NeuroPycon: A free Python toolbox for fast multi-modal and reproducible brain connectivity pipelines

David Meunier[1*], Annalisa Pascarella[2*], Dmitrii Altukhov[3], Mainak Jas[4], Etienne Combrisson[1], Tarek Lajnef[5], Daphné Bertrand-Dubois[5], Vanessa Hadid[5], Golnoush Alamian[5], Jordan Alves[6], Fanny Barlaam[7], Anne-Lise Saive[5], Arthur Dehgan[5], Karim Jerbi[5,8]

Affiliations:

[1] Aix Marseille Univ, CNRS, INT, Inst Neurosci Timone, Marseille, France
[2] Institute for Applied Mathematics Mauro Picone, National Research Council, Roma, Italy
[3] National Research University Higher School of Economics, Centre for Cognition and Decision Making, Moscow, Russia
[4] Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Charlestown, MA
[5] Computational and Cognitive Neuroscience Laboratory (CoCo Lab) , Psychology Department, University of Montreal, Montreal, QC, Canada
[6] Aarhus University, Denmark
[7] Institut TransMedTech de Montréal, QC, Canada
[8] MEG Center, University of Montreal, QC, Canada

* equal contribution

Abstract

Recent years have witnessed a massive push towards reproducible research in neuroscience. Unfortunately, this endeavor is often challenged by the large diversity of tools used, project-specific custom code and the difficulty to track all user-defined parameters. NeuroPycon is an open-source multi-modal brain data analysis toolkit which provides Python-based template pipelines for advanced multi-thread processing of MEG, EEG, functional and anatomical MRI data, with a focus on connectivity and graph theoretical analyses. Importantly, it provides shareable parameter files to facilitate replication of all analysis steps. NeuroPycon is based on the NiPype framework which facilitates data analyses by wrapping many commonly-used neuroimaging software tools into a common Python environment. In other words, rather than being a brain imaging software with is own implementation of standard algorithms for brain signal processing, NeuroPycon seamlessly integrates existing packages (coded in python, Matlab or other languages) into a unified python framework. Importantly, thanks to the multi-threaded processing and computational efficiency afforded by NiPype, NeuroPycon provides an easy option for fast parallel processing, which critical when handling large sets of multi-dimensional brain data. Moreover, its flexible design allows users to easily configure analysis pipelines by connecting distinct nodes to each other. Each node can be a Python-wrapped module, a user-defined function or a well-established tool (e.g. MNE-Python for MEG analysis, Radatools for graph theoretical metrics, etc.). Last but not least, the ability to use NeuroPycon parameter files to fully describe any pipeline is an important feature for reproducibility, as they can be shared and used for easy replication by others. The current implementation of NeuroPycon contains two complementary packages: The first, called *ephypype*, includes pipelines for electrophysiology analysis and a command-line interface for on the fly pipeline creation. Current implementations allow for MEG/EEG data import, pre-processing and cleaning by automatic removal of ocular and cardiac artefacts, in addition to sensor or source-level connectivity analyses. The second package, called *graphpype,* is designed to investigate functional connectivity via a wide range of graph-theoretical metrics, including modular partitions. The present article describes the philosophy, architecture, and functionalities of the toolkit and provides illustrative examples through interactive notebooks. NeuroPycon is available for download via github (https://github.com/neuropycon) and the two principal packages are documented online (https://neuropycon.github.io/ephypype/index.html, and https://neuropycon.github.io/graphpype/index.html). Future developments include fusion of multi-modal data (eg. MEG and fMRI or intracranial EEG and fMRI). We hope that the release of NeuroPycon will attract many users and new contributors, and facilitate the efforts of our community towards open source tool sharing and development, as well as scientific reproducibility.

Keywords

Magnetoencephalography (MEG), electroencephalography (EEG), electrophysiology, MRI, functional connectivity, graph theory, multi-modality, python, MNE, source reconstruction, brain networks, nipype, brain imaging, reproducible science, pipelines

1. Introduction

Recent years have witnessed a massive push towards reproducible experiments in neuroscience. Some of the leading projects include OpenfMRI (now OpenNeuro, Poldrack & Gorgolewski, 2017), allowing researchers worldwide to test hypothesis on a massive cohort, NeuroSynth (Yarkoni et al., 2011) a brain mapping framework to automatically conduct large-scale, high-quality neuroimaging meta-analyses or the development of the Nipype framework (Gorgolewski et al., 2011), a very useful tool developed initially for the MRI field and which facilitates data analysis by wrapping commonly-used neuroimaging software into a common Python framework. Nipype was originally designed to provide rapid comparative development of algorithms and to reduce the learning curve necessary to use different packages. Nipype's original intention was to provide a concrete tool to respond to some criticisms of the neuroscientific community as a whole for the lack of reproducibility of experiments, in particular when it comes to attempts to reproduce research on a wider scale both in basic research and clinical trials (Gilmore et al, 2017). One step forward in this direction is also to provide the source code used for a given analysis pipeline, not to mention sharing data in standard formats (Poline et al, 2012; Gorgolewski et al, 2015).

The release of Nipype was a major step forward allowing researchers to wrap virtually all fMRI and MRI software into a common framework, where all analysis steps and, critically, all the parameter settings are tractable and easily accessible. Nipype is for instance used to wrap, into a common pipeline, some of the most frequently used MRI research tools, ranging from SPM (Penny et al., 2011), FSL (Smith et al., 2004) and AFNI in functional MRI (Cox 1996), ANTS (Avants et al., 2009), Freesurfer in structural MRI (Dale et al., 1999), Camino (Cook et al., 2006) and Mrtrix in diffusion imaging (Tournier et al., 2012). The advantages of having a single unified framework are particularly obvious, especially when it comes to scaling up and/or reproducing neuroimaging research.
Interestingly, while encouraging progress has been achieved with such strategies in the fMRI field, similar initiatives for the fields of MEG and EEG data analysis are still in their early days. Yet, most MEG and EEG analysis consists of a sequence of analysis steps that involve several software packages and often, multiple programming languages and environments. An MEG analysis that starts from raw data and ends up with group-level statistics may, for example, require the use of *Freesurfer* for cortical segmentation, *MNE* for preprocessing and source estimation, *radatools* for connectivity metrics and *Visbrain*[1] for 3D visualizations. Thus, most of the processing is conducted using multiple heterogeneous software and in-house or custom tools leading to workflows that are hard or even impossible to reproduce. Furthermore, with the exponential increase in data dimensionality and complexity, conducting state-of-the-art brain network analyses using MEG and EEG is becoming an increasingly challenging and time-consuming endeavor. Streamlining all the steps of MEG/EEG data analyses into a unified, flexible and fast environment could greatly benefit large-scale MEG/EEG research and enhance reproducibility in this field.

Here, we describe NeuroPycon, a free and open-source Python package, which allows for efficient parallel processing of full MEG and EEG analysis pipelines which can integrate many available tools and custom functions into a single workflow. The proposed package uses the Nipype engine framework to develop shareable processing pipelines that keep track of all analyses steps and parameter settings. Although initially developed with MEG and EEG in mind, NeuroPycon allows for multi-modal brain data analysis thanks to the flexibility and modularity it inherits form Nipype.

[1] visbrain.org

This paper describes the architecture, philosophy and rationale behind NeuroPycon. The functionalities of *ephypype* and *graphpype* are illustrated by describing how NeuroPycon is used to wrap existing tools that analyse electrophysiological data (e.g. MNE-python, Gramfort et al., 2013) and that perform graph-theoretical analysis (radatools[2]). Of course, wrapping many other software tools or packages within NeuroPycon workflows is possible.

