.

3. Introduction

3.1. Features of BESA Connectivity

BESA Connectivity provides optimized, user-guided workflows for time-frequency and connectivity analysis of EEG/MEG data. Multiple well-established methods are provided. The program is maximally user-friendly. All analyses are computed automatically with required user-interaction reduced to a minimum. The time-frequency and connectivity values computed in BESA Connectivity can be directly used for scientific reports. The outcomes can be exported also for further statistical analysis. All results are visualized and can be directly used for publications.

BESA Connectivity integrates optimally with data that were analyzed in BESA Research, but it can also process data from other software packages as long as they conform to the BESA Connectivity file format.

BESA Connectivity will automatically identify connectivity patterns between channels / regional sources or dipole sources, which can be visualized using 2D matrices or 3D visualization.

There are two workflows with four work steps each in BESA Connectivity:

I.   Time-Frequency Analysis

  1. Set Project targets

        a) Complex Demodulation

        b) Wavelet Analysis (Morlet or Mexican Hat)

        c) Multitaper

        d) Number of Conditions and their names

  2. Load Data

  3. Set Parameters

     Various settings can be adjusted which will set the temporal – frequency resolution of further analysis. Here the user can also exclude individual trials from further analysis and set up low and high cutoff frequencies.

  4. Perform Calculations

     A time-frequency analysis will run. After completing of computation results can be evaluated and exported. When finishing this work step, the project can be saved and re-used for connectivity analysis. It is also possible to export analysis results in ASCII format.

II.   Connectivity Analysis

  1. Set Project targets

        a) Coherence (Rosenberg et al., 1989)

        b) Imaginary Part of Coherency (Nolte et al., 2004)

        c) Phase Locking Value (Lachaux et al., 1999)

        d) Phase Lag Index (Stam et al., 2007)

        e) Weighted Phase Lag Index (Vinck et al., 2011)

        f) Directed Phase Lag Index (Stam and van Straaten, 2012)

        g) Granger Causality (Granger, 1969; Geweke, 1982)

        h) Partial Directed Coherence (Baccala and Sameshima, 2001)

        i) Directed Transfer Function (Kaminski and Blinowska, 1991)

  2. Load Data

3. Set Parameters

Non-Parametric Method settings can be adjusted here (number of iterations, tolerance and regularization). Also, time-frequency analysis results from the previous workflow can be reviewed here.

4. Perform Calculations

A connectivity analysis will run. When analysis is completed the results can be reviewed for each method that was selected in the first work step. A 3D mode of visualization is also available. Analysis outcome can be saved and re-opened later. It is also possible to export them in ASCII format.

4. Time-Frequency methods

The general approach to analyse event-related EEG/MEG oscillations is based on the decomposition of the EEG/MEG signals into magnitude and phase information for each frequency and to track their changes over time. This procedure is referred to as 'time-frequency analysis' and comprises those methods that study a signal in both the time and frequency domains simultaneously.

In BESA Connectivity, three approaches for computing time-frequency decomposition are provided:

- **Complex Demodulation** is based on the convolution of the EEG/MEG signal with series of sine and cosine waves.

- **Wavelet Transform** uses series of complex Morlet or Mexican Hat wavelets to extract the magnitude and phase information.

- **Multitaper Transform** uses more than one taper to decompose the signal in its frequencies. It combines the properties of the different tapers to control the leakage and smooth the signal in the frequency domain.

The methods are described in more detail in the following paragraphs.

4.1. Complex Demodulation

Complex Demodulation (Papp and Ktonas, 1977) is based on the convolution of the EEG/MEG signal with series of sine and cosine waves. For each frequency of interest f_0 the following steps are performed:

a) The original time-domain signal is multiplied by $sin(2\pi f_0 t)$ and $cos(2\pi f_0 t)$, respectively. This modulation operation shifts every signal at frequency f to the difference and sum frequencies $(f \pm f_0)$ in the frequency domain.

b) The resulting two signals are low-pass filtered to extract the frequency range that was originally centered around f_0 and was shifted to the low frequency range $f - f_0$. Thus, the low-pass cutoff frequency sets half of the width of the frequency band for which the envelope amplitude and phase is computed. Thereby, this filter implicitly defines the resolution in time and frequency.

c) The two output signals of step b) define the real and imaginary part of a complex signal as a function of time. Its magnitude corresponds to half the envelope amplitude and its phase to the compound phase of the filtered frequency band centered at f_0.

4.2. Wavelet Transform

Like for Complex Demodulation, decomposition of the original EEG/MEG signal time series is based on the convolution with a scaled and translated version of a template function in the time domain. In BESA Connectivity, complex Morlet and Mexican Hat wavelets are provided as template functions. The complex Morlet Wavelet is described as:

$$\psi(t) = \pi^{-\frac{1}{4}}\left(e^{i\omega_0 t} - e^{-\frac{1}{2}\omega_0^2}\right)e^{-\frac{1}{2}t^2},$$

where i denotes the imaginary unit and ω_0 is 2π times the frequency of the unshifted and uncompressed mother wavelet.

The temporal and frequency resolution can be adjusted defining the length of the used wavelets in standard deviations of the implicit Gaussian kernel and the width of the wavelets in number of cycles. 'Shorter' wavelets will provide a finer temporal resolution at the expense of a coarser frequency resolution and vice versa.

The Complex Mexican Hat wavelet is formulated as:

Real part:

$$\psi_{real}(t) = (1 - (\pi t f_0)^2)e^{-\frac{1}{2}(2\pi t f_0)^2} = (1 - \tau^2)e^{-\frac{1}{2}\tau^2}$$

Imaginary part:

$$\psi_{imag}(\text{t}) = A * \left\{2\frac{\tau}{\sqrt{2}} + \sqrt{\pi}\left[erfi\left(\frac{\tau}{\sqrt{2}}\right)e^{-\frac{1}{2}\tau^2}(1 - \tau^2)\right]\right\},$$

where $\tau = \pi t f_0$ with target frequency f_0. A denotes a scaling factor and is heuristically chosen to be $A = 0.54$ for equal scaling of the real and imaginary part.

A review of using wavelets for EEG/MEG analysis is given by Samar et al. (1999). The complex Mexican Hat wavelet was proposed by Addison et al. (2002).

4.3. Multitaper Transform

Multitaper analysis uses several tapers to decompose the signal in its frequencies. Here, Slepian Sequences (Percival and Walden, 1993) are used to construct the tapers, which are then used in a time-frequency decomposition of the signal. Multitapering combines the properties of the different tapers to control the leakage and smooth the signal in the frequency domain. The multitaper transformation uses a sliding time window with a length that decreases with increasing frequency.

Multitapers are sets of functions, designed to reduce leakage between frequencies, rendering them well-suited for nonstationary processes with high dynamic ranges and rapid variations. Because Multitapers imply that the signal is convolved with multiple orthogonal tapers which are then averaged, the variance of this oscillation detection method across repeated measurements is reduced. In theory, the amplitude measurements taken with multitapers will thus have smaller error bars than Wavelets.

The data is multiplied with spectral windows before the frequency decomposition (in this application, Slepian windows). Those window functions are designed to prevent leakage of power to neighbouring frequencies, as often happens for Wavelets. Convolution is repeated with a number of K different (orthogonal) windows, each window gives an independent estimate of the signal because they are orthogonal, thereby making the power estimate more reliable for noisy data. The number of tapers depends on the smoothing parameter set by the user.
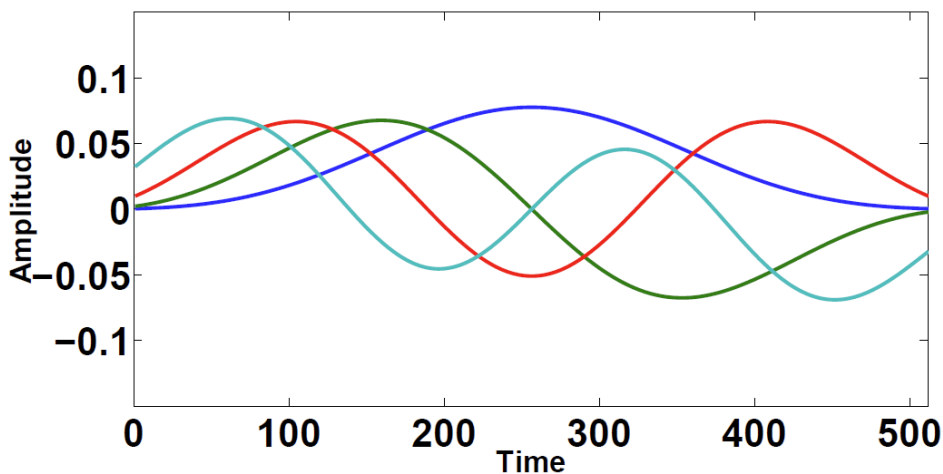
Example of Slepian sequences

4.4. Frequency sampling

In **complex demodulation**, frequency resolution is the same across the spectrum. Thus, the spacing between frequencies is uniform, given by a time-frequency sampling parameter that is adjusted by the user.

A **wavelet** has a frequency-dependent resolution.

For **Morlet wavelets**, σ_f describes the width of the wavelet in the frequency dimension. It is given by

$$\sigma_f = \frac{f}{oscil}$$

The full width at half maximum of a Gaussian bell curve is approximately at $2.3548 \times \sigma$. According to the Nyquist theorem, it would be sufficient to sample this step width 2–3 times in order to reconstruct the shape of the resulting data values. In practice, it is assumed that sampling will be uniform in the logarithmically transformed frequency axis, and the sampling rate is fixed to $0.8 \times \sigma_{f_0}$, where f_0 is the lowest frequency used. For a frequency range of 1–50 Hz sampled with $oscil$ = 5, this results in 27 frequencies:

Frequency	Δ[f_n-f_{n-1}]	ln(frequency)	Δ[ln(f_n) - ln(f_{n-1})]
1.00		0.00	
1.16	0.16	0.15	0.15
1.35	0.19	0.30	0.15
1.57	0.22	0.45	0.15
1.83	0.26	0.60	0.15
2.12	0.30	0.75	0.15
2.47	0.34	0.90	0.15
2.87	0.40	1.05	0.15
3.33	0.47	1.20	0.15
3.87	0.54	1.35	0.15
4.50	0.63	1.50	0.15
5.23	0.73	1.66	0.15
6.08	0.85	1.81	0.15
7.07	0.99	1.96	0.15
8.22	1.15	2.11	0.15
9.55	1.33	2.26	0.15
11.11	1.55	2.41	0.15
12.91	1.80	2.56	0.15
15.00	2.10	2.71	0.15
17.44	2.44	2.86	0.15
20.27	2.83	3.01	0.15
23.56	3.29	3.16	0.15
27.39	3.83	3.31	0.15
31.84	4.45	3.46	0.15

37.01	5.17	3.61	0.15
43.02	6.01	3.76	0.15
50.00	6.98	3.91	0.15

For the **Mexican Hat wavelet**,

$$\sigma_f = \sqrt{2}\, f.$$

Since this would lead to very few wavelets, the factor is adjusted to

$$\sigma'_f = \frac{\sqrt{2}\, f}{4}.$$

With this setting, the frequencies of the same range adjust to 17 frequencies:

Frequency	Δ[fₙ-fₙ₋₁]	ln(frequency)	Δ[ln(fₙ) - ln(fₙ₋₁)]
1.00		0.00	
1.28	0.28	0.24	0.24
1.63	0.35	0.49	0.24
2.08	0.45	0.73	0.24
2.66	0.58	0.98	0.24
3.40	0.74	1.22	0.24
4.34	0.94	1.47	0.24
5.54	1.20	1.71	0.24
7.07	1.53	1.96	0.24
9.03	1.96	2.20	0.24
11.53	2.50	2.45	0.24
14.72	3.19	2.69	0.24
18.80	4.08	2.93	0.24
24.01	5.21	3.18	0.24
30.66	6.65	3.42	0.24
39.15	8.49	3.67	0.24
50.00	10.85	3.91	0.24

This is close to the spacing which emerges for Morlet wavelets with an oscillation parameter of 3.

For **Multitaper** transformations, the spectral resolution also depends on the current frequency. It was adapted such that for a smoothing constant of 1.0, the frequency spacing is the same as for Mexican Hat wavelets:

$$\sigma'_f = \frac{\sqrt{2}\, f\, s}{4},$$

where *s* is the smoothing constant.

For the default smoothing constant of 0.4, the frequencies of the range shown above will adjust to 37 frequencies:

Frequency	$\Delta[f_n - f_{n-1}]$	ln(frequency)	$\Delta[\ln(f_n) - \ln(f_{n-1})]$
1.00		0.00	
1.11	0.11	0.11	0.11
1.24	0.13	0.22	0.11
1.39	0.14	0.33	0.11
1.54	0.16	0.43	0.11
1.72	0.18	0.54	0.11
1.92	0.20	0.65	0.11
2.14	0.22	0.76	0.11
2.39	0.25	0.87	0.11
2.66	0.27	0.98	0.11
2.96	0.31	1.09	0.11
3.30	0.34	1.20	0.11
3.68	0.38	1.30	0.11
4.11	0.42	1.41	0.11
4.58	0.47	1.52	0.11
5.10	0.53	1.63	0.11
5.69	0.59	1.74	0.11
6.34	0.65	1.85	0.11
7.07	0.73	1.96	0.11
7.88	0.81	2.06	0.11
8.79	0.90	2.17	0.11
9.80	1.01	2.28	0.11
10.92	1.12	2.39	0.11
12.17	1.25	2.50	0.11
13.57	1.40	2.61	0.11
15.13	1.56	2.72	0.11
16.87	1.74	2.83	0.11
18.80	1.94	2.93	0.11
20.96	2.16	3.04	0.11
23.37	2.41	3.15	0.11
26.05	2.68	3.26	0.11
29.04	2.99	3.37	0.11
32.37	3.33	3.48	0.11
36.09	3.72	3.59	0.11
40.23	4.14	3.69	0.11
44.85	4.62	3.80	0.11
50.00	5.15	3.91	0.11

4.5. Time sampling

Time sampling is uniform for the complex demodulation and wavelets. Generally, the re-sampled data set (after time-frequency decomposition) has a time sampling rate that is either the same or lower than the original time sampling.

In **complex demodulation**, the time sampling is given by a time-frequency sampling parameter that is adjusted by the user.

In **wavelets**, time sampling is automatically calculated such that no information is lost for the highest frequency wavelet. This will automatically ensure that also for lower frequencies, time sampling retains the time information contained in the data.

For Morlet wavelets:

$$\sigma_t = \frac{1}{2\pi \; \sigma_f} = \frac{oscil}{2\pi f}$$

This value is computed for f_{max}, and again sampled at $0.8 \; \times \sigma_t$ as in the frequency sampling case. If possible, the nearest sampling rate is found (within ±10% of that value) that is rounded to full milliseconds and keeps an integer number for the number of samples.

For Mexican Hat wavelets,

$$\sigma_t = \frac{1}{2\pi f}.$$

The same procedure is followed as for Morlet wavelets.

For example, in a data set of 1600 ms:

| Method	High cutoff frequency	Number of oscillations	Calculated sampling interval	Adjusted sampling interval
Morlet wavelet	60 Hz	5	10.610 ms	10 ms
Mexican Hat wavelet	25 Hz	n/a	5.092958 ms	4 ms

For **Multitaper**, time sampling is automatically calculated such that no information is lost for the highest frequency taper. Sampling thus depends on f_{max} and the smoothing constant.

The value $\sigma_t = 1/f$ is computed for f_{max}, and again sampled at $0.8 \; \times \sigma_t$ as in the frequency sampling case. If possible, the nearest sampling rate is found (within ±10% of that value) that is rounded to full milliseconds and keeps an integer number for the number of samples.

4.6.   Cone of influence

When applying time-frequency decompositions to finite length time-series, the resulting transforms inevitably suffer from border distortions. This is due to the fact that the values of the transform at the start and the end of the time-series are always incorrectly computed, since they involve missing values of the series which are then artificially prescribed. To minimize these edge effects, it is recommended to **pad** the time-series of each epoch with additional data prior to the epoch start and after the epoch end. The region in which the result of a time-frequency decomposition suffers from these effects is called the cone of influence (COI). In this area the results are subject to border distortions and have to be interpreted carefully.

