BIDS-iEEG: an extension to the brain imaging data structure (BIDS) specification for human intracranial electrophysiology

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Abstract

Intracranial electroencephalography (iEEG) data offer a unique combination of high spatial and temporal resolution measures of the living human brain. However, data collection is limited to highly specialized clinical environments. To improve internal (re)use and external sharing of these unique data, we present a structure for storing and sharing iEEG data: BIDS-iEEG, an extension of the Brain Imaging Data Structure (BIDS) specification, along with freely available examples and a bids-starter-kit. BIDS is a framework for organizing and documenting data and metadata with the aim to make datasets more transparent and reusable and to improve reproducibility of research. It is a community-driven specification with an inclusive decision-making process. As an *extension* of the BIDS specification, BIDS-iEEG facilitates integration with other modalities such as fMRI, MEG, and EEG. As the BIDS-iEEG extension has received input from many iEEG researchers, it provides a common ground for data transfer within labs, between labs, and in open-data repositories. It will facilitate reproducible analyses across datasets, experiments, and recording sites, allowing scientists to answer more complex questions about the human brain. Finally, the cross-modal nature of BIDS will enable efficient consolidation of data from multiple sites for addressing questions about generalized brain function.

Keywords: intracranial-Electroencephalography, iEEG, Brain Imaging Data Structure (BIDS), BIDS-iEEG, standardization, datasets, formatting, archive

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Introduction

Human intracranial electroencephalography (iEEG) data are recorded with electrodes placed on or implanted in the human brain (Bancaud & Talairach, 1965; Penfield & Perot, 1963). Electrodes can be placed during epilepsy monitoring, tumor surgery, or for deep brain stimulation (DBS). Given the high spatiotemporal resolution compared to non-invasive measurements, iEEG data give a unique perspective on human brain function (Crone, Korzeniewska, & Franaszczuk, 2011; Jerbi et al., 2009; Johnson & Knight, 2015; Miller, Zanos, Fetz, den Nijs, & Ojemann, 2009; Ritaccio et al., 2014) and may serve as a link between cognitive neuroscience and systems-level electrophysiology work (Chang, 2015, p.; Mukamel & Fried, 2012; Parvizi & Kastner, 2018).

iEEG monitoring is performed for clinical purposes at specialized medical centers, and typically takes multiple days to weeks. During the time that patients are monitored, they can voluntarily participate in scientific experiments in which iEEG data are recorded typically during well-controlled tasks. iEEG data that are recorded for research purposes are relatively rare compared to EEG or MRI data that can be collected non-invasively from healthy participants. In addition, medical centers that record iEEG often see a limited number of cases per year for which the electrode placement depends on clinical presentation. Due to these scarce opportunities in data collection, researchers may have to wait several years before completing a study. This makes it important to have a consistent way of archiving and documenting iEEG data within a lab. In addition, because of its spatiotemporal properties and the high cost of acquisition, it is important that this unique data that are contributed by rare patients is made most-useful and reusable to the scientific community.

Currently, iEEG datasets are stored in myriad formats and structures, with each lab adopting their own unique methods for data storage and metadata organization. There are many existing file formats in which raw electrophysiology data can be stored, and these do not generally allow one to store the many other pieces of information needed to understand, analyze, and reproduce scientific results. This includes the precise position of electrodes, the way channels are referenced prior to digitization, simultaneously recorded physiology data, the timing of task events, details on the presented stimuli, or anatomical imaging data from the same subjects. There is a clear need for a community standard to better describe all aspects of iEEG data and its experimental context.

The Brain Imaging Data Structure (BIDS) is a community-driven specification for structuring MRI and MEG data and metadata (Gorgolewski et al., 2016; Niso et al., 2018). BIDS comprises a standardised structure for the folder and file naming, for the choice of data formats, and for the representation of metadata. Its goal is to make it easier to exchange data across organizations, and to share and build tools for more effective data analyses. BIDS is a modality-agnostic specification, relying on community-driven processes to extend the original structure (written for MRI) to new modalities. As an example of this, the MEG community recently finished the process to extend BIDS for this type of data (Niso et al., 2018), and the EEG community has recently finished the preparation of the respective extension as well (Pernet et al., n.d.).