2. Pipeline design, data structure and analysis workflow

2.1 Overview

Description: NeuroPycon provides computationally efficient and reusable workflows for advanced MEG/EEG and multi-modal functional connectivity analysis pipelines. Because NeuroPycon is powered by the Nipype engine (Gorgolewski, et al, 2015) it benefits from many of its strengths and shares the same philosophy. The NeuroPycon workflows expand and promote the use of the Nipype framework to the MEG/EEG research community. NeuroPycon links different software packages through nodes connected in acyclic graphs. (Fig 1A) The output of one pipeline can be provided as inputs to another pipeline. Furthermore, NeuroPycon is designed to process subjects in parallel on many cores or machines; If the processing is interrupted due to an error, NeuroPycon will only recompute the nodes which do not have a cache (Fig 1B). The current release of the NeuroPycon project includes two distinct packages: The *ephypype* package includes pipelines for electrophysiological data analysis and a command-line interface for on the-fly pipeline creation. A second one called *graphpype,* is designed to investigate functional connectivity via a wide range of graph-theoretical metrics, including modular partitions.

Software download, free license and documentation: NeuroPycon is freely available to the research community as open source code via GitHub (https://github.com/neuropycon). A basic user manual and some example scripts can be found in the tutorial webpages: https://neuropycon.github.io/ephypype/index.html, https://neuropycon.github.io/graphpype/index.html.
The documentation is built using sphinx[3], a tool developed for python documentation that uses reStructuredText as markup language; an extension of sphinx, sphinx gallery[4], was used to create an examples gallery by structuring the example scripts to automatically generate HTML pages.
Graphpype and Ephypype are provided under the permissive BSD 3-Clause license, which allows the use, modification and re-usability, under the condition of propagating the license.

Unit tests, continuous integration and python coding standards: A lot of effort has been put into providing high-quality code that is kept intact through tests and continuous integration (CI). Most of the functions and classes of the package are covered by unit-tests, including tests on several kinds of data (Nifti MRI files, FIF MEG files, numpy arrays and Radatools files). All the code also conforms to a standard Python coding convention known as PEP8 which facilitates readability and consistency with software packages in the Python scientific ecosystem.

[2] http://deim.urv.cat/~sergio.gomez/radatools.php
[3] http://www.sphinx-doc.org/en/master/
[4] https://sphinx-gallery.github.io/index.html

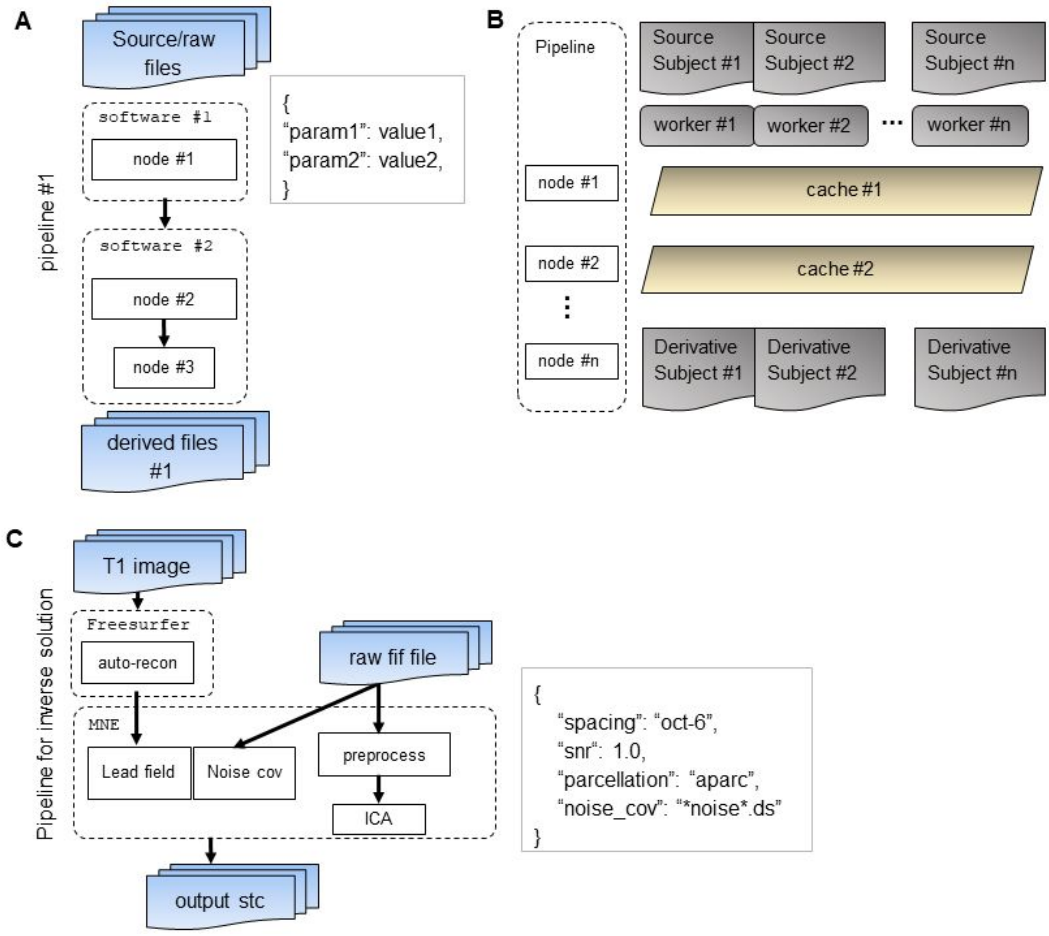

Figure 1. A. NeuroPycon offers reusable NiPype workflows for MEG/EEG processing and functional connectivity pipelines. It interfaces different software packages by linking nodes connected in acyclic graphs. The output of one pipeline can be provided as inputs to another pipeline **B.** The NiPype engine allows NeuroPycon to process subjects in parallel. If the processing interrupts due to an error, NeuroPycon will recompute only those nodes which do not have a cache. **C.** Illustrative example of a NeuroPycon pipeline for processing raw MEG data and anatomical T1 MRI to produce an inverse solution.

2.2 NeuroPycon Packages

Ephypype: Ephypype is a package designed to analyze electrophysiological data using the Nipype engine. In particular, it focuses on MEG/EEG data and exploits many functions from the MNE-Python package (Gramfort et al. 2013), as well as a range of standard Python libraries such as Numpy[5] and Scipy[6] . Current implementations allow for MEG/EEG data import, pre-processing and cleaning by automatic removal of eyes and heart related artefacts, source reconstruction, as well as sensors or source-level spectral connectivity analysis and power spectral density computation. The ephypype package features a convenient and sophisticated command-line interface which is designed to make the best use of UNIX shell capabilities and NiPype framework for parallel processing of MEG/EEG datasets. In brief, the command-line interface utilizes pattern-matching capabilities of UNIX shell to select files we want to process from the nested folder structure of a dataset and then dynamically

[5] http://www.numpy.org/
[6] https://www.scipy.org/

creates a processing pipeline combining computational nodes defined in the ephypype package. In addition to being convenient, the command-line interface enables users with little programming background to easily create complex analysis pipelines that process hundreds of subjects, through a single command line.

Graphpype : The *graphpype* package, includes pipelines for graph theoretical analysis of neuroimaging data. Computations are mostly based on radatools, a set of freely distributed applications to analyze Complex Networks (http://deim.urv.cat/~sergio.gomez/radatools.php). Although it was initially mainly used on fMRI data, the *graphpype* package can be used for the computation of graph metrics for multiple modalities (MEG, EEG, fMRI etc). This package has been developed to address the needs of functional connectivity studies that would benefit from the computation of a wide graph-theoretical metrics, including modular partitions.

It is important to keep in mind that NeuroPycon pipelines can be used in a stand-alone mode but that they can also be combined within building blocks to form a larger workflow (Fig 2), where the input of one pipeline comes from the outputs of another. As an example, the inverse solution pipeline could be used as a stand-alone pipeline to perform source localization or its output could be used as input to a new pipeline that performs all-to-all connectivity and graph analysis on the set of reconstructed time series. In principle, each pipeline, is defined by connecting different nodes to one another, with each node being either a user-defined function or a python-wrapped external routine (e.g. MNE-python modules or radatools functions).