The figure below shows a temporal-spectral evolution plot for power based on a Wavelet transform (Morlet wavelets). The cone of influence, which indicates the region affected by edge effects, is shown with a blue dashed line.
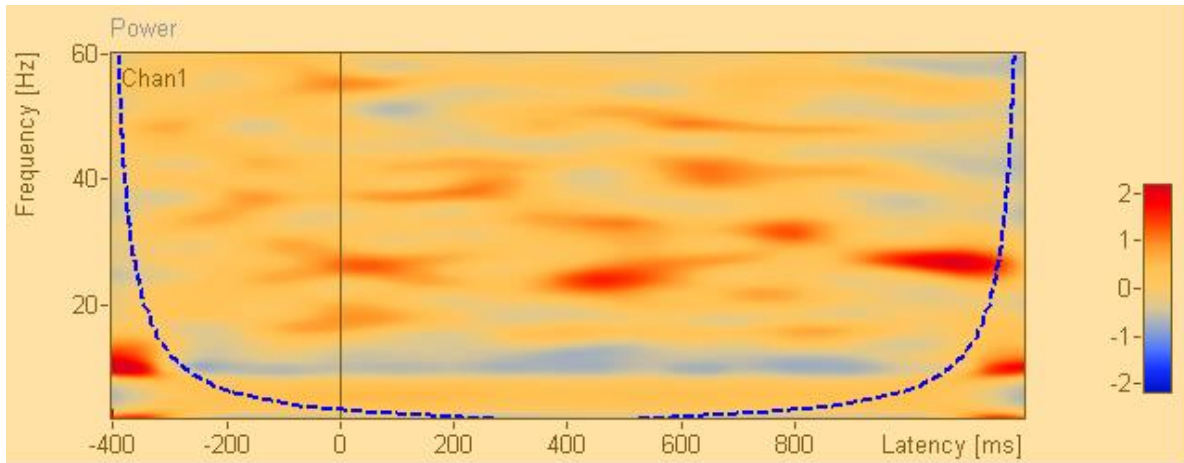
A step-by-step guide to wavelet analysis is given by Torrence and Compo (1998). This paper also introduces the cone of influence and its mathematical description.

Notes

- If you start BESA Connectivity from BESA Research, a default padding of 2 seconds before and after each trial epoch is added. This will in most cases solve the issues of the cone of influence. The tables below show padding values for Morlet wavelet parameters, Mexican hat wavelets, and complex demodulation parameters.

Start frequency [Hz]	Wavelet width	Wavelet oscillations	Padding required [s]
0.5	3	3	2.9
		5	4.8
	5	5	8.0
		7	11.1
1	3	3	1.4
		5	2.4
	5	5	4.0
		7	5.6
2	3	3	0.7
		5	1.2
	5	5	2.0
		7	2.8
5	3	3	0.3
		5	0.5
	5	5	0.8
		7	1.1

Morlet wavelet parameters and required padding to avoid cone of influence for different start frequencies

Start frequency [Hz]	Padding required [s]
0.5	2.7

1	1.6
2	0.9
5	0.41

Mexican hat wavelet: required padding to avoid cone of influence for different start frequencies. There are no wavelet parameters to modify wavelet shape here.

Start frequency [Hz]	Time-frequency sampling [Hz, ms]	Padding required [s]
0.5	0.2, 250	2
	0.25, 200	1.6
1	0.2, 250	2
	0.25, 200	1.6
	0.5, 100	0.8
2	0.2, 250	2
	0.25, 200	1.6
	0.5, 100	0.8
	1.0, 50	0.4
5	0.2, 250	2
	0.25, 200	1.6
	0.5, 100	0.8
	1.0, 50	0.4
	2.0, 25	0.2
	2.5, 20	0.16

Complex demodulation parameter and required padding to avoid cone of influence for different start frequencies

Start frequency [Hz]	Padding required [s]
1	2
2	1
5	0.4

Multitaper: required padding to avoid cone of influence for different start frequencies

- If you are using the TSE (temporal-spectral evolution) option, you should ensure that your baseline interval does not overlap with the cone of influence, since this may distort your TSE results over the whole time range in the affected frequency bands.

5. Connectivity methods

BESA Connectivity offers nine connectivity measures in the frequency domain. Six measures are phase-based methods: coherence, imaginary part of coherency (or imaginary coherence), phase locking value (PLV), phase lag index (PLI), weighted phase lag index (WPLI), and directed phase lag index (dPLI). The other three measures are Granger causality-based connectivity approaches: Granger causality in the frequency domain (or Granger–Geweke causality), partial directed coherence (PDC), and directed transfer function (DTF). An overview of the distinctions between the connectivity measures is given in Table 1.

Table 1. Comparison of the methods for estimating brain connectivity.

	Coherence	Imaginary coherence	PLV	PLI	WPLI	dPLI	Granger causality	PDC	DTF
Nondirectional	●		●	●	●				
Directional		●				●	●	●	●
Bivariate	●	●	●	●	●	●	●		
Multivariate								●	●
Linear	●	●	●	●	●	●	●	●	●
Frequency domain	●	●	●	●	●	●	●	●	●

5.1. Phase-based connectivity methods

5.1.1. Coherence

Coherence is a measure of the linear relationship between two signals at a specific frequency. In practice, the magnitude of the coherency is generally used for coherence. Coherency is defined as the normalized cross-spectrum:

$$C_{xy}(f) = \frac{\langle S_{xy}(f) \rangle}{\sqrt{\langle S_{xx}(f) \rangle \langle S_{yy}(f) \rangle}},$$

where $\langle \cdot \rangle$ indicates averaging over trials, S_{xy} is the cross-spectral density between two signals, and S_{xx} and S_{yy} are the autospectral densities for signals x and y, respectively. Coherence is defined as the magnitude of coherency

$$\text{Coh}_{xy}(f) = \left| C_{xy}(f) \right| = \left| \frac{\langle S_{xy}(f) \rangle}{\sqrt{\langle S_{xx}(f) \rangle \langle S_{yy}(f) \rangle}} \right|.$$

The estimated coherence for a given frequency ranges between 0 and 1. A value of 0 indicating that the two signals are perfectly uncorrelated, and a value of 1 indicates perfect correlation. Coherence is a bivariate measure, which means it considers only two signals simultaneously. It is also a nondirectional connectivity measure, that is, $\text{Coh}_{xy}(f) = \text{Coh}_{yx}(f)$.

5.1.2. Imaginary Part of Coherency

Instead of estimating the magnitude of the coherency, Nolte et al. (2004) proposed using only the imaginary part of the coherency to investigate brain interactions. This is because the imaginary part of the coherency excludes coherent sources with zero phase lag and therefore reduces the effect of field spread due to volume conduction. The imaginary part of coherency is defined as

$$\text{ICoh}_{xy}(f) = imag\left(\text{C}_{xy}(f)\right) = imag\left(\frac{\langle S_{xy}(f)\rangle}{\sqrt{\langle S_{xx}(f)\rangle\langle S_{yy}(f)\rangle}}\right),$$

where $imag(\cdot)$ denotes the imaginary part.

The imaginary part of coherency for a given frequency ranges between -1 and 1. If the value is positive, signals x and y are interacting and y is earlier than x, indicating that information is flowing from y to x. The imaginary part of coherence is a bivariate measure as the coherence, and it is antisymmetric, that is, $\text{ICoh}_{xy}(f) = -\text{ICoh}_{yx}(f)$.

5.1.3. Phase Locking Value

Phase locking value (PLV) is a measure for phase synchronization. The PLV is defined based on the average of phase angle difference between two signals over time at a specific frequency (Lachaux et al., 1999):

$$\text{PLV}_{xy}(f) = \left|\frac{1}{n}\sum_{t=1}^{n} e^{i\cdot\left(\phi_{x,t}-\phi_{y,t}\right)}\right|,$$

where n is the number of time points, i is the imaginary number that results from taking the square root of -1, and ϕ_x and ϕ_y are phase angles from signals x and y at frequency f.

The PLV takes values between 0 and 1. A value close to 1 means perfect phase locking, while a value close to 0 results from a random phase distribution over time. PLV is a nondirectional connectivity measure, that is, $\text{PLV}_{xy}(f) = \text{PLV}_{yx}(f)$.

The coherence and PLV could provide similar results in many cases. However, coherence can be influenced by strong increase or decreases in power as it considered power information of the signals. For instance, if connectivity increases but the amplitudes of signals simultaneously decreases, estimated coherence values could be biased. PLV is insensitive to the amplitudes of signals and only depends on the phase relationship between two signals.

5.1.4. Phase Lag Index

Phase lag index (PLI) is used to measure the asymmetry of the distribution of phase differences between two signals by calculating the consistency of the sign of the imaginary component of the cross-spectrum (Stam et al., 2007). Similar to the imaginary part of coherence, the PLI is also less sensitive to the influence of volume conduction. The PLI is defined as

$$\text{PLI}_{xy}(f) = \left|\langle sign\left(imag(S_{xy}(f))\right)\rangle\right|,$$

where $sign(\cdot)$ is the signum function.

The PLI ranges between 0 and 1. A value of 1 means perfect phase locking, while a value of 0 indicates either no coupling or coupling with a phase difference centered around 0 mod π (i.e. repeating at every π). The PLI will be closer to 1 the stronger this non-zero phase locking is.

The imaginary part of coherence normalizes the imaginary component by the signal amplitudes (i.e., it is not based solely on the imaginary component of the cross spectrum), resulting in decreased

sensitivity for detecting changes in phase-synchronization, and increased sensitivity to noise. The PLI, on the other hand, is based solely on the imaginary component of the cross-spectrum.

5.1.5. Weighted Phase Lag Index

Weighted phase lag index (WPLI) is an extension of the PLI in which phase differences between two signals are weighted by the magnitude of the imaginary component of the cross-spectrum (Vinck et al., 2011):

$$\text{WPLI}_{xy}(f) = \frac{\left| \left\langle \left| imag\left(S_{xy}(f)\right) \right| \, sign\left(imag\left(S_{xy}(f)\right)\right) \right\rangle \right|}{\left\langle \left| imag\left(S_{xy}(f)\right) \right| \right\rangle} = \frac{\left| \left\langle imag\left(S_{xy}(f)\right) \right\rangle \right|}{\left\langle \left| imag\left(S_{xy}(f)\right) \right| \right\rangle}.$$

The application of the weighting decreases the probability of detecting false positive connections when dealing with volume-conducted noise sources with near zero phase lag while enhancing the sensitivity to detect phase synchronization.

The WPLI takes values between 0 and 1 like the PLI. A WPLI value close to 1 means perfect phase locking, while a WPLI value close to 0 results from a random phase distribution over time.

5.1.6. Directed Phase Lag Index

The PLI is a measure of the strength of non-zero phase synchronization, but no longer indicates which of the two signals is leading in phase. On the other hand, the directed phase lag index (dPLI) can reflect which of the two signals is leading and which is lagging in phase. The dPLI is defined as the probability that the phase of one time series is smaller than the instantaneous phase of another signal (Stam and van Straaten, 2012):

$$\text{dPLI}_{xy}(f) = \left\langle heav\left(imag\left(S_{xy}(f)\right)\right) \right\rangle,$$

where $heav(\cdot)$ is the Heaviside step function.

The dPLI is bounded by 0 and 1. When time series x is consistently phase leading compared to y, $0.5 < \text{dPLI}_{xy} \leq 1$. When time series x is phase lagging compared to y, $0 \leq \text{dPLI}_{xy} < 0.5$. In the case neither x or y is leading or lagging on average, $\text{dPLI}_{xy} = 0.5$.

Note that the dPLI values are rescaled to range between -1 and 1 like the imaginary part of the coherency in BESA Connectivity:

$$\widehat{\text{dPLI}}_{xy}(f) = 2\left(\text{dPLI}_{xy}(f) - 0.5\right).$$

Therefore, when time series x is consistently phase leading compared to y, $0 < \widehat{\text{dPLI}}_{xy} \leq 1$. When time series x is phase lagging compared to y, $-1 \leq \widehat{\text{dPLI}}_{xy} < 0$. In the case neither x or y is leading or lagging on average, $\widehat{\text{dPLI}}_{xy} = 0$.

5.2. Granger causality-based connectivity measures

Connectivity measures based on Granger causality in the frequency domain can be calculated with parametric approach (with autoregressive models) or with non-parametric approach (with Fourier or wavelet-based methods) (Dhamala et al., 2008a and 2008b). These approaches differ in how the transfer function matrix computed. The transfer function matrix $\mathbf{H}(f)$ contains information about the relationships between signals and their spectral characteristics, and it allows for estimating causal relationships since it is nonsymmetric matrix. Once the transfer function is estimated, causality measures in frequency domain based on Granger causality can be accordingly computed.

The non-parametric approach is based on the fact that the cross-spectral density matrix $\mathbf{S}(f)$ can be factored into a noise covariance $\mathbf{\Sigma}$ and spectral transfer function $\mathbf{H}(f)$ by applying Wilsons's spectral matrix factorization (Wilson, 1972). In comparison to the parametric estimation technique, the main

advantage using the non-parametric technique is that it does not require the determination of the model order for the autoregressive model. The choice of the appropriate model order can be problematic. In contrast, the non-parametric spectral factorization approach requires more data and a smooth shape of the cross-spectral density matrix (i.e., no sharp peaks as a function of frequency) to converge to a stable result. Moreover, the non-parametric approach utilizes data points from broad frequency range (ideally from 0 Hz to Nyquist frequency).

In the BESA Connectivity, the non-parametric approach is implemented for connectivity measures based on Granger causality.

5.2.1. Granger Causality

Granger causality states that if past values of time series $y(t)$ contains information that helps in the prediction of time series $x(t)$, then $y(t)$ is said to cause $x(t)$ (Granger 1969). The bivariate Granger causality from signal y to signal x can be derived out of the univariate autoregressive model of x and the bivariate model of x and y:

$$\text{GC}_{y \to x} = \ln\left(\frac{\text{Var}_{x|x}}{\text{Var}_{x|xy}}\right),$$

where $\text{Var}_{x|x}$ is the variance of the residual in the univariate model, and $\text{Var}_{x|xy}$ is the variance of the residual in the bivariate model. If the past values of y improve the prediction of x, then the variance $\text{Var}_{x|xy}$ is decrease. In this case, the variance ratio is larger than 1, which leads to a Granger causality value that is larger than 0.

Geweke (1982) applied the concept of the Granger causality in the frequency domain. Therefore, the Granger causality in the frequency domain is also called as Granger-Geweke causality. In the BESA Connectivity, the Granger causality in the frequency domain is implemented.

5.2.2. Partial Directed Coherence

The partial directed coherence (PDC) is a multivariate directional connectivity measure that shows the direct interrelations between signals (Baccala and Sameshima, 2001). The magnitude of PDC is defined as:

$$|\text{PDC}_{ij}(f)| = \frac{|\Lambda_{ij}(f)|}{\sqrt{\sum_{k=1}^{N} |\Lambda_{kj}(f)|^2}},$$

where $\Lambda_{ij}(f)$ is an element of the $\mathbf{\Lambda}(f) = \mathbf{H}^{-1}(f)$ (the inverse matrix of the transfer function). The $\text{PDC}_{ij}(f)$ describes the directional flow of information from the activity in j-th signal to the i-th signal $(j \to i)$. The PDC quantity is normalized between 0 and 1, producing a ratio between transmission from signal j to signal i and total outflow from signal j (the sum along the columns of $\mathbf{\Lambda}(f)$).

5.2.3. Directed Transfer Function

The directed transfer function (DTF) is a multivariate directional connectivity measure that displays the direct and indirect interactions between signals (Kaminski and Blinowska, 1991). The magnitude of DTF is defined as:

$$|\text{DTF}_{ij}(f)| = \frac{|H_{ij}(f)|}{\sqrt{\sum_{k=1}^{N} |H_{ik}(f)|^2}},$$

where $H_{ij}(f)$ is an element of the transfer function matrix $\mathbf{H}(f)$. The $\text{DTF}_{ij}(f)$ expresses the directional flow of information from the activity in j-th signal to the i-th signal $(j \to i)$. The DTF quantity is normalized between 0 and 1, producing a ratio between the influence of signal j on signal i and the summarized inflow to signal i (the sum along the rows of $\mathbf{H}(f)$).

6. The Workflow Concept

BESA Connectivity uses a modern workflow concept that guides you through all the work steps needed to complete a project, suggests and explains necessary inputs and user actions, and performs many work steps automatically. At any time, you may interrupt and inspect earlier work steps or redo them with modified input parameters if required.

A workflow consists of a series of work steps required to finalize a project. Each work step contains a set of user interactions needed to achieve the work step-specific result. Only few user interactions are needed.