This paper extends the BIDS specification to iEEG data. BIDS-iEEG is a community effort, driven by a diverse group of people working with intracranial data from across the world. The BIDS-iEEG structure has several practical advantages. Because all metadata are stored in text files and adhere to a standard structure (.tsv and .json), it is both human- and machine-readable. Because the BIDS specification is not tied to one specific data modality, the BIDS structure allows for storing multi-modal data from complex experimental setups. Finally, because the process of defining BIDS-iEEG was inclusive and involved a large working group with many different stakeholders from the community, it has been designed to broadly cover the iEEG use-cases for research purposes. Adoption of BIDS-iEEG will minimize the burden of data curation, facilitate multimodal data integration, and make intracranial data more valuable to future researchers working in the specific lab and to the wider scientific community.

Results

The BIDS-iEEG specification is the result of about one year of community discussion, and the draft has evolved over time as new voices in the iEEG community have shared their insights. Here we describe the global structure and some highlights of the current BIDS-iEEG specification, which are documented in full detail in the online specification. Note that the BIDS specification is *versioned*, and it may be modified and extended further in the future. In addition to the specification, we provide online examples to help the community store data acquired during a variety of recordings and tasks and templates to create metadata in a starter kit.

The general BIDS specification is designed to modularize data such that it can gracefully handle multiple modalities and recording devices that belong to a single dataset. In addition, metadata fields that are not specific to the iEEG extension are shared with the broader BIDS specification (including EEG and MEG extensions), including e.g. events and participant descriptions. In this section, we focus on the BIDS-iEEG components that are particularly important for iEEG data and that *extend* the BIDS specification. As BIDS is currently primarily concerned with representing raw data (though see bids.neuroimaging.io/ for proposals to extend BIDS to derivatives of raw data), we focus on the metadata needed to describe unprocessed iEEG data to the extent where the data can be analyzed, interpreted, and published in a paper.

iEEG-BIDS

```
visual_task/
├── sub-01
│   ├── anat
│   │   ├── sub-01_T1w.nii.gz
│   │   └── sub-01_T1w.json
│   └── ieeg
│       ├── sub-01_task-visual_run-01_ieeg.eeg
│       ├── sub-01_task-visual_run-01_ieeg.vmrk
│       ├── sub-01_task-visual_run-01_ieeg.vhdr
│       ├── sub-01_task-visual_run-01_ieeg.json
│       ├── sub-01_task-visual_run-01_events.tsv
│       ├── sub-01_task-visual_run-01_channels.tsv
│       ├── sub-01_electrodes.tsv
│       ├── sub-01_coordsystem.json
│       └── sub-01_photo.jpg
│
├── sub-02
│
├── stimuli
│   └── stim01.png
├── participants.tsv
├── dataset_description.json
└── README
```

Figure 1: iEEG-BIDS folder structure. Example of one iEEG dataset stored in BIDS. In this case, the data are stored in the BrainVision format along with a photo showing electrode placement and an anatomical MRI of the same subject. The coordinate space of the electrodes is the anatomical MRI, specified in the _coordsystem.json sidecar (see Figure 2D). Optional folders and labels, such as the session folder and space- label, are mostly left out of this example. For other examples, see the BIDS examples: https://github.com/bids-standard/bids-examples

Instructions for creating a BIDS-compatible iEEG dataset

First, we briefly describe what is required to create an iEEG dataset in BIDS format. The process can be summarized by the following main steps: structure your files in the proper folder hierarchy, rename files such that they adhere to the BIDS naming specification, extract the necessary metadata from your raw data and experimental notes, and add electrode-specific information needed for localization. Below, we will describe each step in the process in more detail.