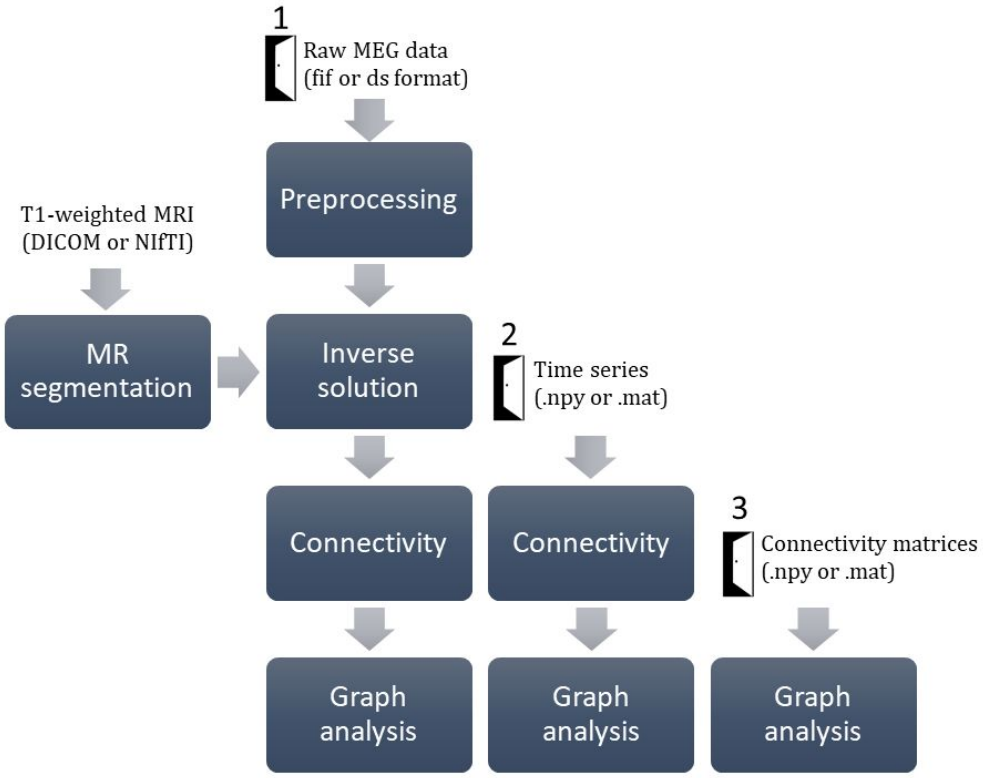

Figure 2. Three doorways to NeuroPycon: Illustrative pipelines showcasing three distinct uses depending on the type of input data: Full MEG preprocessing, source estimation, connectivity and graph analysis starting from raw MEG data (door 1), only connectivity and graph analysis from time series (door 2) or only graph analysis from connectivity matrices computed elsewhere (door 3).

2.3 Data import

Electrophysiology data that one would want to analyze with NeuroPycon can be in various forms and distinct data formats. NeuroPycon is designed to be able to import (1) raw MEG/EEG data, (2) time series and (3) connectivity matrices. Figure 2 showcases three different pipeline options depending on these three distinct import levels (doors). The formats required for the first option are primarily Elekta (.fif) or CTF (.ds), but import from BrainVision data (.vhdr/.eeg extension) or ascii format, is also available. Import options 2 and 3 (i.e. either time series or connectivity matrices) support .mat (Matlab) and .npy (Numpy) formats. Data import for the second option (Fig 2, door 2) expects data structure of sensor or source-level time-series, allowing to read in data that may have already been analyzed by other software (e.g. BrainStorm (Tadel et al., 2011) or FieldTrip (Oostenveld et al., 2011)), and then connectivity data (possibly followed by graph metrics) are calculated using appropriate pipeline of NeuroPycon. The user can alternatively directly import connectivity matrices (Fig 2, door 3) computed elsewhere and solely use NeuroPycon to compute graph-theoretical metrics.

3. Presentation of five main pipelines

We now introduce the 5 main processing pipelines that are currently proposed in the NeuroPycon software suite. These can be seen as pipeline templates or building blocks. Each pipeline may be used either independently (using its own data grabber node) or in combination. A data grabber node allows the users to define flexible search patterns, which can be parameterized with user defined inputs (such as subject ID, session, etc.). It is also possible to reassemble the preprocessing steps as required. For example, we can directly feed the pre-processed sensor-space signals to the spectral connectivity pipeline (i.e. skipping the source estimation step).
In the online documentation, we provide some key example scripting which allow the user to interactively run implementations. All example scripts are based on one of a sample MEG dataset from the OMEGA project (https://www.mcgill.ca/bic/resources/omega). The original data format follows BIDS specification (K. J. Gorgolewski et al., 2016; Niso et al., 2018). The NeuroPycon parameters settings (e.g. for the connectivity method, the source reconstruction algorithm, etc.), which are necessary for each example script, are defined in a *json* file that can simply be downloaded from the documentation page. JSON format has the advantage that it can be edited very easily and, in addition, it is also very structured and maps directly to data structures in Python and other programming languages.

3.1 Data preprocessing pipeline (ephypype) [Pipeline #1]

The preprocessing pipeline performs filtering, it optionally down-samples the MEG raw data and runs an ICA algorithm for automatic removal of eye and heart related artifacts. The implementation is primarily based on the MNE-Python functions that decompose the MEG/EEG signal by applying the FastICA algorithm (Hyvarinen, 1999.). An HTML report is automatically generated and can be used to correct and/or fine-tune the correction in each subject. The inclusion and exclusion of more ICA components could be performed either interactively in a Jupyter notebook (or IPython), or by re-running the same preprocessing pipeline with different option parameters. Figure 3 shows the ICA decomposition obtained by running the pipeline on the sample dataset. The corresponding example script can be download as Jupyter notebook in the documentation website
https://neuropycon.github.io/ephypype/auto_examples/plot_preprocessing.html