When pressing the **Next** button or **Space**, a work step is completed and the next work step is loaded. Thus, the workflow of a project sequentially proceeds from one work step to the next.

The layout of the BESA Connectivity screen is optimized for this workflow concept. The workflow menu—as shown on the left in the **Workflow Window**—gives an overview over all the work steps to be completed in the selected project (see 7.1). The workflow menu can be used to switch between the work steps. For example, you may redo an earlier step with different or advanced parameters and continue with automatic processing of all subsequent steps as defined before.

The current results during a work step are shown in the **Main Window** in the center of the screen (see 7.2). The **Information Window** below (see 7.3) provides advice and help information for the current work step.

During each work step a specific dialog is shown in the **Interaction Window** on the right to allow for optimized user interaction relevant for the current work step (see 7.4). After completing all interactions, press the **Next** button at the bottom or **Space** to proceed to the next work step. Press the **Previous** button to go back one work step. After completing the last work step of the workflow, press the **Finish** button at the bottom of the Interaction Window to save all data created during the project. This saving step enables reloading the full workflow of a project with all work steps at a later time.

A project is defined by a specific workflow together with the stored individual input and output data. Stored projects can be viewed by selecting the menu item **File → Open Project**, by using the **Open** button in the toolbar, or by pressing the **Open Project** buttons on the start screen. After opening a stored completed project, the final workflow result is displayed.

7. Elements of the BESA Connectivity Screen

The layout of BESA Connectivity screen is optimized for the workflow concept as described in chapter 6. The figure below shows the BESA Connectivity screen with all its elements:
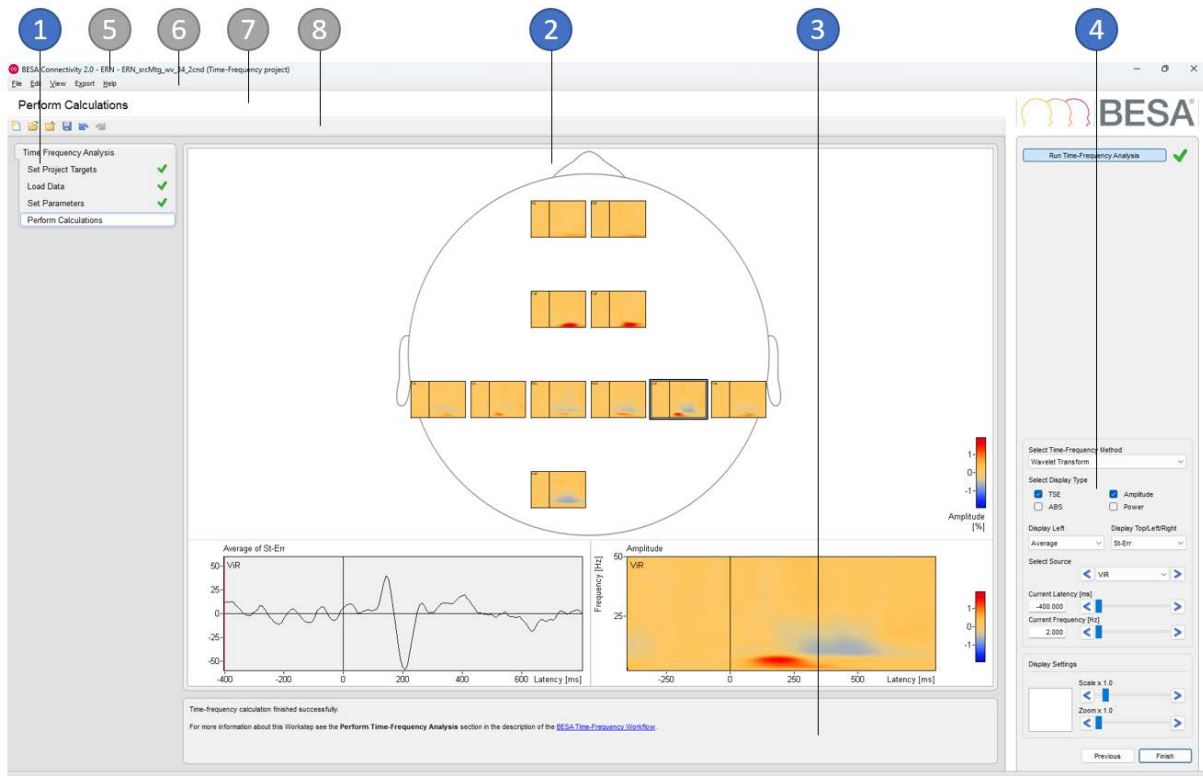
1   Workflow Window (see chapter 7.1)

2   Main Window (see chapter 7.2)

3   Information Window (see chapter 7.3)

4   Interaction Window (see chapter 7.4)

5   Title Bar (see chapter 8.1)

6   Menu Bar (see chapter 8.2)

7   Caption (see chapter 8.3)

8   Toolbar (see chapter 8.4)

7.1. Workflow Window

The Workflow Window on the left displays the workflow menu. The workflow menu gives an overview of the sequential steps needed to finish the current project. Steps already completed are marked with a green check mark. ✔

The current work step is highlighted. This step is also shown in the caption.

The workflow menu can be used like any other menu to jump to another work step provided that the previous work steps have already been completed.

7.2. Main Window

The Main Window area displays the results of the current work step.

7.3. Information Window

The information window displays a comprehensive help text related to the current work step. The help texts provide additional information, e.g. which file has been loaded. They suggest and explain the next user interaction to be done in the current work step.

Underlined text in blue provides a hyperlink. Click on such a link to open the BESA Connectivity help at the indicated topic.

Use the check boxes in Interaction Window to select the methods that will be used for calculating the time-frequency analysis. The Main Window lists the targets to be achieved by the workflow.
To start the workflow, you can type Space or Enter or press the Start button.

For more information see description of the BESA Connectivity Workflow.

7.4. Interaction Window

The Interaction Window provides the user interaction for the current work step.

The **upper interaction elements** are used to set parameters needed in the work step by using standard elements like buttons, edit boxes, and sliders. The effect of changing parameters is seen in the Main Window left of the Interaction Window.

In some work steps, additional interaction elements are shown at the bottom of the Interaction Window to enable changing visualization parameters.

Current parameters are accepted by pressing **Space**, or by pressing the **Next** button at the bottom prompting the workflow to proceed to the next work step.

The **Previous** button is used to jump back to the previous work step.

Notes

1. You can also undo or redo a work step using the menu items **Edit → Undo** and **Edit → Redo** or by pressing **Ctrl-Z** or **Ctrl-Y**.

2. Moving on to the next work step is fastest by pressing **Space** or **Enter**.

8. Program Bars

8.1. Title Bar

The title bar of BESA Connectivity displays the program name and version number. In addition, it shows information on the current project:

- Group name

- Project name

- Project type

8.2. Menu Bar

The Menu Bar provides the menus listed below. Click on a menu to select and choose from the menu items that pop up.

8.2.1. File Menu

The **File** menu contains the following items:

File menu item	Description
Create New Project	Start a new project.
Open Project	Load an existing project. A choice can be made between project types time-frequency and connectivity.
Close Project	Close currently active project. Show the Select Project Page.
Save	Save the currently active project.
Save As…	Specify a filename for currently active project and save it.
Delete Projects…	Select one or multiple projects that shall be.
Select Data Folder	Select the folder to be used as BESA Connectivity Data Folder (see 2.3.1).
Update Data Folder Info	Update the information file in the BESA Connectivity Data Folder (see 2.3.1).
Exit	Terminate the BESA Connectivity program.

8.2.2. Edit Menu

The **Edit** menu contains the following items:

Edit menu item	Description
Undo	Undo the last step completed in the current work step.
Redo	Redo the last step that was undone in the current work step.

8.2.3. View Menu

The **View** menu can be used to change display settings for BESA Connectivity. It contains the following entries:

View menu item	Description
Show Workflow Window	By selecting or deselecting this menu item the Workflow Menu is displayed or hidden (see 7.1).
Show Information Window	By selecting or deselecting this menu item the Information Window is displayed or hidden (see 7.3).
Standard Font Size, **Large Font Size**, **Extra Large Font Size**	Select one of these menu items to specify the size of the font to be used in BESA Connectivity.
Settings	The following themes can be selected from the Themes menu item: • BESA Standard: the main window has a sandy background. • BESA White: the main window has a white background. The colormap used in 2D time-frequency and connectivity displays can be adjusted using the following menu items – separately for the case of sequential data and diverging data: • Sequential Colormap: Standard, Blue to Red • Diverging Colormap: Standard, Rainbow, Viridis, White to Red

8.2.4. Export Menu

The **Export** menu can be used for exporting vector graphics (*.eps), scalable vector graphics (*.svg) or bitmap images (*.png) of the Main Window, of the detail windows, or of a combination of all windows. For 3D visualization in the Connectivity workflow (see 11.4.1), the connectivity changes over time can be exported as video (*.mpg).

Results can be exported in ASCII format for further processing in external programs if needed. For time-frequency analysis it is possible to export single trial data, averaged data, and averaged waveforms. Connectivity data can be also exported.

Export menu item	Description
Image	Allows exporting images of the Main Window, the left detail window, the right details window, or all windows (see 12.1). In the Save dialog, the format (*.eps, *.png, or *.svg) can be specified. Images can also be exported by right-clicking in the according window.
Video	For 3D visualization in the Connectivity workflow this item allows exporting video animations of the Main Window, the left detail window, the right details window, or all windows (see 12.2). In the Save dialog, the resolution, start time, end time, and duration per latency step can be specified. The rotation can be applied in degrees. Rotation can be uni-directional or bidirectional. Also, the background color can be changed. After pressing the recording

Export menu item	Description
	button, video generation starts. When it is finished it can be previewed and saved as *.mpg file.
Export Results	Functionality of this menu entry is workflow-dependent.
	For the Time-frequency workflow it is possible to export ASCII data for single trials TF (*.tfcs), averaged TF (*.tfc), and averaged waveforms (*.avr) (see 12.3).
	In the Connectivity workflow, connectivity data can be exported as well (*.conn). All these files are ASCII files with appropriate header line (see 12.4).

8.2.5. Help Menu

Use the **Help** menu to open the program help or to get information about BESA Connectivity.

Help menu item	Description
BESA Connectivity Help	Open the program help.
About…	Get information about the current program version.

8.3. Caption

The caption is located between the Menu Bar and the Toolbar and specifies the current work step.

8.4. Toolbar

The Toolbar provides direct access to the most important menu items:

- **File → Create New Project**
- **File → Open Project**
- **File → Close Project**
- **File → Save Project**
- **Edit → Undo**
- **Edit → Redo**

9. How to use BESA Connectivity

Before working with BESA Connectivity, please consult chapter 7 on the elements of the BESA Connectivity screen.

9.1. Starting BESA Connectivity

9.1.1. Welcome Screen

Start BESA Connectivity from its icon on the desktop.

When starting BESA Connectivity, a welcome screen appears. It provides some information on the BESA Connectivity program including the current version number and date:

Press **Accept** to start BESA Connectivity.

9.2. The Workflows of BESA Connectivity

Two different workflows can be chosen: **Time-Frequency Analysis** and **Connectivity Analysis**. Each workflow consists of specifying the analysis method, loading EEG/MEG data (for the Connectivity workflow a Time-Frequency analysis project outcome has to be used), specifying parameters, and calculation. The work steps are described in detail in the following chapters.
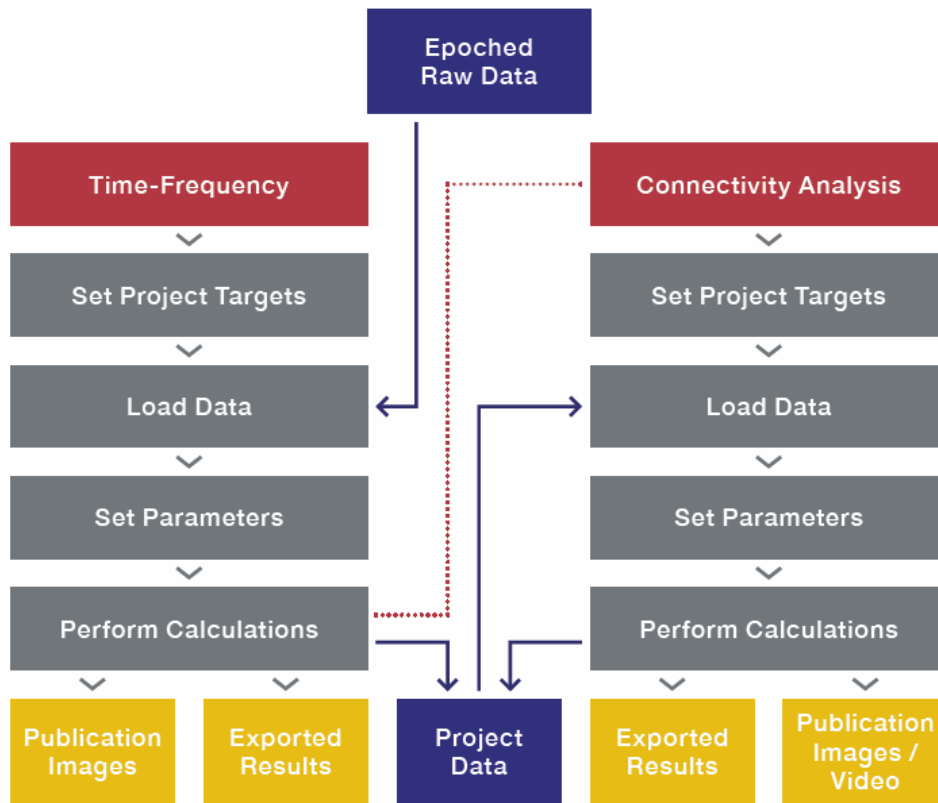
9.3. Select workflow – Analysis type

In order to start a workflow, a selection of the analysis type must be made:

- **Time-Frequency Analysis**

- **Connectivity Analysis**

- **Open Project**

Press **Start** to initialize the selected workflow. For a more detailed description of the analysis methods, please see the previous chapters 4 and 5.

Note: Projects can also be started or opened at any time by selecting the menu items **File → Create New Project** or **File → Open Project**.

9.4. Important Dialogs

This section describes important user interactions realized by dialogs.

9.4.1. Select the BESA Connectivity Data Folder

If required, you may switch to different or create a new BESA Connectivity Data Folder by selecting the menu item **File → Select Data Folder**. In the dialog box below, select an existing folder to store all result data of BESA Connectivity or create a new folder accessible to all users in your workgroup.

Select a folder in this dialog and press **Select Folder** to set this folder as the current BESA Connectivity Data Folder. After selecting a new BESA Connectivity Data Folder, the following confirmation dialog appears:
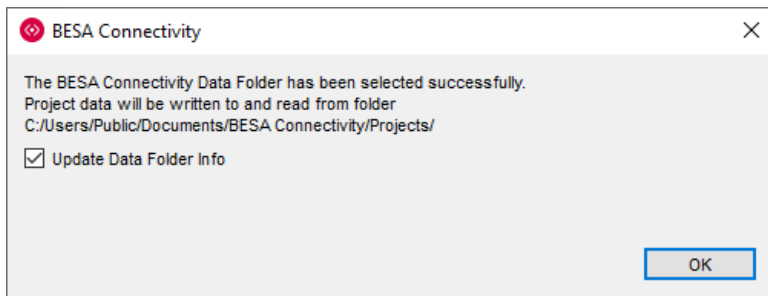
Press **OK** to activate the new BESA Connectivity data folder.

It is recommended to leave the tick mark on to update all existing projects in the new BESA Connectivity Data folder, if you switch between folders.

Note: When switching between different BESA Connectivity Data folders, the project data are preserved in each folder and are not copied to the new folder.

9.4.2. Open Projects

The **Open Project** dialog box shows the available projects. Project type can be selected using the **Project Type** option in the dialog box. The left pane shows Group, and the right pane shows all projects available for that Group, with their modification date.
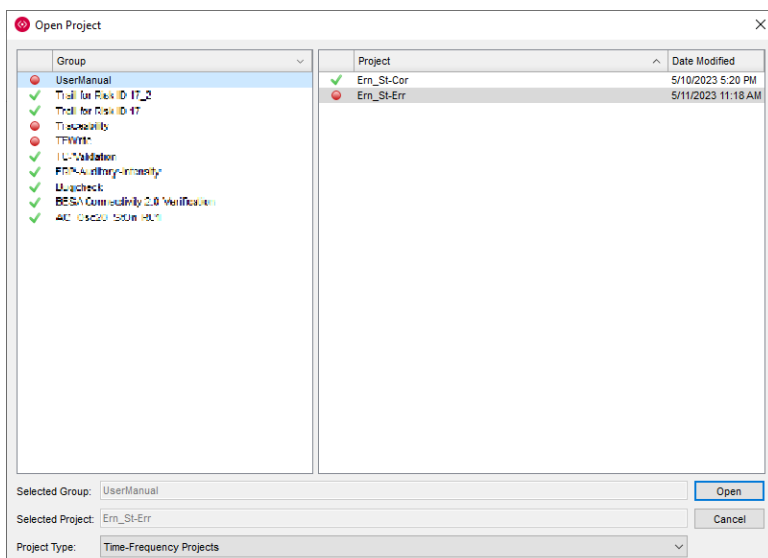
The previously used project is automatically selected.