Step 1: Folder structure. At the highest level, BIDS is a specification for how to structure your files in folders, and how to name files such that one can easily infer their contents. Thus, the first step is to create the proper folder/file hierarchies. For example, the top level of a BIDS folder must contain a dataset_description.json file, a README, and a CHANGES file. In addition, there are a set of sub-folders, one per subject, that contain all data from a given subject. These must be named according to the convention “sub-<label>”. Within these folders there is an optional “session” folder (called “ses-<label>”) and finally a collection of “acquisition folders” that correspond to datasets from different modalities (such as functional imaging, EEG, and iEEG data) that corresponds to this dataset. In our example, there is a folder called "ieeg" that stores all iEEG data for the subject.

Step 2. Add raw iEEG data. Once a folder hierarchy is defined, the folders can be populated with the correct files. Here we focus on the files relevant for iEEG data. Within the "ieeg" folder, we first copy the raw iEEG data and renamed such that they adhere to the BIDS file naming scheme (e.g. "`sub-<subjectname>_ses-<sessionname>_task-<taskname>_run-<runnumber>_ieeg.<extension>`"). These data are unprocessed and can have one of several file formats (e.g., BrainVision and EDF formats are supported and NWB (Teeters et al., 2015), EEGLab (Delorme & Makeig, 2004) and MEF3 (Stead & Halford, 2016) formats are allowed). This list of file formats has been chosen to include formats that are well-documented, have known units, are readable in two major neuroscience computing languages (Matlab and Python), and could be read with open source tools in other languages such as R, Julia, Javascript, and C++.

Step 3. Add iEEG amplifier metadata. BIDS datasets should specify **all** of the metadata needed to analyze and understand a dataset, and these are all contained within text based JavaScript Object Notation (JSON, field-value) and Tab Separated Value (TSV) metadata files (Figure 2). The iEEG amplifier metadata are stored for each run in a JSON file with the same name structure as the raw data (`<raw-data-filename>_ieeg.json`) and a TSV file with amplifier metadata (`<raw-data-filename>_channels.tsv`) (Figure 2A, left). The JSON file contains the metadata that are the same for all the data in this run, such as the task name and description, the amplifier brand, and where the experiments were performed. The TSV file contains all the settings that differ between iEEG channels such as filters, sampling frequency and reference. These metadata allow for the plotting of the data from each recorded iEEG channel with the correct units on the axes (Figure 2A, right).

Step 4. Add electrode-specific metadata. In iEEG recordings, each channel in the amplifier is sampled from a specific electrode implanted in the brain (Figure 2B, left). The metadata on the type of electrodes and their coordinates is stored in a TSV file with a row for each metallic electrode contact (`_electrodes.tsv`). The names of each electrode are used in the amplifier metadata to specify the recorded channel and reference to link these two files. In order to interpret the position of each electrode, the coordinate system is defined in a JSON file (`_coordsystem.json`). The _coordsystem.json file specifies a reference image file, which can be an MRI, surface rendering, standard space (e.g., MNI) or operative photo, such that electrode positions can be displayed (Figure 2D, right). In addition, any raw data collected for the purpose of localizing electrodes is stored in a corresponding anatomy folder (called "`anat`") that lives at the same folder level as the "ieeg" folder. This can contain files like structural volume data or electrode placement photos.

Step 5. Add optional metadata. There are several optional data types that can be stored in BIDS. The way in which events, stimuli, continuous physiology data, and participant information are stored is the same as for BIDS MRI data. These optional metadata are stored within TSV and JSON files as well as any task-specific stimulation files (e.g., photos or sounds that were presented to the subject during the task, or videos of the subject and experimental setup).

Step 6. Validate the iEEG-BIDS data. In order to verify that a dataset adheres to the BIDS specification, we need to *validate* the structure, naming conventions, and information inside the dataset. The BIDS validator is a web- and command line-based tool that can validate whether a dataset is BIDS compliant. As a part of the iEEG extension to the BIDS specification, this validator has been updated to check for new conventions related to iEEG data.