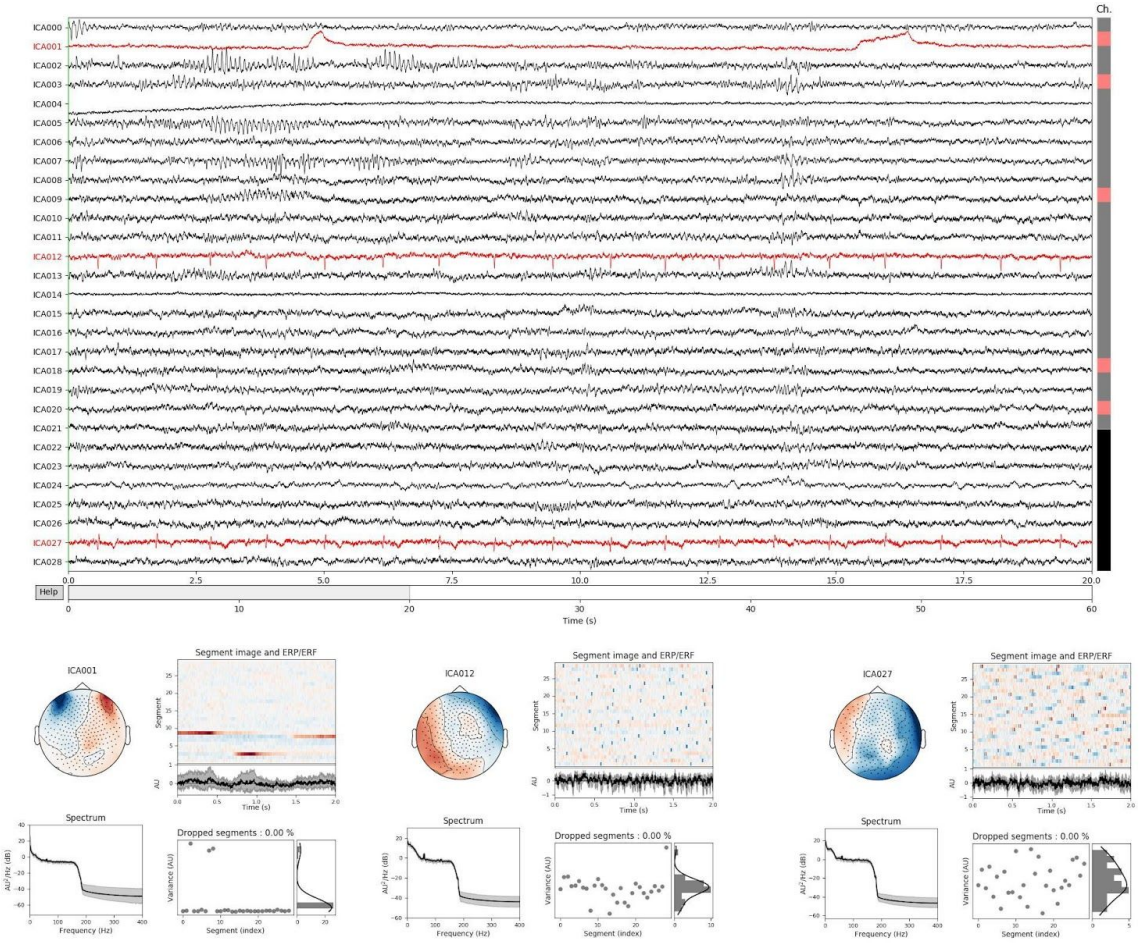

Figure 3. The preprocessing pipeline runs an ICA algorithm for an automatic removal of ocular and cardiac artifacts. Here we show the time series, topomap and some properties (e.g. power spectrum) of ICA components obtained by running the example script provided in the documentation website (https://neuropycon.github.io/ephypype/auto_examples/plot_preprocessing.html) on the raw MEG sample dataset.

3.2 Source reconstruction pipeline (ephypype) [Pipeline #2]

The inverse solution pipeline performs the source reconstruction step, i.e. the estimation of the spatio-temporal distribution of the active neural sources starting either from the raw/epoched data specified by the user, or from the output of the preprocessing pipeline (the cleaned raw data). The output of the source reconstruction pipeline will be the matrix of the estimated sources time series that could alternatively also be used as input of the spectral connectivity pipeline to study functional connectivity.

The nodes of the inverse solution pipeline wrap the MNE python functions performing the source reconstruction steps, i.e. the computation of the lead field matrix and the noise covariance matrix. These matrices are the main ingredients to solve the MEG/EEG inverse problem by one of the three

inverse methods currently available in the ephypype package: MNE (Hämäläinen et al., 1993, Lin et al., 2006), dSPM (Dale et al., 2000), sLORETA (Pascual-Marqui 2002).

In particular, the lead field matrix is computed by the Boundary Element Method (BEM) (Gramfort et al., 2010) provided in MNE-Python. We use a single layer, i.e. the brain layer for MEG data, while for EEG datasets a three compartment BEM (scalp, skull and brain layers) is chosen.

To use this pipeline, a user would either need a template MRI or the individual anatomical data. In the latter case, the segmentation of the anatomical MRI has to be performed by Freesurfer in order to generate surfaces and parcellations of the structural data. The anatomical segmented data will be used in the pipeline to extract the BEM surfaces and to create the source space. By default it is expected that the current dipoles are situated on the cortical surface, but it is also possible to set a mixed source space constituted by the cortical surface and the volumes of some user-selected subcortical regions, as amygdala, thalamus, cerebellum, etc. Finally, the segmented MRI data are also used to perform the coregistration step between the MEG/EEG and MRI coordinate system. This is the only manual step one has to perform before using the source reconstruction pipeline and can be performed by *mne_analyze* process of MNE-C[7] or an MNE-Python Graphical User Interface (GUI). In the future, automatic co-registration will become available when this feature becomes a robust function in MNE python. A template MRI, just like the one provided by the Freesurfer software, could be used if the individual anatomical data are not available. Figure 5 shows the results obtained by running the inverse solution pipeline on the sample dataset. The script used to generate this figure can be downloaded as Jupyter notebook from the documentation website https://neuropycon.github.io/ephypype/auto_examples/plot_inverse.html.

3.3 Spectral power pipeline (ephypype) [Pipeline #3]

The power pipeline computes the power spectral density (PSD) in either sensor or source space. It also computes the mean PSD for each frequency band specified by the user. The latter can choose to compute the PSD by Welch's method or multitapers. The input of the pipeline can be either raw/epoched data specified by the user or simply the output of another pipeline, e.g. the cleaned raw data from the preprocessing pipeline or the estimated source time series from the source reconstruction pipeline. Figure 4.A shows the results obtained by running the power pipeline on the sample dataset. The script used to generate this figure can be downloaded as Jupyter notebook in the documentation website https://neuropycon.github.io/ephypype/auto_examples/plot_power.html.

3.4 Spectral connectivity pipeline (ephypype) [Pipeline #4]

The spectral connectivity pipeline computes the connectivity matrices in the frequency domain. The current implementation is based on the spectral connectivity computation in MNE, and can be computed on time series in numpy format (in either sensor or source space), or even from Matlab format after conversion using the *scipy* package. All the frequency-domain coupling measures available in MNE-Python are directly accessible through this pipeline (e.g. Coherence, Imaginary Coherence, Phase Locking Value, Phase-Lag Index). Figure 4.B shows the results obtained by running the

[7] https://www.mne-cpp.org/

connectivity pipeline on the sample dataset. The script used to generate this figure can be downloaded as Jupyter notebook in the documentation website https://neuropycon.github.io/ephypype/auto_examples/plot_connectivity.html.

3.5 Graph-theoretical analyses pipeline (graphpype) [Pipeline #5]

Once a connectivity matrix has been obtained, the most common step to compute graph theoretical (GT) analyses involves a form of thresholding to "sparsify" the matrix and keep only the most relevant edges. One classical thresholding option is the use of a density-based thresholding (e.g. only keep edges with the 5% highest connectivity values)(Rubinov and Sporno, 2010, Bassett and Lynall, 2013). Another possibility is fixed value thresholding (e.g. all coherence values lower than 0.5 are put to zero). For signed metrics, such as Pearson correlation, the sign will be taken into account at this step.
The computation of standard GT metrics (includes weighted and signed versions) primarily relies on wrapping one of the most efficient modularity optimisation software tools called Radatools (http://deim.urv.cat/~sergio.gomez/radatools.php). Radatools offers the possibility to compute GT properties for several classes of networks (binary/weighted, unsigned/signed) and allows the computation of most global (e.g. mean path length, global efficiency, clustering coefficient, assortativity, as well as their weighted counterparts) and nodal metrics (e.g. degree, betweenness centrality, etc.). Radatools is mostly known for highly efficient modularity optimisation possibilities. In addition to being amongst the few tools to offer modular partition on weighted signed networks, it also offers the choice of several algorithms ranging from lower quality with a fast execution algorithm (Newman et al, 2006) to exhaustive searches (high quality but time consuming). Interestingly, it is possible to define a sequence of these algorithms to combine the advantages of these algorithms. Some specific metric computation, mostly related to node roles (participation coefficient and within-module normalized degree, see Guimera et al , 2005) have also been specifically coded and are part of Radatools' standard modular decomposition pipeline. The script used to generate this figure can be downloaded as Jupyter notebook on https://neuropycon.github.io/graphpype/_downloads/c7d8056e39a517111ff88942ed0cc51b/plot_inv_ts_to_graph.ipynb

4 Postprocessing connectivity and graph-theoretical metrics

4.1 Gathering results

The output of a NeuroPycon pipeline results in a specific directory architecture, where all the results of each iteration are sorted by nodes. A post-processing step allows us to gather results in a handy way for subsequent statistical analyses and further result representation and visualization. For the graph-metrics computed via graphpype, the most straightforward way is to gather graph-based results in a dataframe, for further processing outside in Excel (TM) or R. The postprocessing tools allowing for generic post-processing steps can be found in the "gather" directory of ephypype and graphpype.