Icons in the list of projects:

- **Green tick mark**: The project has been finalized.

- **Green circle**: All steps have been computed, but the project has not yet been finalized.

- **Yellow circle**: All manual steps have been completed, but the project is still in progress.

- **Red circle**: Some manual steps have not yet been completed.

Icons in the list of groups:

- **Green tick mark**: All projects of this group have been finalized.

- **Green circle**: All steps have been completed for all projects of this group, but at least one project has not yet been finalized.

- **Yellow circle**: All manual steps have been completed, but at least one project is still in progress.

- **Red circle**: For at least one project, some manual steps have not yet been completed.

After opening a finalized project, the project is unlocked and run through the worksteps automatically.

9.4.3. Finish, Save, and Close Projects

Finish a project

The **Save Project As…** dialog box comes up proposing a group name if the project is new (see figure below). If a previous project has been opened and modified, the previous name is proposed.

The selected group and proposed project names are highlighted automatically. To save under a different project name, the user enters a new project name in the **Selected Project** edit field.

Pressing the **Save** button stores the project data. If the selected project name does not yet exist, the project is saved with all result files automatically.
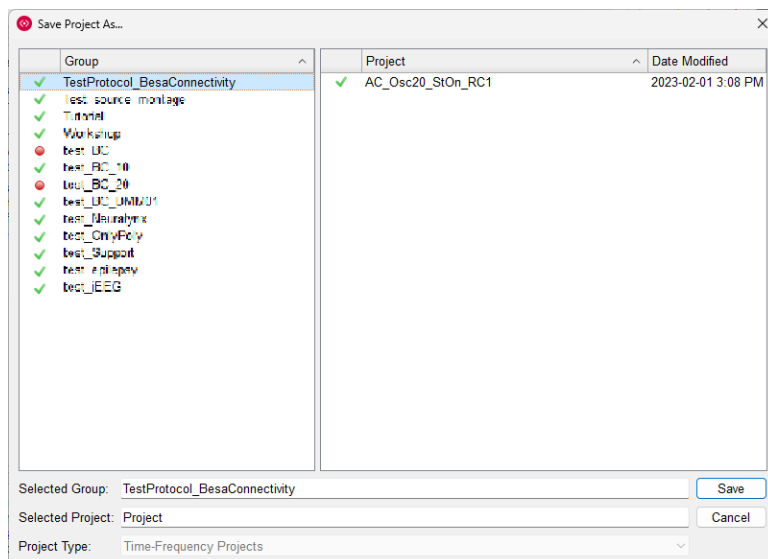
If the user keeps the highlighted project name of a previous project or selects another previous project name of the current Group in the **Projects** selection box on the right, he/she will be asked whether to replace the previous project by the new project data:
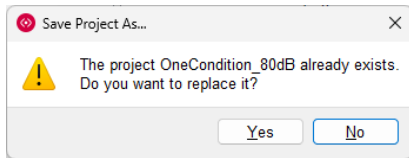
- **Yes** discards the previous project data and stores the new data under the previous project name.

- **No** saves under a different project name. The **Save Project As…** dialog box comes up again.

Close a project

At any time during the workflow, you may close the current project using the **Close Project** button in the toolbar or the menu item **File → Close Project**.

When closing a project, the following dialog box comes up:
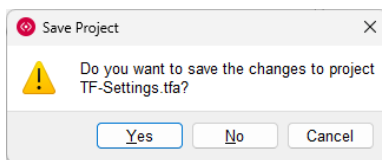
- Press **Yes** to save the changed project data. Previously stored data will be overwritten.

- Press **No** if you want to discard all changes, e.g. when accidentally modifying user defined parameters during reinspection after opening an existing project. In this case, the stored data of the current, previously saved project will not be overwritten and changes to the project will not be stored.

- Press **Cancel** to return to the project workflow, e.g. if you want to save the current changes under a new project name using the menu item **File → Save As**.

Save a project

At any time during the workflow, data can be saved by selecting the menu item **File → Save** or typing **Ctrl+S**. However, previously stored data will be overwritten automatically.

Notes on closing and saving:

- Closing and saving can be done at any time during the preparation of a project to preserve the user input up to the completed workstep.

- If a previously completed project has been opened, previous project data will be overwritten and replaced by the current state of the project. Therefore, do not use the save function when opening a previous project simply for inspection. In this case, use the menu item **File → Save As**.

- Select the menu item **File → Save As** to store a modified project under a new project name.

- The current project name can always be seen in title bar.

9.4.4. Delete Projects

Stored BESA Connectivity projects can be deleted if no longer needed. To delete a project, select the menu item **File → Delete Projects…**. The **Delete Projects…** dialog box appears:
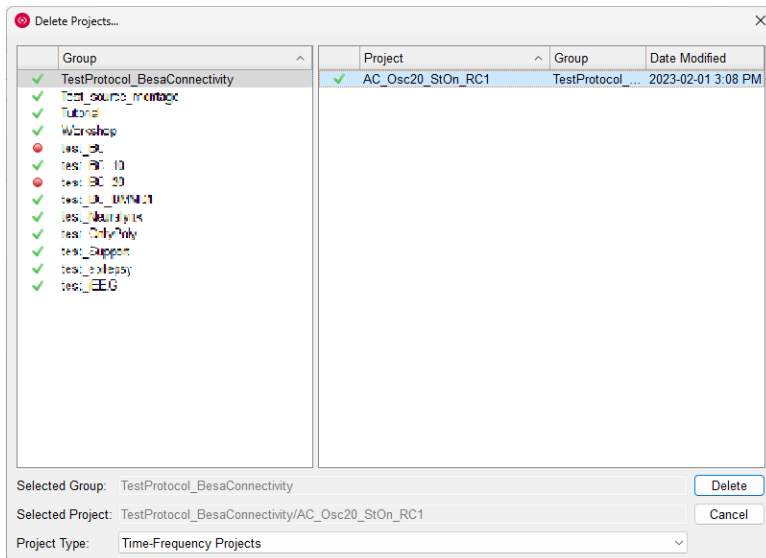
In the **Project Type** drop down selection box at the bottom, select the type(s) of projects to be deleted. Select **All Projects** to delete Time-Frequency and Connectivity projects.

In the Group selection box, mark a group for which project data shall be deleted. Then, select the projects to be deleted in the Projects selection box (multiple Groups or Projects can be selected by holding the **Ctrl** or **Shift** key while selecting).

A confirmation box is displayed, after selecting and pressing **Delete**.

- Press **Yes** if you do not need the listed project data any more. Restoring is no longer possible after deleting.

- Press **No** to prevent deleting.

9.4.5. Select Files

When selecting input data, the following dialog appears:
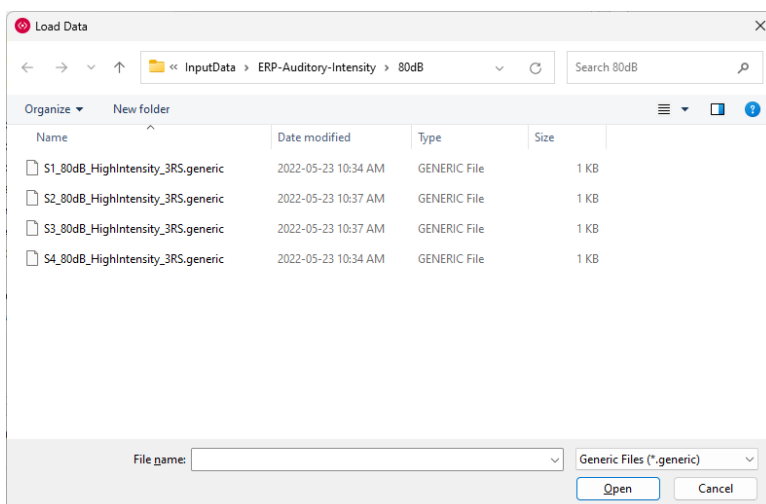
Use the drop-down folder list at the top to navigate to the desired input folder. Then, select files in the current folder and press **Open**.

10. Workflow: Time-Frequency Analysis

10.1. Set Project targets

The time-frequency analysis method needs to be specified from multiple selection options:

- **Complex Demodulation:** Data will be transformed to time-frequency domain using complex demodulation (see chapter 4.1 for more details).

- **Wavelet Transform:** Data will be transformed to time-frequency domain using one of two possible wavelet approaches (see chapter 4.2 for more details).

    o **Wavelet Morlet**

    o **Wavelet Mexican Hat**

- **Multitaper:** Data will be transformed to time-frequency domain using Multitaper transform (see chapter 4.3 for more details).

- **Number of Conditions:** Up to ten conditions (e.g. target and control) can be provided.

- **Define Condition Names:** Condition names can be set for all of the selected **Number of Conditions.**

The number of conditions and condition names will be automatically detected if the workflow is started from the BESA Research software.

After selecting the analysis method data has to be loaded and some further settings need to be specified. Press **Next** to go to the next work step.

10.2. Load data

In this work step data for the analysis have to be provided. The number of datasets to load depends on the number of conditions declared in the previous step. BESA Connectivity reads the ***.generic** file format which is the output from BESA Research. The generic files can be easily generated from any other software following the format description. Please see chapter 14.3 for further details.

Pressing the first **Load Data for <Condition 1>** button will bring up a file selector box (Condition 1 text will be replaced with the actual name of the first condition).

If several conditions were indicated in the **Set Project Targets** work step, multiple buttons **Load Data for <Condition>** will be available. Pressing this button will also bring up a file selector box.

Note: When selecting multiple data files for each condition, make sure that the condition names of the selected data files are the same.
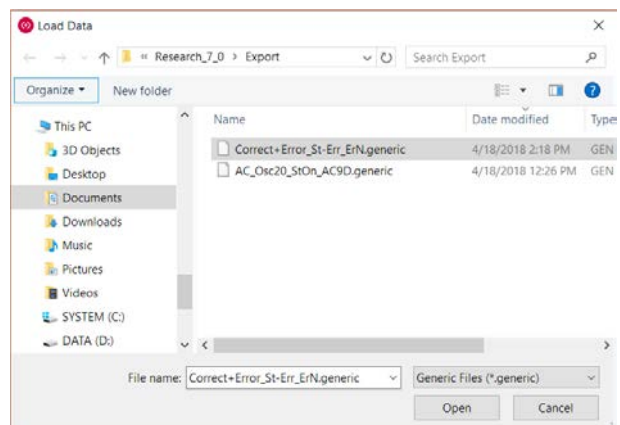

After file opening, the details of each loaded file will be displayed. The following screenshot shows an example data set containing 3 conditions 60dB, 70dB and 80dB with several files loaded for each condition.

Condition name	60dB	70dB	80dB
Number of trials (per file)	19 / 26 / 19 / 19 / 26 / 26	24 / 18	23 / 31 / 31 / 23
Number of channels	9	9	9
Sampling rate	250 samples/s	250 samples/s	250 samples/s
Epoch start	-300 ms	-300 ms	-300 ms
Epoch end	1000 ms	1000 ms	1000 ms
Epoch length	1300 ms	1300 ms	1300 ms
Pre-stimulus interval	300 ms	300 ms	300 ms
Baseline start	-100 ms	-100 ms	-100 ms
Baseline end	0 ms	0 ms	0 ms
Padding	2000 ms	2000 ms	2000 ms
Folder	M:/Examples - BESA Connectivity/ Feature - Batch Processing/60dB	M:/Examples - BESA Connectivity/ Feature - Batch Processing/70dB	M:/Examples - BESA Connectivity/ Feature - Batch Processing/80dB
Files	S1_60dB_HighIntensity_3RS S2_60dB_HighIntensity_3RS S3_60dB_HighIntensity_3RS S4_60dB_HighIntensity_3RS S5_60dB_HighIntensity_3RS S6_60dB_HighIntensity_3RS	S1_70dB_HighIntensity_3RS S2_70dB_HighIntensity_3RS	S1_80dB_HighIntensity_3RS S2_80dB_HighIntensity_3RS S3_80dB_HighIntensity_3RS S4_80dB_HighIntensity_3RS

Press **Next** to go to the next work step or Previous to switch back to the **Set Project Targets** work step.

10.3. Set Parameters

The window layout for the **Set Parameters** work step in the Time-Frequency workflow is presented below.
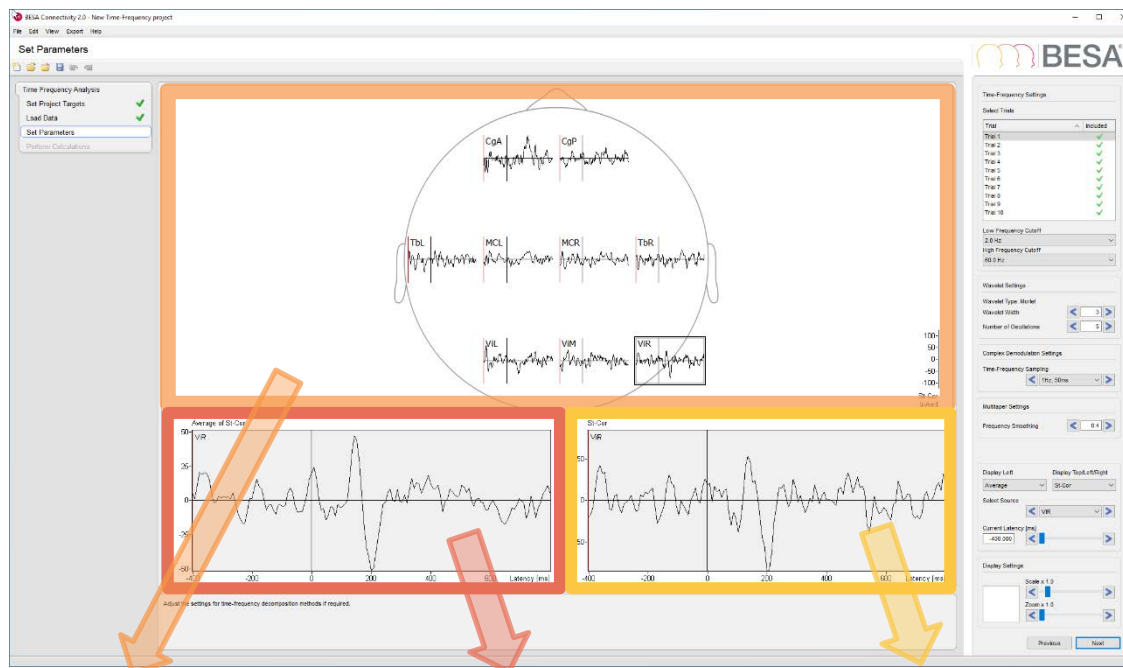
The Main Window shows single trial waveforms, as selected in the interaction window, for the indicated condition and every channel / source.

The left Detail Window displays an averaged waveform from all selected trials, for the selected channel.

The right Detail Window displays the selected single trial waveform for the indicated condition and channel / source.

The **Time-Frequency Settings** consist of three parameters.

The **Select Trials** or **Select Files** window allows to review the single trials before performing time-frequency computation. Individual trials can be excluded if needed. To exclude trial from further analysis a green checkbox adjacent to the trial number has to be unchecked.

In case Grand Average has been selected in the **Select Data Set** element, all files for the current condition will be displayed.

After selecting any of the trials, you can browse through the individual trials quickly by using the **cursor up** and **cursor down** keys on the keyboard.

The **Low Frequency Cutoff** can be adjusted. By default, the low frequency cutoff is set to the minimum value possible for the provided data and method. The lowest frequency possible depends on the method settings of Complex Demodulation and/or Wavelet.