To facilitate these steps, we have created a "bids-starter-kit" repository on GitHub (https://github.com/bids-standard/bids-starter-kit) with templates for all metadata files for fMRI, MEG, and iEEG data. For each file, there are two templates, one with all the required, recommended and optional fields and one with only the required fields. The bids-starter-kit wiki includes a description of how to easily edit these files in non-programming languages (online or using a text editor), with Matlab, Python, and R.

Metadata for iEEG

The steps above will ensure that a dataset adheres to the BIDS specification for iEEG and will pass the BIDS validator. This section covers several iEEG-specific information and metadata that were added in order to accommodate iEEG datasets. As in the original BIDS specification, these metadata are stored either as TSV files (`.tsv`, for tabular data) or as JSON files for "key-value" data (`.json`). These file formats have the advantage of being both human and machine-readable. A subset of metadata fields is *required* for a given dataset, while others are recommended or completely optional.

There were several new types of metadata files created, as well as additions to pre-existing metadata standards in BIDS, for the extension to iEEG data. These include developing the file content and naming for the metadata for the iEEG data files (_ieeg.json), amplifier settings for each channel (_channels.tsv), as well as the metallic electrode contacts (_electrodes.tsv) and their coordinate space with a link to a specific reference image (_coordsystem.json).

The details and composition of each metadata file were developed over the past year along with extensive input from stakeholders in the iEEG community. Below we list several topics of discussion that are particularly relevant to iEEG data.