4.2 Statistical analyses

Within NeuroPycon, it is possible to conduct group-level statistics in several ways. Any statistical analysis functions available through tools wrapped by NeuroPycon are obviously available for use in

NeuroPycon pipelines (e.g. all statistical analyses provided by MNE python). Additionally, the graphpype package offers several modules to compute statistics on connectivity and graph data. These include assessing statistical significance by computing parametric tests (paired and unpaired t-test, binomial , Mann-Whitney, etc.) between groups of matrices or vectors. Of course, with the increasing number of dimensions we also need to address the multiple comparison problem. It is possible to compute several levels of significance accounting for multiple comparisons, tailored for connectivity and graph metrics: For instance, a False Positive metric (1/#of tests) has been suggested to be an acceptable threshold when hundreds or even thousands of nodes are at play (Bassett and Lynall, 2013). Other implemented tools include False Discovery Rate (Benjamini and Hochberg) and Bonferroni correction. An alternative approach is of course to implement non-parametric permutation testing over mean connectivity matrices. The time-consuming steps of permutation computing here critically benefit from the parallelization available in NeuroPycon (via Nipype engine). A reasonable number of computations (e.g. 1000) can be achieved in a relatively short time (a few hours for the full network pipeline computation, including modular decomposition, assuming typical network sizes of ~100 nodes). The gather_permuts module of graphpype package in the "gather" directories offer a range of functions allowing for computation of the corresponding p-values.

4.3 Visualization tools (graphpype, visbrain)

Numerous tools can be used to visualize the results and data computed by or manipulated within NeuroPycon. One option is to use visualization tools currently used within MNE python, such as pysurfer[8] and mayavi[9]. An example of visualization provided by MNE python is shown in Figure 3 containing the output of preprocessing pipeline, i.e. the topographies and time series of the ICA components. Another more recent option to visualize the results is to use visbrain (http://visbrain.org), which is the solution we recommend. Below we describe visualization procedures for different data using visbrain (pysurfer and mayavi descriptions can be found elsewhere).

4.3.1 Overview of visbrain

The visbrain package is a python based open-source software dedicated to the visualization of neuroscientific data (Combrisson et al., 2019). It is built on top of PyQt[10] and VisPy (Campagnola et al., 2015), a high-performance visualization library that leverages the Graphics Processing Units (GPU). Consequently, Visbrain efficiently handles the visualization of large and complex 2D/3D datasets. The different modules that form visbrain provide also an intuitive GUI that allows users with no or little programming knowledge to easily use its core functionalities.

4.3.2 Visualization of sensor-space data

Figure 4 uses the source object (SourceObj) class of visbrain that allows to represent MEG sensors and assign additional data values to each one of them. One available option is to represent the input data (i) through a color bar and (ii) a marker radius proportional to its amplitude. Figure 4.A depicts the output of the spectral power pipeline (see section 3.3), where the PSD was computed in sensor-space over three different frequency bands (theta, alpha and beta). Here we show the results on alpha band.

[8] http://pysurfer.github.io/
[9] https://docs.enthought.com/mayavi/mayavi/
[10] https://wiki.python.org/moin/PyQt

By contrast, Figure 4.B is generated using the source object class together with the visbrain's connectivity object (ConnectObj) used to draw connectivity lines between nodes. Here we show the results of the connectivity pipeline, i.e. the sensor-level connectivity matrix obtained by computing the coherence among MEG sensors in alpha band.

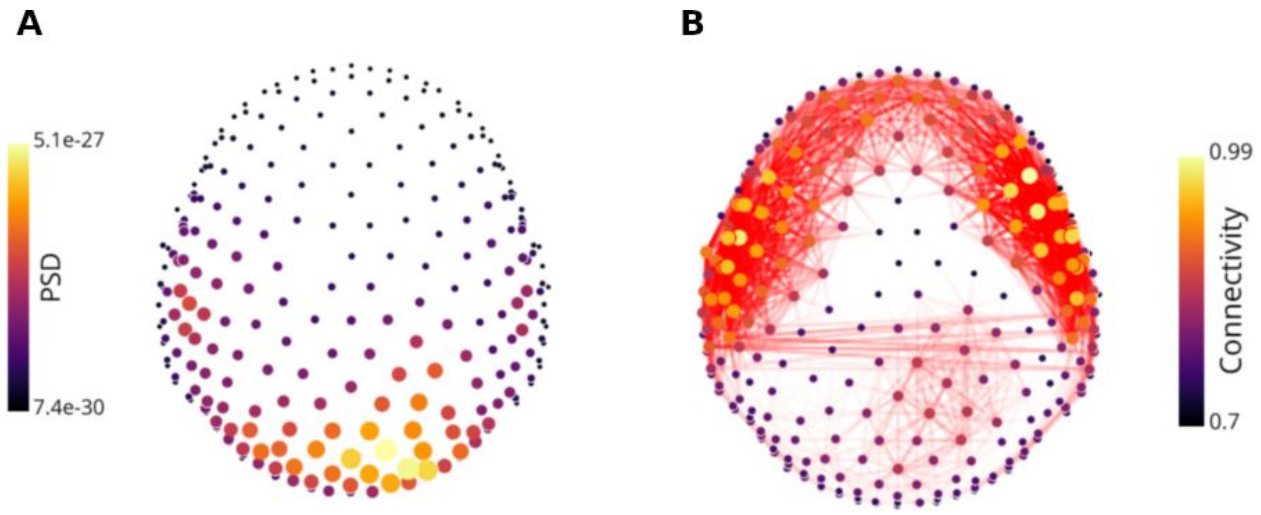

Figure 4. (A) The spectral power pipeline computes single-trial and mean PSD for each selected frequency band. Here we show illustrative results of computing alpha power running the NeuroPycon power pipeline template on the sample MEG data. The size and color of each sensor vary with the alpha power value. The script used to generate this figure is provided in the documentation website: https://neuropycon.github.io/ephypype/auto_examples/plot_power.html. **(B)** The connectivity pipeline performs connectivity analysis in sensor or source space. Here we show illustrative results obtained using the connectivity pipeline to compute coherence between MEG sensors in alpha band. Connectivity edges are colored according to the strength of the connection, while the node size and color depend on the number of connections per node. These results are obtained by running the examples script in the documentation webpage:
(https://neuropycon.github.io/ephypype/auto_examples/plot_connectivity.html,

4.3.3 Visualization of source space data

To achieve 3D brain visualizations, the output data resulting from the different pipelines (power, connectivity, inverse solution and graph) can be interfaced with the *Brain* module of Visbrain (http://visbrain.org/brain.html) that can be used to visualize the estimated source activity, connectivity results, PSD on source space, and graph analysis results. Illustrative figures that can be produced by the *Brain* module are shown in Figures 5 and 6. Figure 5 shows the output of the inverse solution pipeline, i.e. the reconstructed neural activity in each ROI of a user defined atlas (Desikan-Killiany Atlas) at a given time point. Figure 6 shows a graph obtained for alpha band after computing functional connectivity between all pairs of regions starting from the ROI estimated time series computed by the inverse solution pipeline. The graph is obtained after thresholding at 5% highest coherence values.

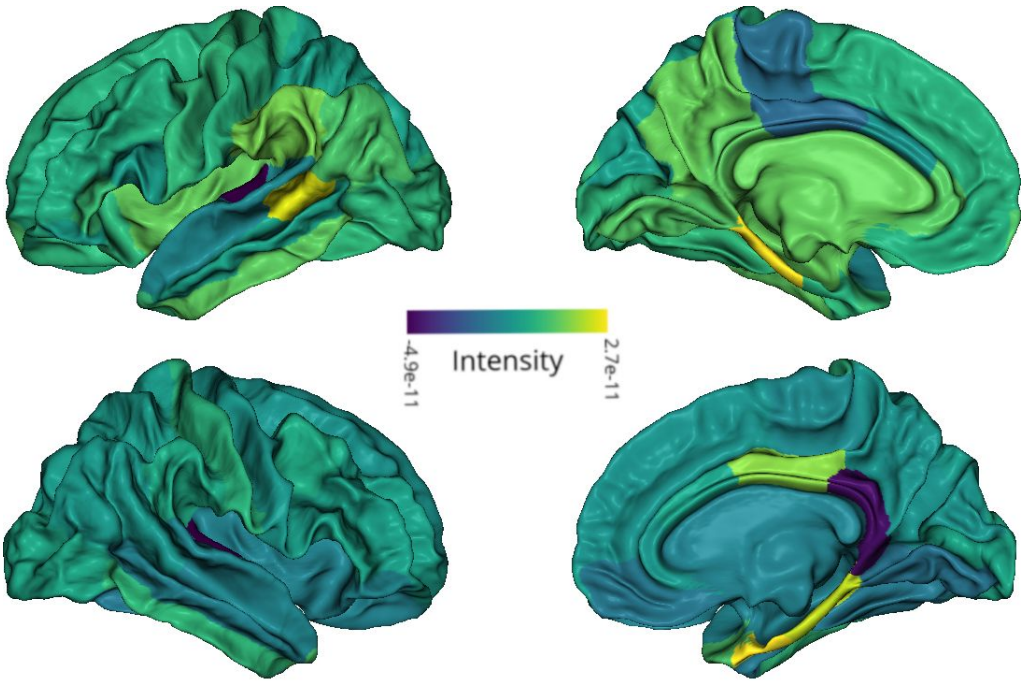

Figure 5: Here we show the output of the inverse solution pipeline, i.e. the reconstructed neural activity at a given time point, in ROIs from a user defined atlas (Desikan-Killiany Atlas). The results are obtained by running the example script in the documentation webpage (https://neuropycon.github.io/ephypype/auto_examples/plot_inverse.html).