The **High Frequency Cutoff** is detected from the data sampling and set to the highest possible value (that is below the Nyquist frequency). This value can be adjusted by selecting the value from the dropdown list.
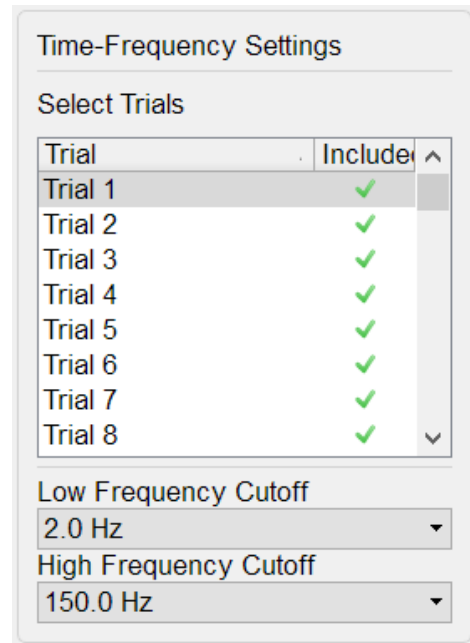
The **Wavelet Settings** depend on the wavelet type selected in the Set Project Targets workstep. The **wavelet type** is indicated in the widget. For Morlet wavelets, the following settings can be adjusted:

Wavelet Width determines the width of the envelope function (Gaussian kernel) used for creation of the wavelet. Shorter wavelets will provide a finer temporal resolution at the expense of a coarser frequency resolution and vice versa.

Number of Oscillations determines the number of oscillations present in the wavelet. Wavelets with lower number of oscillations will provide a finer temporal resolution at the expense of a coarser frequency resolution and vice versa.

Larger wavelet widths or larger number of oscillations require longer wavelets, which in turn requires more padding at each side of the data for calculation. If not enough padding is available, zero padding is added. Please note that this can influence the data (cf. chapter 4.6 for more information).

In the **Complex Demodulation Settings**, the resolution of the time-frequency transform can be adjusted using the **Time-Frequency Sampling** combo box. If a high resolution in the frequency domain is selected (e.g. 0.5 Hz sampling rate), this goes along with a low resolution in
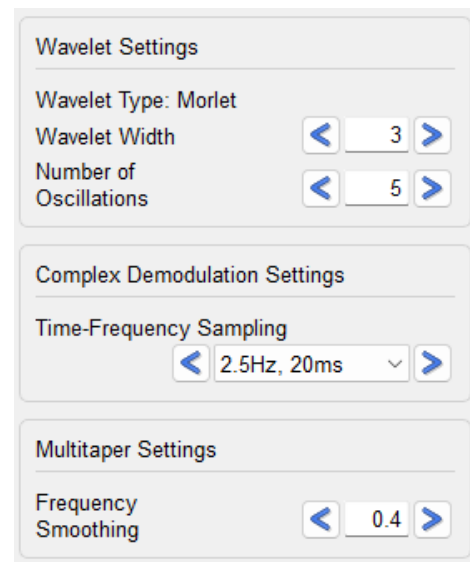
the time domain (in this case: 100 ms sampling rate). Accordingly, a high time resolution (e.g. 10 ms sampling rate) is accompanied by a low frequency resolution (5 Hz sampling rate). The default value of this setting is "1 Hz, 50 ms".

In the **Multitaper Settings**, the **Frequency Smoothing** parameter can be adjusted between 0.2 and 1.8 in steps of 0.1, and the default value of this parameter is 0.4. Specifying larger frequency smoothing values will result in more frequency smoothing.

Select Data Set is shown if several files have been loaded for the current condition. The combo-box allows the selection of the conditions Grand Average or single files.

Display Left enables or disables the presentation of average signal from all trials used for further analysis (defined in Select Trials/Files widget) in the left Detail Window. If Grand Average has been selected, the average signal from all included files will be displayed.

Display Top/Left/Right allows to switch previously defined conditions in the Main Window, the left and the right Detail Window. In main and right windows, the currently selected waveform of a single trial is presented, whereas in the left detail window an average waveform of the selected channel for the selected condition is shown.

Select Channel / Source: Depending on the loaded data file montage (source montage or channel montage) an appropriate text is displayed. This dropdown selection box allows the selection of a desired channel / source to be displayed in the Detail Windows. Alternatively, the channel / source of choice can be selected in the Main Window by a left-click. The arrow buttons left and right of the channel selector box can be used to quickly browse through all channels / sources.

Current Latency allows setting a cursor at a particular latency (the slider can be dragged to the point of interest or the arrow buttons at the left and right of the slider bar can be used to adjust the position).

Scale allows altering the scaling of the data. The arrow buttons at the left and right of the slider bar can be used to scale the data up or down.

Zoom allows viewing the Main Window contents in greater detail. The arrow buttons at the left and right of the slider bar can be used to adjust the zoom factor. For zooming the mouse wheel can be used as well. The black frame at the left of the Zoom slider displays the position of the currently displayed window fraction relative to the
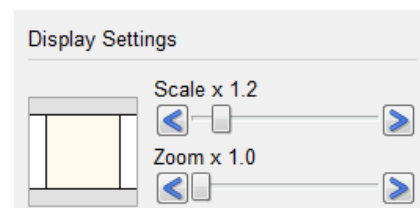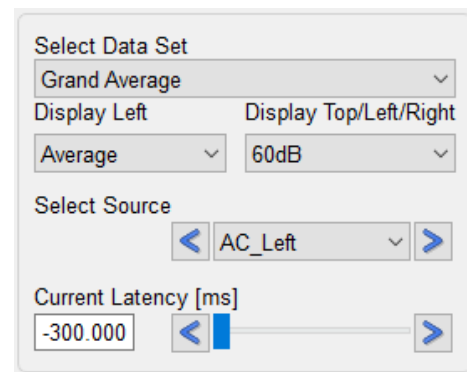
complete window. The frame can be left-dragged to another relative position. Alternatively, it is possible to left-drag the Main Window while holding down the control key.

10.4. Perform Calculations

Pressing **Run Time-Frequency Analysis** opens a window with a summary of the Time-Frequency Analysis Settings.

- If *Wavelet* computation was selected, the name of the selected wavelet is indicated and, if applicable, its width and number of oscillations.

- If *Complex Demodulation* was selected, the time-frequency sampling values are shown.

- If *Multitaper* was selected, the frequency smoothing value is displayed.
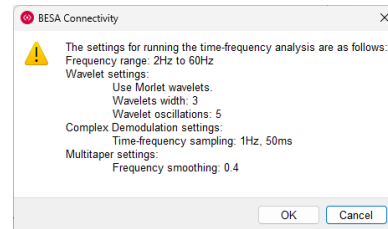
If these values need changing, it is possible to return to the **Set Parameters** work step by pressing **Cancel** and the **Previous** button. Confirming the summary window with **OK** will start the time-frequency analysis.

Please note that depending on the number of channels/sources and data points, the computation might take several minutes.

After performing the computation, the results are displayed:

The Main Window shows the time-frequency plot for each channel / source for the selected time-frequency analysis method, display type, and condition.

The left Detail Window displays an averaged waveform from all selected trials, for the selected channel.

The right Detail Window displays a time-frequency plot for the chosen channel / source with the selected time-frequency analysis method, display type, and condition.

If more than one files was loaded for the currently selected condition, it is possible to switch between them or the Grand Average by selecting one of the files from the **Select Data Set** dropdown list.

If more than one Time-Frequency analysis method was used, it is possible to switch between them by selecting one of the methods from the **Select Time-Frequency Method** dropdown list.

In the **Select Display Type** selection group, the display can be switched between temporal-spectral evolution (**TSE**) or Absolute (**ABS**) value, for **Amplitude** or **Power**.

When the **TSE** check box is selected, time-frequency plots are shown where the power/amplitude for each time is normalized to the mean power/amplitude of the baseline epoch for that frequency. Whether amplitude or power is used for the calculation depends on the state of the Amplitude/Power check box. The x-axis shows the time relative to the event, and the y-axis shows the frequencies. The intensities are displayed as a color-coded plot. The resulting TSE value (%) is computed as

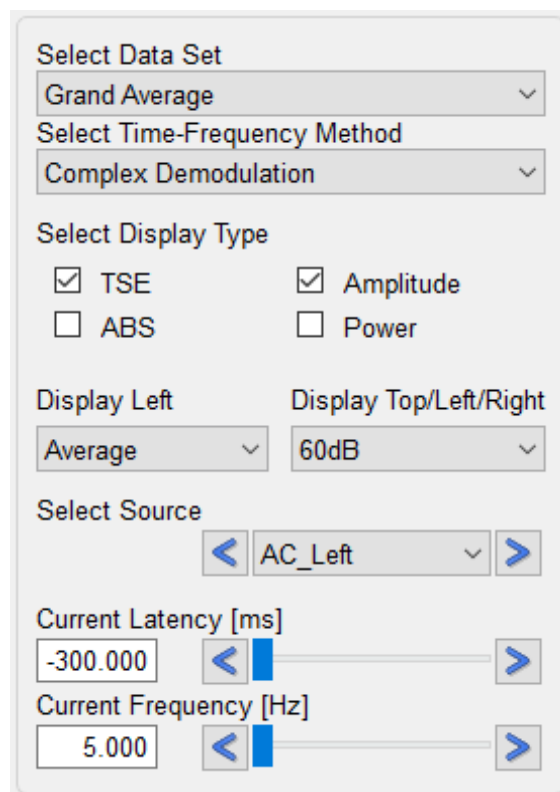$$\text{TSE}(t,f) = \frac{A(t,f) - A_{baseline}(f)}{A_{baseline}(f)} \cdot 100\%$$

with

$A(t,f)$ = activity at time t and frequency f (either power or absolute amplitude)

$A_{baseline}(f)$ = mean activity at frequency f over the baseline epoch

The TSE value is in the range from [–100%, +inf] and describes the spectral change of activity at sampling time t relative to the activity during the baseline epoch. A value of +100% means that activity is twice as high as during the baseline epoch.

The averaged waveform display of the Detail Window can be switched on or off in the **Display Left** checkbox. By changing the selection in **Display Top/Left/Right** the

condition for which data are displayed can be changed (if more than one condition was selected in the beginning of the work flow).

Select Channel / Source: Depending on the loaded data file montage (source montage or channel montage) an appropriate text is displayed. This dropdown list allows the selection of a desired channel / source to be displayed in the Detail Windows. Alternatively, the channel / source of choice can be selected in the Main Window by a left-click. The arrow buttons left and right of the channel selector box can be used to quickly browse through all channels / sources.

The crosshair position over the time-frequency plot can be selected either by left mouse click on the desired position in the right Detail Window, by a double click in the Top View display, or by adjusting the **Current Latency [ms]** and **Current Frequency [Hz]** settings sliders.

The remaining settings in the Interaction Window are analogous to the Set Parameters (see 10.3).

Pressing **Finish** saves the current project

Note that the color map for showing the data can be changed in the **View** menu: For **TSE** display, the currently selected diverging color map is used; for **ABS** display, the currently selected sequential color map is used.

When hovering over the left or right detail window, the value of waveform amplitude or time-frequency decomposed data for the given time-frequency sample is displayed in a tooltip text.
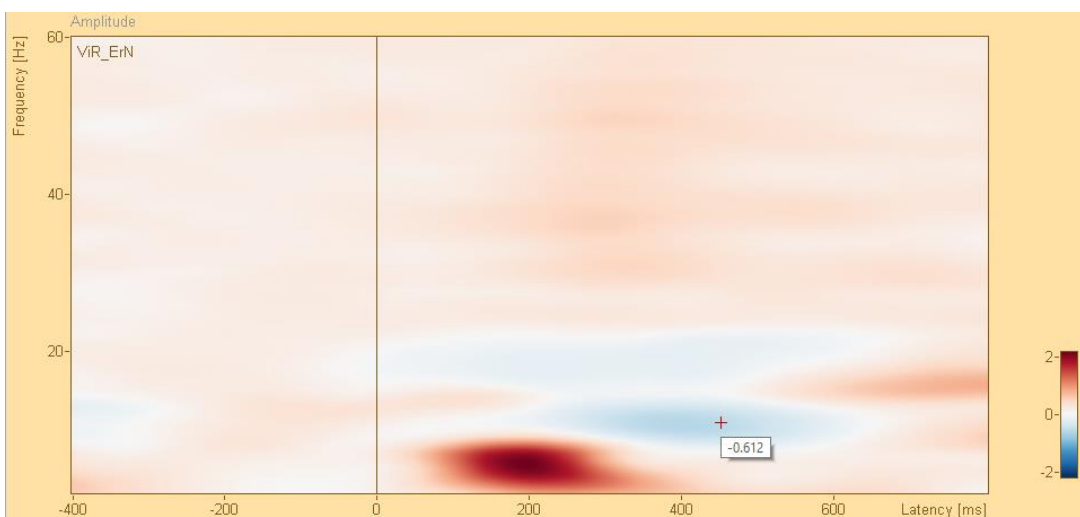
Using the Blue-to-Red diverging color map in TSE display

After specifying a group and project name, projects including all completed workflows steps will be saved and marked with a green check mark. Completed, but not finished projects are marked by a green dot. Incomplete projects are marked by a red dot.

A project can be re-opened at any time by pressing **File / Open Project.**
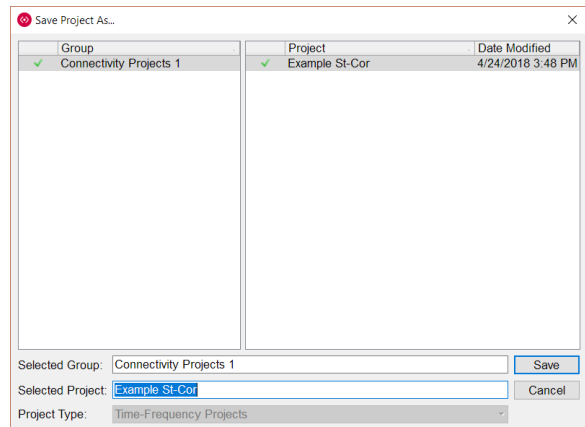
11. Workflow: Connectivity Analysis

11.1. Set Project targets

There are multiple selection options for specifying the connectivity analysis method:

- **Coherence**: describes the amount of in-phase components of two signals at a specific frequency (Rosenberg et al., 1989).

- **Imaginary Part of Coherency**: excludes coherent sources with zero phase lag and therefore reduces the effect of field spread due to volume conduction (Nolte et al., 2004).

- **Phase Locking Value**: is the average of phase angle difference between both signals over time at a specific frequency (Lachaux et al., 1999).

- **Phase Lag Index**: measures the asymmetry of the distribution of phase differences between two signals and is less sensitive to volume conduction effects and reference electrode issues (Stam et al., 2007).

- **Weighted Phase Lag Index**: is an extension of the PLI in which phase differences between two signals are weighted by the magnitude of the imaginary component of the cross-spectrum (Vinck et al., 2011).

- **Directed Phase Lag Index**: is an extension of the PLI in which the direction of information flow can be determined (Stam and van Straaten, 2012).

- **Granger Causality:** states that if past values of time series $y(t)$ contains information that helps in the prediction of time series $x(t)$, then $y(t)$ is said to cause $x(t)$ (Granger, 1969; Geweke, 1982).

- **Partial Directed Coherence:** measure that only shows the direct interrelations between the signals (Baccala and Sameshima, 2001).

- **Directed Transfer Function:** was introduced to reveal indirect information transfer between signals (Kaminski and Blinowska, 1991).

For more details about each connectivity analysis method please refer to chapter 5 or to the original research papers mentioned for each method.

11.2. Load data

Since connectivity computation is based on time-frequency data, this workflow requires data from a time-frequency analysis project.

Pressing the **Select Time-Frequency Input Project** button will bring up a project selector box with project type filter fixed to Time-Frequency Projects. Choose the desired project from any group and press **Open** to proceed.

If an unfinalized project is selected (indicated by a red dot) a prompt dialog will be shown. Press **Yes** if workflow type should be switched back to time-frequency analysis in order to finalize the project. Press **No** or **Cancel** to select another project.