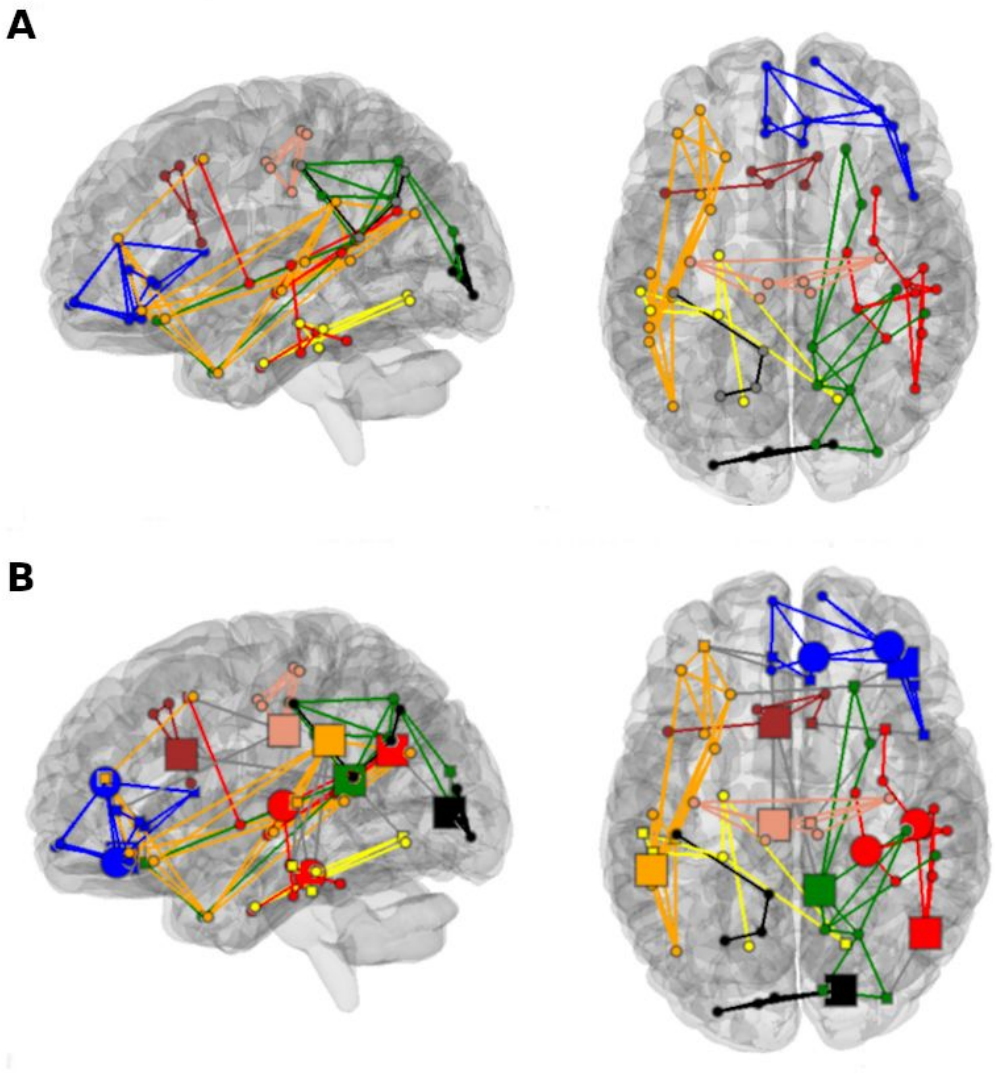

Figure 6: Representation of a graph obtained from resting-state MEG data for alpha band (left part = seen from left; right part = seen from top) after computing functional connectivity between all pairs of regions (Figure 5). The graph is obtained by retaining the 5% highest coherence values. The results of modular decomposition are displayed with the same color for the edges between two nodes in the same module, and in grey for edges between nodes belonging to different modules. Two representations of the same results are displayed: with modules (panel A), and with modules and node roles definition of Meunier *et al.* (2009) as the shape (square = connector) and size (bigger shape = hub) of the nodes (panel B). In the lower part, inter-modular edges are represented in grey. From a given size in decreasing order, modules are all represented in black.

5 NeuroPycon Command Line Interface (Neuropycon_cli)

As previously mentioned, the construction of neuropycon data processing pipelines is done in a python script specifying the affinity and arguments of the processing nodes and the source of input

data. Such scripts can be distributed, shared and reused later, which facilitates reproducibility and results sharing. However, this can arguably sometimes be tedious if we want to construct and run simple pipelines quickly. To address this problem, we've provided neuropycon with a command line interface which is organized into a separate NeuroPycon_cli package (https://github.com/neuropycon/neuropycon_cli). At the moment the command line interface wraps some of the functionality of the ephypype package only but will be expanded in the future.

The command line interface is aimed at building the processing workflows on the fly leveraging the UNIX shell wildcards mechanism for flexible input specification (Fig. 8). It wraps the processing nodes of ephypype together with their options and arguments exposing to the end user a subcommand for each node. Specifying these subcommands in order, the user in effect chooses the desired processing steps which are assembled together into the nipype workflow at the command invocation. More precisely, *Neuropycon_cli* provides the terminal command *neuropycon* which is followed by the sequence of subcommands corresponding to the desired processing nodes with specified options and arguments for each. This chain of subcommands to *neuropycon* determines the specific form of the processing pipeline we want to apply to our data.

In practice, the use of the neuropycon terminal command looks like the example shown in Figure 7, where a sequence of commands segments the data into 1 second epochs, converts them to numpy format and computes the default connectivity measure in the 8-12 Hz frequency band.

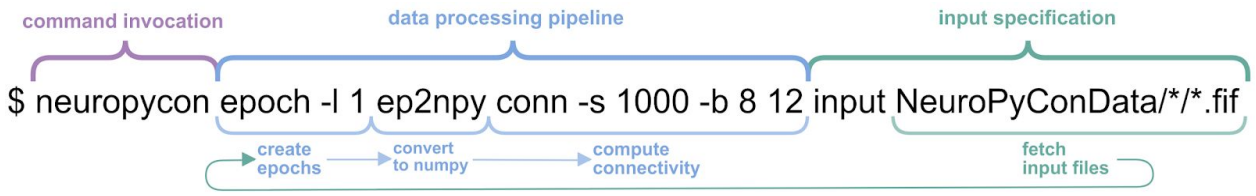

Figure 7: Example of the CLI command computing connectivity metrics on a group of files. This command grabs all the .fif files in the two-level nested folder structure, creates one-second epochs from them, converts the epochs to numpy arrays format, performs a default connectivity metrics calculation -between 8-12 Hz- on the converted data and saves the results.

The command can be split into three functional blocks. First goes the command name *neuropycon.* Then it is followed by a chain of processing subcommand for each of which we specify options and arguments unique to each processing node. In the example depicted in Figure 7, the supplied processing subcommands are *epoch, ep2npy* and *conn,* which perform data epoching, conversion to numpy format and spectral connectivity computations. The last block is always the input specification. Although the input node really goes first in the stream of data processing, putting the input specification to the rightmost position of the composite command allows us to specify an arbitrary number of input files to the pipeline which is beneficial when working with wildcards matching.

The input block always starts with the *input* subcommand and is followed by a list of file paths we are applying the processing pipeline to. In the example shown in Figure 7, the list of files is specified using the UNIX wildcards matching mechanism and can be spelled out as 'Go to each subfolders of the NeuroPyConData folder and take all the '.fif' files contained in it' (here we presume that there's only

one level of nesting in NeuroPyConData folders structure, i.e. files are organized according to the following scheme: NeuroPyConData/<SubjectName>/<subject_data.fif>).

Integration with the UNIX wildcards pattern matching is one of the biggest strengths of the supplied CLI since it allows for flexible and concise fetching of files in the nested folders hierarchy given that these folders are organized in a regular and well-defined fashion, which is often the case for electrophysiological datasets. A more detailed explanation of the command line interface operation principles and examples can be found on the documentation webpage (https://neuropycon.github.io/neuropycon_cli/index.html).

6. Strengths of NeuroPycon and advantages of its Nipype-based framework

NeuroPycon is based on the Nipype engine and fully adheres to its architecture and global software philosophy. In this section, we will here briefly summarize the rationale and key components of Nipype, and then outline the strengths and added-value that NeuroPycon brings to the community through this architecture.

6.1 Nipype in a nut-shell

Nipype is an open-source, community driven, python-based software package that enables interactions between existing neuroimaging software in a common framework and uniform semantics (Gorgolewski, et al, 2015). The design of workflows using Nipype allows for intuitive and tractable implementations of even quite complex processing pipelines. To appreciate concrete advantages that NiPype confers to NeuroPycon, it is useful to briefly overview Nipype's three main components: **(I)** *Interfaces* to external tools that provide a unified way for setting inputs, executing and retrieving outputs. The goal of Interfaces is to provide a uniform mechanism for accessing analysis tool from neuroimaging software packages (e.g. Freesurfer, FSL, SPM, etc). **(II)** A *workflow engine* allows to create analysis pipelines by connecting inputs and outputs of interfaces as a directed acyclic graph (DAG). In order to be used in a workflow the Interfaces have to be encapsulated in node objects that execute the underlying Interface in their own uniquely named directories, thus providing a mechanism to isolate and track the outputs resulting from the Interface execution. Nodes can be connected together within a workflow: by connecting the outputs of some node to input of another one, the user implicitly specifies dependencies. Furthermore, workflow can itself be a node of the workflow graph. Nodes provides also an easy way to implement function defined by the user. **(III)** A *plug-in* executes a workflow either locally or in a distributed processing environment. No changes are needed to the workflow to switch between these execution modes. The user simply calls the workflow run function with a different plug-in and its arguments.

6.2 NeuroPycon's main assets and advantages

(a) Multiprocessing: the implementation of multiprocessing is very easy, and can be either made for multi-processing on a same machine with multiple cores (Multiproc plugin) or a cluster with multiple machines in parallel (q-sub/ipython plugin). In addition to substantially speeding up the computations for a planned analysis, the ability to easily launch multiprocessing computations also encourages users to rapidly test and compare different analyses options (e.g. various preprocessing strategies, or different source localisation methods, or even optimizing parameter selection, such as matrix thresholding or graph construction, or frequency band choices, etc.). Easy definition of

multiprocessing is also an advantage over Matlab-based scripting when it comes to handling big datasets. While multiprocessing exists in Matlab its implementation requires specific coding, whereas in NeuroPycon the exact same code is used for both sequential and parallel processing, except for one line that specifies the option.

(b) Caching: Thanks to the use of Nipype, NeuroPycon stores intermediate files, and tests if the source code of each node has been modified. Hence, if a part of the pipeline is modified, only the modified parts will be recomputed. This has a significant impact on the speed of the analyses.

(c) Report: Each node of the workflow creates a subfolder (under the workflow directory) called _report containing a text file (report.rst) with all relevant node information, i.e. the name of the node, the input and output parameters, the computational time to execute the node.

(d) Access to numerous python-wrappers for image analysis: It is not uncommon in the literature to see that graph analysis of EEG or MEG data is achieved by combining distinct independent software tools (e.g exporting connectivity data from one of the MEG/EEG analysis toolboxes available to a functional connectivity software such as the Brain Connectivity Toolbox (BCT) (Rubinov and Sporns, 2010)). By contrast, NeuroPycon provides a unified framework with seamless interactions between tools allowing to compute graph properties on MEG/EEG data. It should be noted that the general « wrapping » concept makes it possible to expand NeuroPycon's workflows to include software combinations other than those currently proposed.

(e) Multimodal analysis: NeuroPycon also provide an advantageous framework for multimodal analyses (e.g. combining electrophysiological and neuroimaging data). Indeed, in addition to its own pipelines, NeuroPycon can benefit from the interfaces already made available for neuroimaging analysis via Nipype. For example, since the latter wraps most of the functions available in Freesurfer (Dale et al., 1999), MRI segmentation and parcellation, and subsequent MEG source space processing can all be completed with a single reproducible, light-weight and shareable NeuroPycon pipeline.

(f) Open-source, readability and reproducibility: Because it is written in python, the NeuroPycon code is compact and highly readable. In addition, python is free (which is not the case of other high-level scientific languages such as Matlab). As a result, NeuroPycon is a freely accessible tool that can be readily used by students and researchers across the globe without the need to purchase commercial software. Being open source, NeuroPycon promotes pipeline sharing and enhances reproducibility in an open-science mind set.

7 Discussion

NeuroPycon is an open-source analysis kit which provides python pipelines for advanced multi-thread processing of multi-modal brain data, with a focus on connectivity and graph analyses. NeuroPycon is based on the Nipype engine and inherits thereby its philosophy of wrapping multiple established processing software tools into a common data analysis framework. The use of NeuroPycon allows for portability, simplified code exchange between researchers, and reproducibility of the results by sharing analysis scripts.

Additionally, conducting graph-theoretical analysis in NeuroPycon allows for comparing and merging graph results from different imaging modalities and different toolboxes (which might be implemented in different programming languages).

NeuroPycon is designed for users with a reasonable knowledge of the software tools that it can wrap. but who would like to benefit from automatic implementation (ready-to-use pipelines) of features that would be otherwise more complex (or impossible) to implement. Parallel processing and caching are features that are particularly powerful and convenient when it comes to large data sets. NeuroPycon is also most valuable for users who want to process multimodal data (e.g. MEG and fMRI) in a unified

framework. Last but not least, students and researchers will hopefully find NeuroPycon to be a convenient framework to easily share MEG/EEG analysis pipelines.

In terms of ongoing and future development, we plan-among other things- to make NeuroPycon BIDS-compatible so that the inputs are BIDS datasets and the intermediate outputs comply to the upcoming BIDS derivative specification. One of the current shortcomings is the limited softwares/packages that have so far been wrapped (primarily MNE python, radatools in addition to the tools already accessible through Nipype). Hopefully, the community of NeuroPycon users and developers will continue to expand, and thus increase its functionalities and range of pipelines available.

Acknowledgements

AP was supported by a CNR short-term mobility grant. KJ was supported by funding from the Canada Research Chairs program and a Discovery Grant (RGPIN-2015-04854) from the Natural Sciences and Engineering Research Council of Canada, a New Investigators Award from the Fonds de Recherche du Québec - Nature et Technologies (2018-NC-206005) and an IVADO-Apogée fundamental research project grant.

References

Achard, S., Salvador, R., Whitcher, B., Suckling, J., & Bullmore, E. D. (2006). A resilient, low-frequency, small-world human brain functional network with highly connected association cortical hubs. *Journal of Neuroscience*, *26*(1), 63-72.

Avants, B. B., Tustison, N., & Song, G. (2009). Advanced normalization tools (ANTS). *Insight j*, *2*, 1-35.