After loading the project, the related details will be displayed in the Main Window, similarly to the **Load data** work step of the Time-Frequency analysis workflow (10.2)

Press **Next** to go to the next work step or **Previous** to switch back to the **Set Project targets** work step.
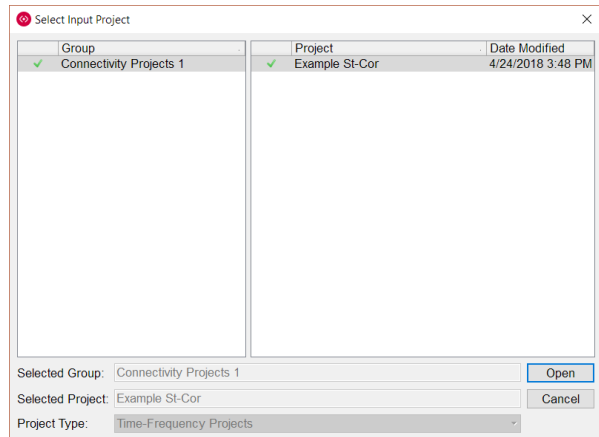
11.3. Set Parameters

The window layout for the **Set Parameters** work step in the Connectivity workflow reflects the calculations performed in time-frequency analysis and is presented below.

The Main Window shows the time-frequency plot for each channel / source for the selected time-frequency analysis method, display type, and condition.

The left Detail Window displays an averaged waveform from all selected trials, for the selected channel.

The right Detail Window displays a time-frequency plot for the selected channel / source with the selected time-frequency analysis method, display type, and condition.

If any of the non-parametric connectivity methods were selected in the **Set Project Targets** work step (Granger Causality, Partial Directed Coherence, or Directed Transfer Function), the additional **Non-Parametric Methods Settings** widget is available.

The **Number of Iterations, Tolerance,** and **Regularization** can be adjusted either by editing the values manually or by clicking the left arrow to decrease / right arrow to increase.
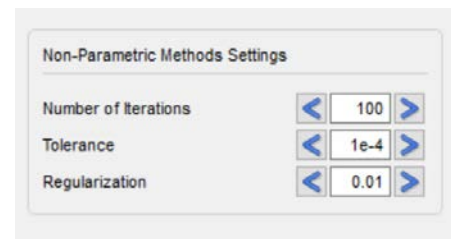
These parameters are required during the factorization of the cross-spectral density matrix. In each iteration, the estimation error of the spectral factors is recomputed. If the estimation error is lower than the tolerance threshold, the computation of this iteration is finished. The regularization (%) is applied in order to ensure a smooth shape of the cross-spectral density matrix. The regularization of 0.01 indicates that a regularization parameter is set to 1% of mean of power spectral density values.

The remaining settings in the **Interaction Window** are analogous to the Perform Calculation work step of the Time-Frequency Analysis workflow (chapter 10.4).

11.4. Perform Calculations

Pressing **Run Connectivity Analysis** opens a window with a summary of the Connectivity Analysis Settings. All selected methods are listed.

- If non-parametric methods are planned to be computed (Granger Causality, Partial Directed Coherence, or Directed Transfer Function) the related settings are also displayed.
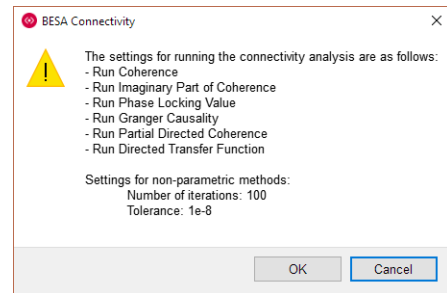
If any of the values need to be changed, it is possible to return to the **Set Parameters** work step by pressing **Cancel** and the **Previous** button. Confirming the summary window with **OK** will start the connectivity analysis.

Please note that depending on the selected connectivity method, the number of iterations in non-parametric settings, number of channels/sources and data points, the computation might take several minutes.

After finalizing the computation, the results are displayed:

In the Main Window, results are displayed either in a grid view to show all connectivity patterns in one view, or in a 3D view (11.4.1), which shows either connectivity with connection strength encoded by thickness of connecting arrows, or the sum of inflow/outflow.

The left Detail Window displays backward connectivity between channels / sources indicated by row and column in Top Window (Left and Right Source in selection widget).

The right Detail Window displays forward connectivity between channels / sources indicated by row and column in Top Window (Left and Right Source in selection widget).

Note that the color map for showing the data can be changed in the **View** menu: for display of **Imaginary part of Coherency** and **Weighted Phase Lag Index**, the currently selected **diverging color map** is used; for display of **the other connectivity** methods, the currently selected

sequential color map is used. When hovering over the left or right detail window, the value of connectivity for the given time-frequency sample is displayed in a tooltip text.

If more than one files was loaded for the currently selected condition, it is possible to switch between them or the Grand Average by selecting one of the files from the **Select Data Set** dropdown list.

Select Connectivity Method dropdown menu and **Select Time-Frequency Method** can be used to change the displayed results in the Main Window.

View modes can be switched by checking the **TFC View**, **3D View** or **Circular Graph View** checkboxes. These modes are described in more detail in chapter 11.4.1.
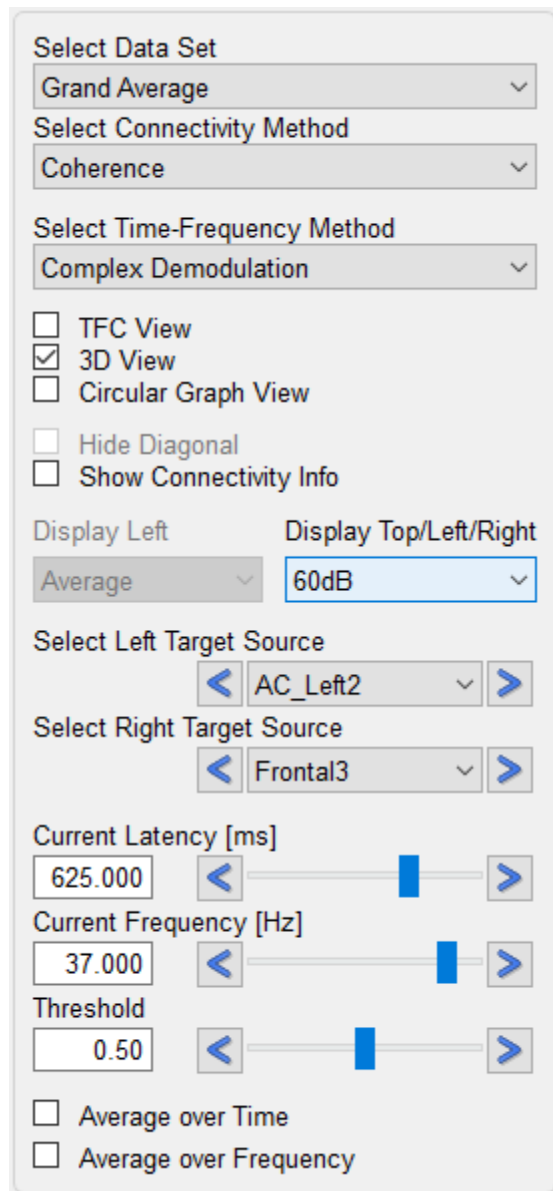
If the analysis was performed for more than one condition, the displayed condition can be changed by selection in the **Display Top/Left/Right** section.

The displayed connectivity between selected channels in left and right Detail Windows can be changed either by clicking on one of the plots available in the matrix in the Main Window, or by indicating the desired channels/sources in the **Select Left Target Channel\Source** and **Select Right Target Channel\Source** dropdown menus. These menus can also be scrolled by the arrows adjacent to both menus.

The crosshair horizontal position can be adjusted by changing the position of the **Current Latency [ms]** slider. The crosshair vertical position can be altered by changing the position of the **Current Frequency [Hz]** slider. If the crosshair position is manually changed by clicking the left mouse button on the desired position in either the Left or Right Detail Window, the values of the Current Latency slider and Current Frequency slider will be automatically updated. Finally, the crosshair position is also updated by a double click into the selected channel in the top part of the Main Window display.
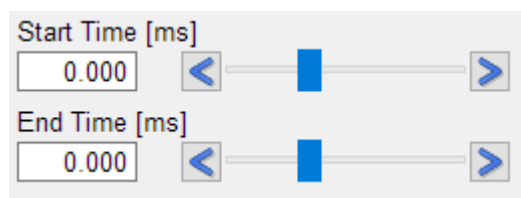
If the **Average over Time** checkbox is enabled additional controls are shown and plots are averaged over time. The **Start Time [ms]** slider and **End Time [ms]** sliders indicate the time window that will be averaged over. The display changes: the X axis shows frequency and the Y axis shows connectivity values for the selected method (e.g. Coherence).

The averaging can be performed also in the frequency domain by enabling **Average over Frequency**. Now, the averaging window can be

adjusted by the displayed **Start Frequency [Hz]** slider and **End Frequency [Hz]** slider. Plots show time values on the X axis; the Y axis shows connectivity values for the selected method (e.g. Coherence).
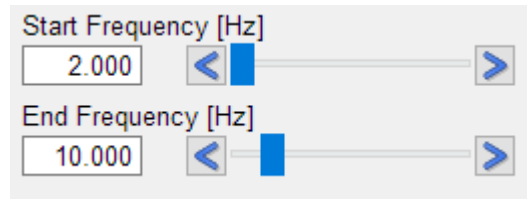
The remaining settings in the Interaction Window are analogous to the Set Parameters work step (10.3)

11.4.1. View Modes

For display of Connectivity results, several viewing options are available:

- **TFC View**

- **3D View**

- **Circular Graph View**

TFC View

The **TFC View** will display the connectivity matrix between all pairs of sources or sensors for the currently selected method. If averaging over time and/or frequency is applied, connectivity values are shown for the selected time and/or frequency intervals.
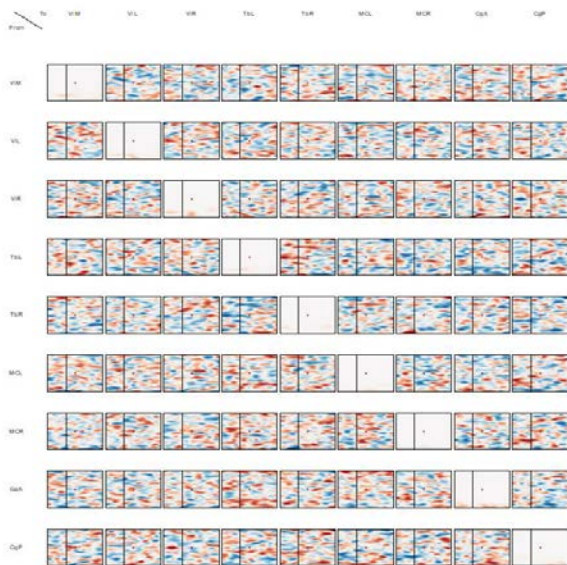
The matrix diagonal (Normalized Power Spectral Density – Normalized PSD) can be hidden by checking the **Hide Diagonal** checkbox.

The **TFC View** provides the so-called Freeze Pane functionality, that allows you to keep the header row and header column visible on the screen, even as you scroll through a large data sets with a large number of sources or sensors.
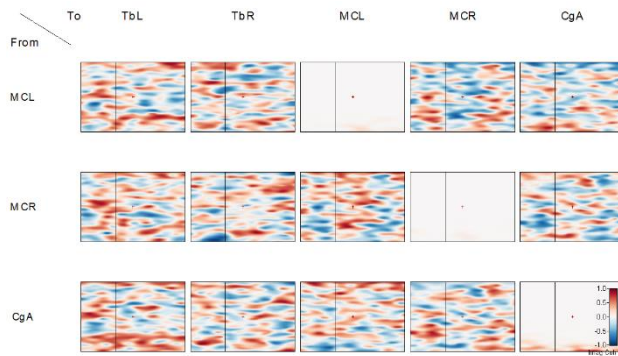
3D View

If the **3D View** checkbox is enabled in the Interaction Window, the Main Window will display an averaged transparent brain surface (in case that brain sources are analyzed) or a non-transparent scalp surface (for sensor data analysis). The brain surface was kindly supplied by John E. Richards, University of South Carolina, USA (Richards et al., 2016).

This view shows the brain connectivity for the selected time and frequency, also if averaging over time and/or frequency is applied. The controls available in the Interaction window are adjusted for the purpose of 3D view settings.
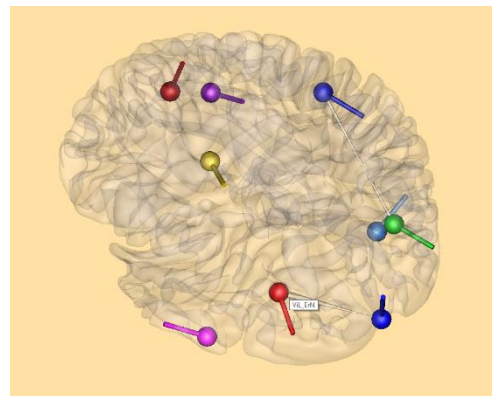
Hover with the mouse pointer over any of the channels to view the channel label in a tool tip. The current connectivity values of the detail window channels are displayed at the bottom left part of the central window.

If **Show Connectivity Info** checkbox is checked, further information for the currently selected pair of sources/sensors is shown in the main window.

The **Threshold** slider is available only for Connectivity Strength visualization. Adjust this value either by manual editing, by moving the slider, or by pressing the left or right arrow to reject (hide) connectivity arrows with values below the selected value.

Auto Thresholding: The **Auto** checkbox computes a threshold based on statistics.

• For each frequency, the connectivity value distribution over the baseline interval is computed. For non-symmetric connectivity methods (e.g. Coherence), the threshold is set to the value corresponding to the 95th centile of the distribution. For symmetric methods (e.g. Imaginary Part of Coherency), the threshold is set to the value corresponding to the 97.5th centile. In case of averaging over a frequency range, the 95th (97.5th) centile values are also averaged over that range to provide the auto-thresholding value.

• If no baseline interval is provided, then the full interval will be used to compute the statistical threshold. Note that the baseline interval is read from the raw data, and is listed in the Load Data work step.

In 3D view mode the **Zoom** and the **Scale** settings in **Display Settings** are not available. These settings are replaced by the 3D view specific ones. One of three **Display** modes can be selected: Connectivity Strength, Sum Inflow and Sum Outflow.

If **Connectivity Strength** is checked, cones will be displayed that indicate direction of information flow between two channels/sources: The thicker the base of the cone, the stronger the connection from the source to the destination. The reverse direction is also shown in the same way, except for Imaginary Part of Coherency and Directed Phase Lag Index where only the positive values are used.

If **Sum Inflow** is selected, all input information flow for each node (channel/source) is summarized and expressed by the node size. Similarly, if **Sum Outflow** is selected, all output information flow for each node is summarized and expressed by the node size.
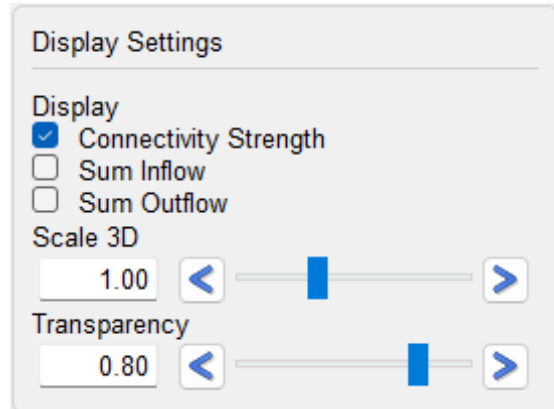
The **Scale 3D** slider allows changing the size of all connectivity arrows or inflow/outflow nodes.

To change brain visibility, adjust the **Transparency** slider value. The higher the value, the more transparent the brain will look.

In scalp visualization, the Sum Inflow, Sum Outflow, and Transparency options are not available.

In both brain and scalp visualization modes, zooming is done interactively.

The 3D image can be rotated by left-dragging the mouse. The displayed brain or head can be moved / zoomed by left-dragging the mouse while holding down the **Ctrl** / **Ctrl+Shift** key.

The mouse cursor symbol signals the available interaction associated with clicking and/or dragging:

Rotate 3D image.

Move 3D image.

Zoom 3D image.
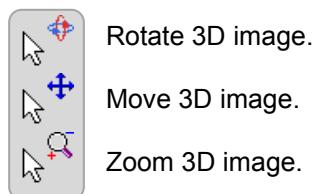
Circular Graph View

The **Circular Graph View** will display connectivity values from the connectivity matrix shown as links between sources / sensors.

The sources/sensor labels are placed according to their position in the anterior or posterior region and left or right hemisphere. Connections are represented by colored lines. Connectivity values are represented through a colormap, which you can see in the colorbar on the bottom right of the window.

By adjusting the **Threshold** slider, the minimum connectivity value that will be displayed on the graph can be selected.

For directional connectivity methods, one arrowhead will be displayed for each link, indicating the directionality of the information flow.

When averaging in the time and/or frequency is active, the **Circular Graph View** will visualize results for the selected time and frequency ranges.