Bassett, D. S., & Lynall, M. E. (2013). Network methods to characterize brain structure and function. *Cognitive Neurosciences: The Biology of the Mind*, 1-27.

Benjamini, Y., & Hochberg, Y. (2000). On the adaptive control of the false discovery rate in multiple testing with independent statistics. *Journal of educational and Behavioral Statistics*, *25*(1), 60-83.

Bullmore E, Sporns O (2009) Complex brain networks: graph theoretical analysis of structural and functional systems. *Nat Rev Neurosci* 10:186-198.

Campagnola, L., Klein, A., Larson, E., Rossant, C., and Rougier, N. P. (2015). VisPy: Harnessing The GPU For Fast, High-Level Visualization. in *Proceedings of the 14th Python in Science Conference* Available at: https://hal.inria.fr/hal-01208191/ [Accessed May 23, 2017].

Combrisson, E., Vallat, R., O'Reilly, C., Jas, M., Pascarella, A., Saive, A. L., ... & Ruby, P. (2019). Visbrain: A multi-purpose GPU-accelerated open-source suite for multimodal brain data visualization. *Frontiers in Neuroinformatics*, *13*.

Cook, P. A., Bai, Y., Nedjati-Gilani, S. K. K. S., Seunarine, K. K., Hall, M. G., Parker, G. J., & Alexander, D. C. (2006, May). Camino: open-source diffusion-MRI reconstruction and processing. In *14th scientific meeting of the international society for magnetic resonance in medicine* (Vol. 2759, p. 2759). Seattle WA, USA.

Cox, R. W. (1996). AFNI: software for analysis and visualization of functional magnetic resonance

neuroimages. *Computers and Biomedical research*, *29*(3), 162-173.

Dale, A. M., Fischl, B., & Sereno, M. I. (1999). Cortical surface-based analysis. I. Segmentation and surface reconstruction. *NeuroImage*, *9*(2), 179–194.

Dale, A. M., Liu, A. K., Fischl, B. R., Buckner, R. L., Belliveau, J. W., Lewine, J. D., & Halgren, E. (2000). Dynamic statistical parametric mapping: combining fMRI and MEG for high-resolution imaging of cortical activity. *Neuron*, *26*(1), 55-67.

Gilmore RO, Diaz MT, Wyble BA, Yarkoni T. Progress Toward Openness, Transparency, and Reproducibility in Cognitive Neuroscience. *Annals of the New York Academy of Sciences*. 2017;1396(1):5-18. doi:10.1111/nyas.13325.

Glasser, M. F., Coalson, T. S., Robinson, E. C., Hacker, C. D., Harwell, J., Yacoub, E., ... & Smith, S. M. (2016). A multi-modal parcellation of human cerebral cortex. *Nature*, *536*(7615), 171-178.

Gorgolewski K, Burns CD, Madison C, Clark D, Halchenko YO, Waskom ML, Ghosh SS (2011) Nipype: a flexible, lightweight and extensible neuroimaging data processing framework in Python. *Front. Neuroinform.* **5**:13. doi: 10.3389/fninf.2011.00013

Gorgolewski, K. J., Varoquaux, G., Rivera, G., Schwarz, Y., Ghosh, S. S., Maumet, C., ... & Yarkoni, T. (2015). NeuroVault. org: a web-based repository for collecting and sharing unthresholded statistical maps of the human brain. *Frontiers in neuroinformatics*, *9*.

Gorgolewski, K. J., Auer, T., Calhoun, V. D., Craddock, R. C., Das, S., Duff, E. P., … Poldrack, R. A. (2016). The brain imaging data structure, a format for organizing and describing outputs of neuroimaging experiments. *Scientific Data*, *3*, 160044.

Gramfort, A., Papadopoulo, T., Olivi, E., & Clerc, M. (2010). OpenMEEG: opensource software for quasistatic bioelectromagnetics. *Biomedical engineering online*, *9*(1), 45.

Gramfort A, Luessi M, Larson E, Engemann DA, Strohmeier D, Brodbeck C, Goj R, Jas M, Brooks T, Parkkonen L and Hämäläinen M (2013) MEG and EEG data analysis with MNE-Python. *Front. Neurosci*. **7**:267. doi: 10.3389/fnins.2013.00267

Guimera, R., Mossa, S., Turtschi, A., & Amaral, L. N. (2005). The worldwide air transportation network: Anomalous centrality, community structure, and cities' global roles. *Proceedings of the National Academy of Sciences*, *102*(22), 7794-7799.

Hämäläinen, M., Hari, R., Ilmoniemi, R. J., Knuutila, J., & Lounasmaa, O. V. (1993). Magnetoencephalography—theory, instrumentation, and applications to noninvasive studies of the working human brain. *Reviews of modern Physics*, *65*(2), 413.

Hyvarinen, A. (n.d.). Fast ICA for noisy data using Gaussian moments. In *ISCAS'99. Proceedings of the 1999 IEEE International Symposium on Circuits and Systems VLSI (Cat. No.99CH36349)*. https://doi.org/10.1109/iscas.1999.777510

Yarkoni, T., Poldrack, R. A., Nichols, T. E., Van Essen, D. C., & Wager, T. D. (2011). Large-scale automated synthesis of human functional neuroimaging data. *Nature methods*, *8*(8), 665.

Lin, F. H., Witzel, T., Ahlfors, S. P., Stufflebeam, S. M., Belliveau, J. W., & Hämäläinen, M. S. (2006).

Assessing and improving the spatial accuracy in MEG source localization by depth-weighted minimum-norm estimates. *Neuroimage*, *31*(1), 160-171.

Meunier, D., Achard, S., Morcom, A., & Bullmore, E. (2009). Age-related changes in modular organization of human brain functional networks. *Neuroimage*, *44*(3), 715-723.

Meunier, D., Fonlupt, P., Saive, A. L., Plailly, J., Ravel, N., & Royet, J. P. (2014). Modular structure of functional networks in olfactory memory. *NeuroImage*, *95*, 264-275.

Newman, M. E. (2004). Fast algorithm for detecting community structure in networks. *Physical review E*, *69*(6), 066133.

Niso, G., Gorgolewski, K. J., Bock, E., Brooks, T. L., Flandin, G., Gramfort, A., … Baillet, S. (2018). MEG-BIDS, the brain imaging data structure extended to magnetoencephalography. *Scientific Data*, *5*, 180110.

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.-M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, *2011*, 156869.

Pascual-Marqui, R. D. (2002). Standardized low-resolution brain electromagnetic tomography (sLORETA): technical details. *Methods Find Exp Clin Pharmacol*, *24*(Suppl D), 5-12.

Penny, W. D., Friston, K. J., Ashburner, J. T., Kiebel, S. J., & Nichols, T. E. (Eds.). (2011). *Statistical parametric mapping: the analysis of functional brain images*. Elsevier.

Poline, J.-B., Breeze, J. L., Ghosh, S., Gorgolewski, K., Halchenko, Y. O., Hanke, M., et al. (2012). Data sharing in neuroimaging research. *Front. Neuroinform*. 6:9. doi: 10.3389/fninf.2012.00009

Poldrack, R. A., & Gorgolewski, K. J. (2017). OpenfMRI: Open sharing of task fMRI data. *NeuroImage*, *144*(Pt B), 259–261.

Rubinov, M., & Sporns, O. (2010). Complex network measures of brain connectivity: uses and interpretations. *Neuroimage*, *52*(3), 1059-1069.

Smith, S. M., Jenkinson, M., Woolrich, M. W., Beckmann, C. F., Behrens, T. E., Johansen-Berg, H., ... & Niazy, R. K. (2004). Advances in functional and structural MR image analysis and implementation as FSL. *Neuroimage*, *23*, S208-S219.

Tadel, F., Baillet, S., Mosher, J. C., Pantazis, D., & Leahy, R. M. (2011). Brainstorm: a user-friendly application for MEG/EEG analysis. *Computational Intelligence and Neuroscience*, *2011*, 879716.

Tournier, J. D., Calamante, F., & Connelly, A. (2012). MRtrix: diffusion tractography in crossing fiber regions. *International journal of imaging systems and technology*, *22*(1), 53-66.