Imaginary Part of Coherency
Latency: -350.0ms
Frequency: 10.0Hz
OrR to FrR: -0.805
FrR to OrR: 0.805
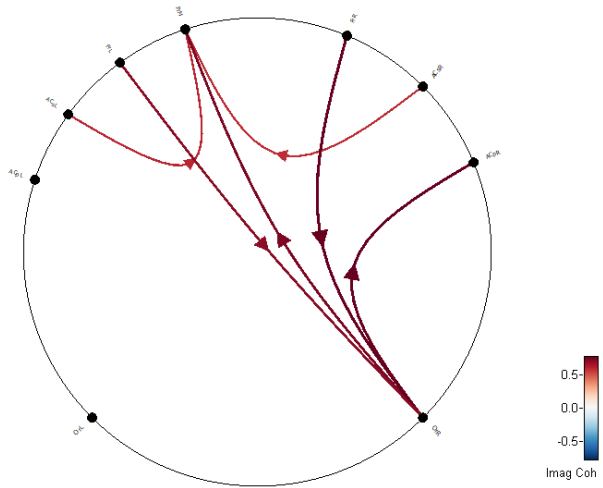
If **Show Connectivity Info** checkbox is checked, further information for the currently selected pair of sources/sensors is shown in the main window.

12. Exporting Images, Video, and Results

12.1. Exporting Images

For the **Set Parameters** work step and after completing computation in the **Perform Calculations** work step for all workflows, it is possible to export resulting images in the Main Window and the Detail Windows. This can be achieved via the menu bar (see 8.2.4) or via right-clicking in the corresponding window.
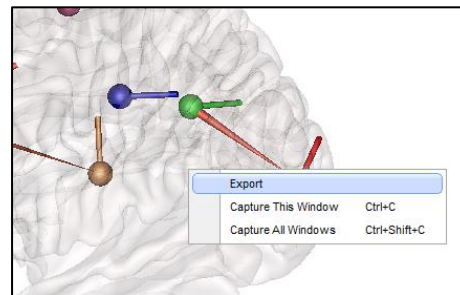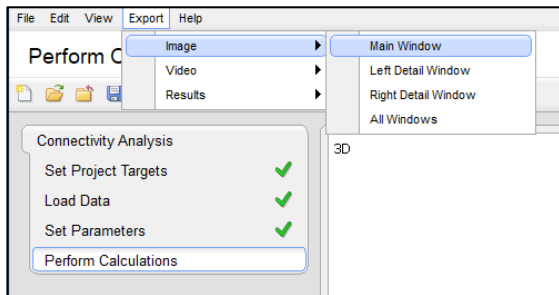

Images can be saved as **portable network graphics** (*.png), **vector graphics** (*.eps) or **scalable vector graphics** (*.svg).

The selection can be made in the saving dialog under **Save as type:**
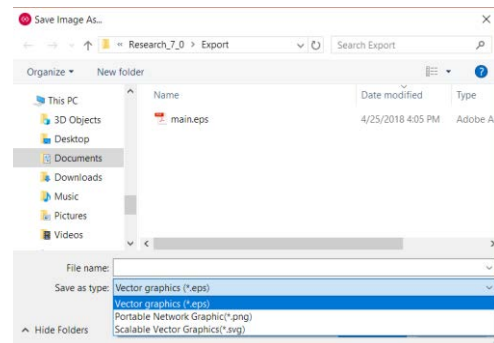
When saving *.png files, the dimension and resolution of the resulting image can be defined. By default, the current size of the image on the screen is used. Width and height can be altered with or without constraining proportions using mm or inch as units. The resolution can be set to 150, 300 or 600 dots per inch.

When saving *.eps or *.svg file, the image size cannot be changed as vector graphics are by definition fully resizable.
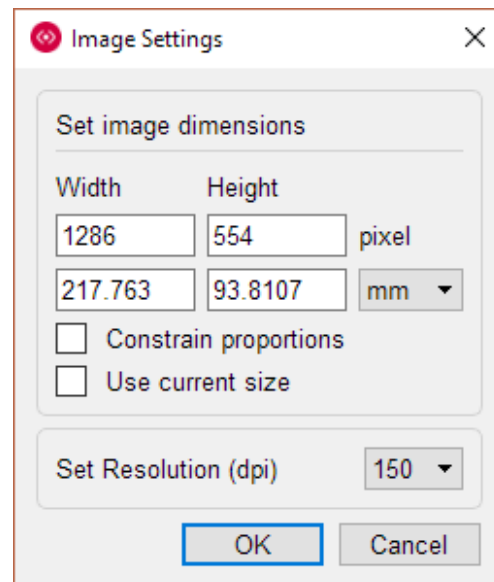
Capture Images

The main, left detail, and right detail windows can be captured to the clipboard using the context menu **Capture This Window** and **Capture All Windows** (right-clicking in the corresponding window).

The windows can be also captured to the clipboard using the following shortcut:

- **Ctrl+C**: capture a window under the mouse cursor

- **Ctrl+Shift+C**: capture all windows

12.2. Exporting Video

Video export can be used to record a temporal evolution of brain connectivity for the selected frequency (or frequency range if Average over Frequency is active) in 3D view mode in the Connectivity analysis work step.

After selecting the Video export option, a settings dialog will be shown. The video can be saved with standard cinematic resolution ranging from SD (720 × 480 px) to UHD (3840 × 2160 px). The desired value can be selected from the **Resolution** dropdown menu.

A start and end time can be set using **Start Time [ms]** and **End Time [ms]** sliders. These values can be adjusted by manual editing, by setting the slider position or by pressing left and right arrows to increase or decrease the selected value, respectively. The time step of this settings is the same as the time sampling of the selected time-frequency method.

The setting **Duration Per Latency Step [s]** can be used to decide how long one latency position will be shown in the video. This directly influences the video length which depends also on the temporal resolution, and on starting and ending time (number of temporal samples). The final video length is automatically computed and returned in the **Video Length [s]** field.

The **Rotation [deg]** value can be adjusted to decide if the 3D rendered object (brain surface or scalp) should be rotated during the video. To disable rotation, use 0 degree as rotation value. A default value of 360 degree generates a full turnaround. A checkbox marked by symbol sets the rotation to go forth and back, which may be useful if the video should loop around.

The **background color** of the video can be easily changed by clicking one of three rectangles with predefined colors (white, BESA sandy, or black). In addition, any color can be chosen by clicking of the button with three dots . After pressing this button an advanced color picker menu will be shown.

To start **video recording** press the button. The video generation can be observed in the
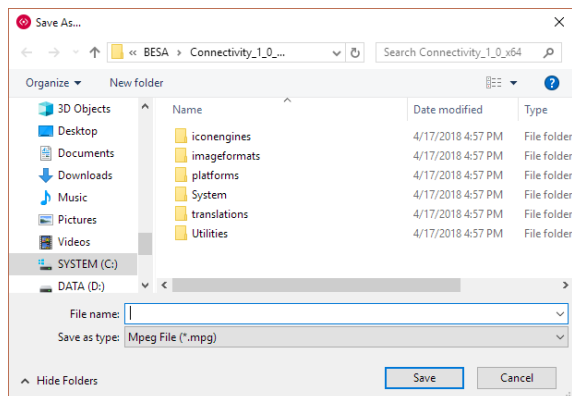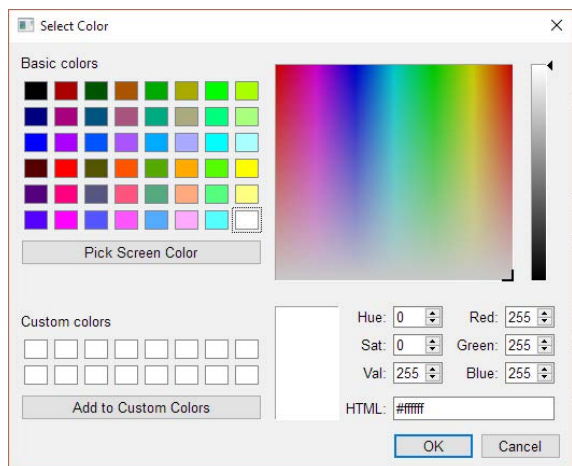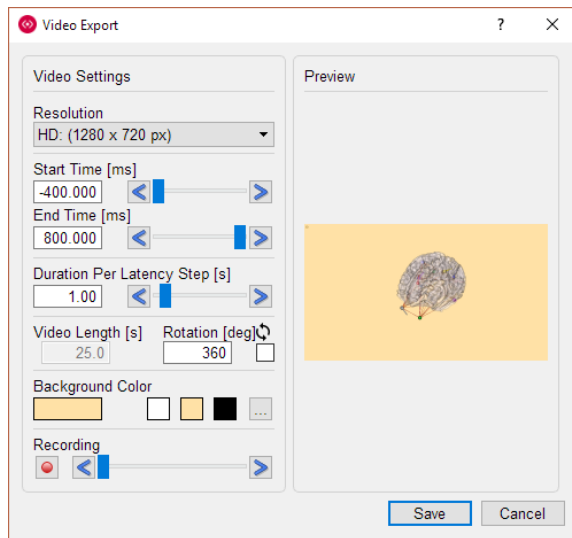
Main Window[1]. After video registration is finished, the results can be previewed in the preview sub-window. To change the latency shown in the preview sub-window, use a slider in the Recording section.

After finishing preparation of the video it can be saved by pressing the **Save** button or discarded by pressing the **Cancel** button. If the **Save** button was pressed a file save dialog will be shown. The video can be saved as *.mpg* file.

12.3. Exporting Time-Frequency Analysis Results

After the Time-Frequency analysis is completed in the **Perform Calculations** work step, it is possible to export analysis results via the menu bar (see 8.2.4) A choice can be made between "Single Trial TF Data", "Averaged TF Data" , "Averaged Waveforms" and "Project Results". The result files are stored as comma-separated ASCII files. If more than one condition was used during analysis, the exported condition will be the one currently selected in the Interaction Window (10.4).
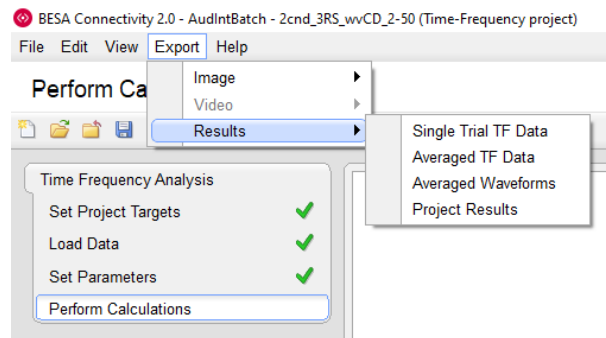
Single Trial TF Data will output the Time-Frequency analysis result for each trial which was selected in the **Set Parameters** work step (see chapter 10.3) to a *.tfcs* file. See chapter 14.2 for more details on the file format.

Averaged TF Data will output averaged data of time-frequency analysis. The exported data will be exactly the same data as the one used to create the Main Window display data, i.e., correspond to the choices made in the **Select Display Type** selection group for the visualization after the Time-Frequency analysis has been performed (see chapter 10.4). Recall that the available display options are temporal-spectral evolution (**TSE**) or Absolute (**ABS**) value, for **Amplitude** or **Power**. Data will be exported to a *.tfc* file – see chapter 14.1 for details.

Averaged Waveforms will output time-domain averaged data across all trials. Before exporting the averaged waveforms for individual channels, the waveforms can be reviewed in the left Detail Window of the Main

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[1] Due to the OpenGL limitation a flickering may be visible when video is recorded. Please move the mouse cursor outside the main window to remove this effect.

Window. Data is exported in *.avr format (se chapter 14.6).

Project Results will output averaged data of time-frequency analysis for all data sets and conditions that are part of the current project. The exported data will follow the current display type, but will also contain all time-frequency methods that were selected (see chapter 14.1). The results will be arranged in sub-folders suitable for import into BESA Statistics. The top folder lists the date. The next level contains the type of time-frequency decomposition. The next level contains the condition sub-folders. Each of these sub-folder contains the *.tfc file of all data sets for the condition, and a file describing the sensor configuration. Within the date folder, a text file containing the project settings is also stored.

12.4. Exporting Connectivity analysis results

After the Connectivity analysis is completed in the **Perform Calculations** work step it is possible to export analysis result via the menu bar (see 8.2.4). If connectivity analysis was performed for more than one condition, the condition currently selected in the Interaction window is exported (see 11.4).

Connectivity Data will output channel to channel (or source to source) connectivity matrices as shown in the Main Window. The data for the currently selected connectivity analysis method and the currently selected time-frequency analysis method is exported (selection in the Interaction window, see 11.4). Data is exported as ASCII file of type *.conn. Check chapter 14.8 for more details.

Project Results will output connectivity matrices for all data sets and conditions that are part of the current project, for all time-frequency methods and connectivity methods applied. The data export folder hierarchy follows the description for the project results listed in the section above, with the additional level of connectivity measure.
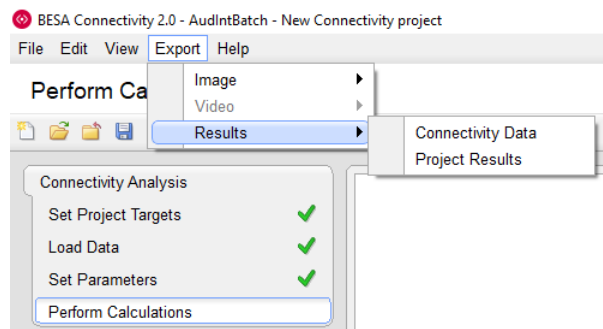
13. Appendix

13.1. The BESA Connectivity Data Folder

The BESA Connectivity Data Folder is the folder or path where BESA Connectivity stores all project data to and reads completed or prepared projects from. This folder should exclusively be used for storing BESA Connectivity data.

When starting BESA Connectivity for the first time (see 2.3.1), a local folder accessible to all users is suggested as the **default folder**. Depending on the operating system, this folder is located as follows:

- Windows 11: **C:\Users\Public\Documents\BESA Connectivity\Projects**

- Windows 10: **C:\Users\Public\Documents\BESA Connectivity\Projects**

In most cases, however, it might be more useful to create a shared folder on a server drive, e.g. **E:\Server\BESA Connectivity Data** that is accessible to all users from anywhere in the local network. This is more convenient, since BESA Connectivity uses a network support BESA License Key that allows the software to be run from any computer in the local network where BESA Connectivity has been installed and configured with the shared BESA Connectivity Data folder.

Notes:

- If you have a multi-license installation, make sure that two user do not work on the same Group and Project at the same time. Currently, BESA Connectivity does not lock projects within the network.

- If there are several major research studies with different Groups, you might want to create separate folders to store the data of the different studies separately. BESA Connectivity offers the choice to switch between different BESA Connectivity Data folders by selecting the menu item **File → Select Data Folder**.

- When switching between different BESA Connectivity Data Folders, the project data are preserved in each folder and are not copied to the new folder. Thus, you may have to compute a Group's Connectivity twice unless you copy the Group's subfolder to the new BESA Connectivity Data Folder using, e.g. File Explorer, and update the Data Folder Information as described below.

13.2. The BESA Connectivity Data Folder Information File

For faster access on the different projects in the BESA Connectivity Data Folder, an information file called Data Folder Info is created in the subfolder **BesaInternal** within each BESA Connectivity Data folder. The Data Folder information stores the Group and Project file names of all projects in the BESA Connectivity Data folder.

After copying or moving Group data folders from a previous to a new BESA Connectivity Data folder using, e.g. Windows Explorer, update the Data Folder information by selecting the menu item **File → Update Data Folder Info**. When switching between folders, make sure that the tick mark of the update option stays on in the confirmation dialog box (see 9.4.1).
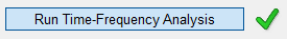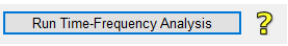
13.3. List of error and warning messages

13.3.1. Error messages

Workflow Workstep	Message Text / Symbol	Description

Workflow Workstep	Message Text / Symbol	Description
BESA Connectivity	**Sentinel LDK Protection System** No valid license detected. Please attach a BESA license key in your local network. Make sure that the HASP driver is installed. Also ensure that your HASP is up-to-date and that you own a license for this version of BESA Software (contact sales@besa.de). (H0007)	This message shows up when a BESA License Key with a valid license is not found or the license driver is not correctly installed.
BESA Connectivity	BESA Connectivity is already running. A second instance cannot be run on this PC.	When you run BESA Connectivity while BESA Connectivity is already running, BESA Connectivity displays this error message.
BESA Connectivity	The internal error MF_211 occurred. Please contact our support portal.	The error MF_211 means that something unexpected happened (e.g., there is not enough space available on the disk or you do not have permission to write files on the disk) and the program noticed that. You can request support using our support portal (see chapter 1).
Start Workflow *Select Project*	**Select the BESA Connectivity Data Folder** You don't have write privileges for the selected folder. Please select a valid BESA Connectivity Data Folder.	This message appears when you select a folder where you do not have permission to write as the BESA Connectivity Data Folder.
Start Workflow *Select Project*	Your current BESA Data Folder does not contain any projects.	When there are no saved projects, this message shows up after clicking the **Open Project** button.
Time-Frequency Analysis *Load Data*	The file C:/xxx/xxx.generic does not exist!	This message shows up when the selected Generic file (.generic) does not exists.
Connectivity Analysis *Load Data*	The file C:/xxx/xxx.generic does not exist!	This message shows up when the Generic file (.generic) for the selected Time-Frequency project does not exists.
Connectivity Analysis *Load Data*	The time-frequency project you have specified as input for this project has not been completed. Do you wish to finalize the input project? [Yes] [No] [Cancel]	This message shows up when selected Time-Frequency project exists but has currently no completed state. • Yes: The current workflow is closed; instead, the Time-Frequency workflow is resumed. • No: The dialog box closes. • Cancel: Same as No.
Connectivity Analysis *Load data*	The time-frequency project you have specified as input for this project does not exist anymore. Do you wish to select a new input project? [Yes] [No] [Cancel]	This message shows up when selected Time-Frequency project does not exists anymore. • Yes: The dialog box is closed to select another time-frequency project. • No: The dialog box closes. • Cancel: Same as No.

13.3.2. Warning messages

Workflow Workstep	Message Text / Symbol	Description
BESA Connectivity	Connectivity Analysis Set Project Targets ✔	A green check mark shows up next to the finished worksteps in the Workflow window.

BESA Connectivity	[Run Time-Frequency Analysis] ✔	A green check mark shows up next to a button in order to indicate that the related process is successfully finished.
BESA Connectivity	[Run Time-Frequency Analysis] ❓	A yellow question mark shows up next to a button in order to indicate that the related process is not successfully finished.
Start Workflow *Select Project*	The last BESA Connectivity session was not closed properly. Do you wish to restore the previous session? [Yes] [No]	This message appears when you run BESA Connectivity again after abrupt termination during running a project. • Yes: You can restore the previous project. • No: The dialog box closes.
Time-Frequency Analysis	Another program has requested to start a time-frequency analysis. Do you wish to close the current project and start time-frequency analysis? [Yes] [No]	This dialog box appears when another program (e.g. BESA Research) requests a new Time-Frequency project while a project is opened or processed in BESA Connectivity. • Yes: A new Time-Frequency project is started. • No: The dialog box closes.
Time-Frequency Analysis *Perform Calculations*	The settings for running the time-frequency analysis are as follows: Frequency range: Wavelet settings: Complex Demodulation settings: [OK] [Cancel]	Pressing **Run Time-Frequency Analysis** opens a window with a summary of the Time-Frequency Analysis Settings. If Complex Demodulation was selected the time-frequency sampling values are shown. If Wavelet computation was selected the name of the selected wavelet is indicated and, if applicable, its width and number of oscillations. • OK: Confirming the summary window with **OK** will start the time-frequency analysis • Cancel: If these values need changing, it is possible to return to the **Set Parameters** work step by pressing **Cancel** and the **Previous** button.
Connectivity Analysis	Another program has requested to start a connectivity analysis. Do you wish to close the current project and start connectivity analysis? [Yes] [No]	This dialog box appears when another program (e.g. BESA Research) requests a new Connectivity project while a project is opened or processed in BESA Connectivity. • Yes: A new Connectivity project is started. • No: The dialog box closes.
Connectivity Analysis *Perform Calculations*	The settings for running the connectivity analysis are as follows: Settings for non-parametric methods: Number of iterations: Tolerance: Regularization: [OK] [Cancel]	Pressing **Run Connectivity Analysis** opens a window with a summary of the Connectivity Analysis Settings. All selected methods are listed. If non-parametric methods are planned to be computed the related settings are also displayed. • OK: Confirming the summary window with **OK** will start the connectivity analysis. • Cancel: If any of the values need to be changed, it is possible to return to the **Set Parameters** work step by pressing **Cancel** and the **Previous** button.

13.4. Range, accuracy and precision of displayed values

The following table lists measured quantities that are displayed to the user during certain work steps in clinical usage of BESA Connectivity. The range, accuracy and precision are also listed.

Workflow *Workstep*	Measured quantity	Range	Accuracy	Precision
Time-frequency analysis *Perform Calculations*	Mean amplitude over all trials at specific time	Range in µV or fT (surface channels) or nAm (source channels) covers physiological range: [-100000 … 100000]	±0.1 µV / fT / nAm	±0.1 µV / fT / nAm
Time-frequency analysis *Perform Calculations*	Absolute amplitude at specific time and frequency	[0 … 100000]	±0.1 µV / fT / nAm	±0.1 µV / fT / nAm
Connectivity Analysis *Perform Calculations*	Coherence value at specific time and frequency	[0 … 1]	±0.1	±0.02

14.   File Formats

All BESA Connectivity output data formats are in ASCII format to facilitate human readability. All floating-point numbers are represented in scientific notation with up to eight significant digits. All complex numbers are represented in scientific notation as well, following the scheme: $a + ib$, where a and b are real number and i is a solution of the equation $x^2 = -1$.

BESA Connectivity uses the BESA generic file format v1.1 (see chapter 14.3 for more details) which can be directly exported to BESA Connectivity from BESA Research version 7.0 and higher. The generic file can easily be created manually if any other MEG/EEG analysis software is intended to be used with BESA Connectivity.

14.1. The BESA Time-Frequency File Format (*.tfc)

The header line contains the following data descriptors (14 descriptors displayed in **bold**, the values shown are only examples and comments are in *italic*):

1. **VersionNumber=__v_5.1**: *Version number of the current tfc file format.*

2. **DataType**= TIME_FREQUENCY_AMP: *Data type contained in the file. It reflects the options selected in the Select Display Type selection group (see chapter 10.4) for the visualization of the result once the Time-Frequency analysis has been performed:*

   - TIME_FREQUENCY_TSE_AMP: temporal-spectral evolution combined with amplitude.

   - TIME_FREQUENCY_TSE_POW: temporal-spectral evolution combined with power.

   - TIME_FREQUENCY_ABS_AMP: absolute value combined with amplitude.

   - TIME_FREQUENCY_ABS_POW: absolute value combined with power.

3. **ConditionName**=s: *Condition name. Usually indicated by experiment. E.g. "high-" or " low intensity".*

4. **NumberTrials**=250: *Number of trials.*

5. **NumberTimeSamples**=25: *Number of time samples.*

6. **TimeStartInMS**=-100.0: *Start time in [ms].*

7. **IntervalInMS**=25.0: *Interval length in [ms].*

8. **NumberFrequencies**=24: *Number of frequency bins.*

9. **FreqStartInHz**=4.0: *Starting frequency in [Hz].*

10. **FreqIntervalInHz**=2.0: *Frequency interval in [Hz] (only relevant for complex demodulation).*

11. **NumberChannels**=127: *Number of channels in the data set.*

12. **StatisticsCorrection**=Off: *Statistics correction flag. Currently always Off.*

13. **EvokedSignalSubtraction**=Off: *Flag to signal evoked signal subtraction (On if evoked signal is subtracted, Off otherwise). Currently always Off.*

14. **Frequencies**=4.00;4.47;4.98;…: *The frequencies used (only used for wavelets and multitapers).*

The second row of the header contains the labels of the channels. Their labeling can be chosen freely provided only letters and number are used and the amount of characters per entry does not exceed eight (e.g. E1 E2 ... for electrodes).

The remaining lines contain **NumberChannels** blocks starting from the first channel. Each block is separated from the next one by an empty line. Each block contains **NumberFrequencies**-rows and **NumberTimeSamples**-columns. The values for each time-frequency entry in the blocks are floating point numbers and should be separated by a tab.

14.2. The BESA Single Trial Time-Frequency File Format (*.tfcs)

The file is created without a header.

The start of each trial export is indicated by the text "Trial" followed by the trial number. The Trial statement also separates trials in the exported file. Every time-frequency matrix (block) is preceded by the channel number, and the Channel statement separates blocks. The time-frequency data points are reported as complex numbers. Each block is organized in a table where columns represent time points (increasing from left to right) and rows represent frequencies (increasing from bottom to top). Columns are separated by tabulators.

14.3. The BESA Generic File Format v1.1 (*.generic)

The BESA generic dataset consists of:

- The header file (*.generic)
- The electrode/source definition file(*.elp for electrodes– see 14.4 or *.bsa for sources – see 14.5)
- Data file (*.dat – see 14.6)

The first line **must** consist of the text: "*BESA Generic Data v1.1*" (without the inverted commas). Previous versions are not supported.

Subsequent lines must contain the following parameters, in any order (note that the parameters are case insensitive). They contain the following data descriptors (descriptors displayed in **bold**, the values shown are only examples and comments are in *italic*):

nChannels = 11	*The number of channels*
sRate = 125.000	*The sampling rate (samples/sec)*
nSamples = 141918	*The total number of time samples in the data.*
format = float	Currently only *float is supported*.
file = binarydata.dat	*The data file name, without path information. See 14.6 for more information*
prestimulus = 400.000	*Prestimulus interval in milliseconds*
epochs = 218	*This specifies the number of equally sized epochs in the data.*
baselineStart = -350.000	*Start of baseline relative to the trigger onset for each epoch in original dataset. The value should be given in milliseconds.*
baselineEnd = 0.000	*End of baseline relative to the trigger onset for each epoch in the original dataset. The value should be given in milliseconds.*

epochLength = 1200.000	*Length of epoch. Each epoch is indicated by the trigger position in the original dataset. The value should be given in milliseconds.*
Padding = 2000.000	*Information concerning extra data values that surround the epoch to provide padding for wavelets, expressed in milliseconds. If exported from BESA Research, the default value is 2000 ms.*
ConditionName = name	*Name of condition*
channelUnits= Cz μV	*A pair consisting of Channel/Source name and unit that was used for this Channel/Source (Volts for channels, Amperemeters for sources, with appropriate scaling indicator: e.g. μV). The pair is separated by a space. The number of channeUnits entries has to be equal to nChannels*

14.4. The BESA Channel Definition File Format (*.elp)

Each line of the channel definition file contains a label, an identifier, and 2D coordinates in angles. The format is: **Identifier Label Theta-coordinate Phi-coordinate**.

Identifiers can be:

- **EEG** - scalp electrode (use also instead of SCP).

- **POL** - polygraphic channel (use also instead of PGR).

- **ICR** - intracranial electrode.

- **MEG** - MEG sensor.

- **REF** - reference electrode. This can only occur once.

Labels should have at most 8 characters and be constituted only by letters and numbers, but can otherwise be chosen freely. Note though that the corresponding *.generic files (see 14.3) have to use the same convention for the label naming.

Coordinates are represented as floating point numbers in [deg] in the Head coordinate system. This coordinate system is defined by reference points on the head known as fiducials. The reference points are normally the nasion (NAS), the left preauricular point (LPA), and the right preauricular point (RPA). The x axis is defined by the line joining LPA and RPA, positive towards RPA. The y axis is defined by the line through NAS that is perpendicular to the x axis (positive towards NAS). The z axis is perpendicular to the x and y axes and goes up out of the upper part of the head (e.g. Cz). The Theta-coordinate (azimuth) is zero at the z axis, 90 deg at the x axis and -90 deg at the negative x axis. The Phi-coordinate instead goes from [-90 deg, 90 deg] from the negative y axis to the positive y axis for positive theta (i.e. for the right-hand side of the scalp), while it goes from [90 deg, -90 deg] from the negative y axis to the positive y axis for negative theta (i.e. for the left hand side of the scalp).

14.5. The BESA Solution File Format (*.bsa)

The file contains the position and orientation of dipoles/sources.

The first line of the file contains a version identifier **BSA_1.04.19990715**.

The second line of the file if the header, identifying the content of each column:

- **Type:** defines the type of the respective source. Type can assume the values with the corresponding visualization in the 3D window:

SngDip	single dipole source	
RegSrc	regional source	
RegSrcOri	oriented regional source	
RegSrcBFVS	virtual Beamformer regional source	
Ring	ring object	

- **x-loc**, **y-loc**, **z-loc:** the position of the dipole/source in unit sphere Cartesian coordinates.

- **x-ori**, **y-ori**, **z-ori**: the unit vector orientation of the dipole/source.

- **color:** defines the color of the respective object in the 3D visualization. The RGB values (ranging from 0 to 255) can be retrieved with the following calculation:

    Red = color % 256

    Green = (color / 256) % 256

    Blue = (color / 65536) % 256

    The reverse operation to get the color (code) from RGB values can be formulated as:

    color = Red * 256 * 256 + Green * 256 + Blue;

- **state**

- **size:** size of visualized 3D object (default value: 4.50).

This coordinate system is defined by a sphere with unit dimensions, which is fitted to the coordinates of sensors on the head. In the absence of co-registration information with individual MRI data, the axes are defined by reference points on the head known as fiducials. The reference points are normally the nasion (NAS), the left preauricular point (LPA), and the right preauricular point (RPA). The direction of the x axis is defined by the line joining LPA and RPA, positive towards RPA. The direction of the y axis is defined by the line through NAS that is perpendicular to the x axis (positive towards NAS). The z axis is perpendicular to the x and y axes, and goes up out of the upper part of the head (e.g. Cz). On average, the center of the unit sphere is about 4 cm above the origin of the Head coordinate system.

14.6. The BESA Binary Data Format (*.dat)

File containing data associated with generic dataset. Data is written to a floating point binary matrix with the extension ".**dat**". The matrix has the dimension: *number of samples × number of channels*. The information about number of samples and number of channels is retrieved from the header file (see 14.3). The epochs are written continuously one after the other including the padding interval.

14.7. The BESA ERP / ERF ASCII Vectorized File Format (*.avr)

The first of two header lines contains the following data descriptors (7 descriptors, the values shown are only examples):

1. **Npts=** 200*: number of sampled points in each channel.*

2. **TSB=** -500*: time sweep begin [ms]. Time of first data point relative to zero of epoch.*

3. **DI=** 5*: digitization or sampling interval [ms].*

4. **SB=** 1*: default scaling bins/nAm in file.*

5. **SC=** 200*: default scaling calibration.*

6. **Nchan=** 27: *number of channels.*

7. **SegmentName=** 60dB *: an optional label describing the data.*

The second line of the header contains the labels for each channel separated by a blank space.

Each of the subsequent **Nchan** lines of the file contains floating point values for all **Npts** time points.

14.8. The BESA Connectivity File Format (*.conn)

The file contains connectivity data. The header line contains the following data descriptors (descriptors displayed in **bold**, the values shown are only examples and comments are in *italic*):

VersionNumber = 1.0	*Version of file format standard*	
DataType = Coherence	*Connectivity analysis method*	
DecompositionType = Complex Demodulation		
	Decomposition type used during time-frequency analysis	
ConditionName = Cond1	*The name of the condition*	
NumberTrials = 218	*The number of trials used during analysis*	
NumberTimeSamples = 25	*The number of time samples*	
TimeStartInMS = -350.0000	*The starting time position – the first available time point in milliseconds*	
IntervalInMS = 50.0000	*The time interval expressed in milliseconds*	
NumberFrequencies = 59	*The number of frequencies*	
FreqStartInHz = 2.0000	*The starting frequency – the first available frequency in Hertz*	
FreqIntervalInHz = 1.0000	*The frequency interval expressed in Hertz (only relevant for complex demodulation)*	
Frequencies=4.00;4.47;4.98;…:	*The frequencies used (only used for wavelets and multitapers)*	
NumberChannels = 11	*The number of channels*	

The second row of the header contains the labels of the channels / sources.

The remaining lines contain connectivity data. Data is divided into blocks (2D tables). The number of tables is equal to **NumberChannels** to the power of 2 since every channel is compared with all other channels (including itself, but here all connectivity values are equal to 1). Each block is separated from the next one by an empty line. Each block contains **NumberFrequencies**-rows and **NumberTimeSamples**-columns. The values for each time-frequency entry in the blocks are floating point numbers and are separated by a tab.

15. References

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