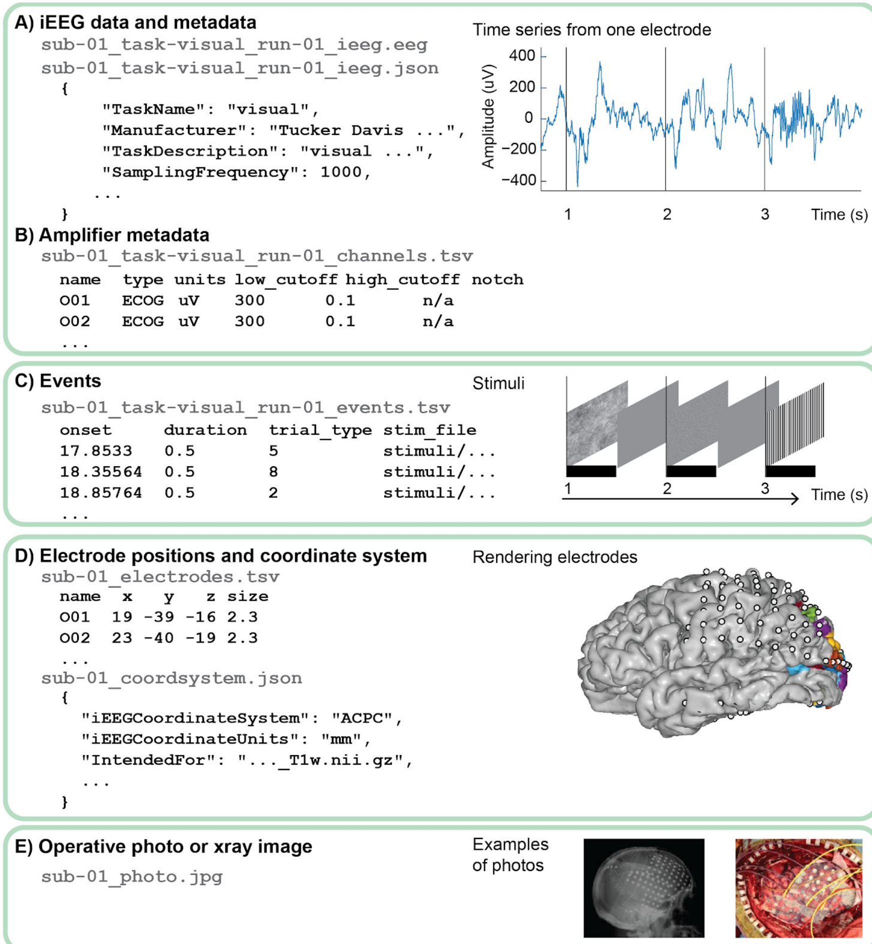

Figure 2: Pictures with data types. Extending the BIDS specification to iEEG data involved the creation of several new file types and pieces of metadata. These include the following categories. (A) Information for acquisition systems and their parameters for iEEG data. (B) Metadata about channel-specific information, such as hardware filters or electrophysiological units. (C) Events during an iEEG recording. (D) Electrode coordinates are stored in an _electrodes.tsv files and the coordinate system is stored in an _coordsystem.json file. If electrode coordinates are in 3D and are intended for a specific anatomical volume images (.nii.gz), this allows automatically making surface renderings with electrodes and displaying labels from different atlases, here shows with probabilistic maps of visual areas (Wang, Mruczek, Arcaro, & Kastner, 2015). (E) Other images that are relevant for iEEG, such as surface models and 2-D images can be stored in a systematic manner.

Electrode locations in iEEG-BIDS

A necessary component to interpret iEEG data are the electrode locations on the cortical surface or embedded in brain tissue. Electrode locations are generally obtained by integrating data from a CT, post-operative MRI, X-ray, or operative photo. Electrodes are then identified and sorted according to medical records, such as a sketch made by the neurological or neurosurgical team. There are several semi-automated software packages available that allow researchers to do this. The iEEG-BIDS structure requires that any electrode locations are paired with explicit coordinate systems and, where applicable, the path to an image that can be used to visualize the electrodes on a brain. These may be volume files (e.g., `.nii.gz`), cortical surfaces, or 2-D images of the patient's brain.

Channels vs. electrodes

Another distinction is the difference between *electrodes* (a physical object), and *channels* (a part of an acquisition system). These two terms can potentially overlap, and several definitions were discussed and added as a part of the BIDS-iEEG and BIDS-EEG specifications. Making an explicit distinction between the two is important since terminology for "electrodes" and "channels" differs between stereo EEG (sEEG), electrocorticography (ECoG), deep brain stimulation (DBS), MEG, and EEG. As such, final decisions about these definitions were made along with input from members of each of these communities. We include the final definitions for "electrode" and "channel" below.

A "channel" will be defined as "*a single analog-digital converter in the recording system that regularly samples the value of a transducer, which results in a signal being represented as a time series in the data. This can be connected to two electrodes (to measure the potential difference between them), a magnetic field or magnetic gradient sensor, temperature sensor, accelerometer, etc.*"

An "electrode" will be defined as "*a single point of contact between the acquisition system and the recording site (e.g., scalp, neural tissue, ...). Multiple electrodes can be organized as caps (for EEG), arrays, grids, leads, strips, probes, shafts, etc.*"

Electrophysiology units

As the original BIDS specification dealt primarily with data from an MRI machine, it was also necessary to create standards around the units to be used for electrophysiology data. This was done in partnership with the BIDS-EEG and -MEG communities as well. Physical units of any data in a BIDS structure are presented according to their SI unit symbol and possibly prefix symbol (e.g., mV, µV, with the µ as unicode U+00B5), now specified in the BIDS specification ("BIDS Section 15 Appendix 5: Units," 2018).

Intraoperative photos and non-traditional electrode localization

One piece of information that is particularly common in the iEEG community is intra-operative photos to assist with electrode localization. While most other cognitive neuroimaging modalities have control over the kinds of volume or surface rendering to collect along with the data, the iEEG community is constrained by medical decisions rather than scientific ones. As such, there are more diverse ways that iEEG researchers localize electrodes on the subject's brain (such as using a 2-D photo along with electrode positions in X/Y space). To accommodate this, BIDS-iEEG added several new options for localization metadata in "`_electrodes.tsv`" and "`_coordsystem.json`" files. Electrodes can be localized in multiple spaces by specifying multiple JSON files, and the `IntendedFor` field makes it straightforward to pair electrode position data with its corresponding image (2D or 3D). Finally, BIDS-iEEG explicitly allows for electrode positions to be given in 2-dimensional space in the event that anatomical data are only provided in the form of either operative photos or cortical surface photos.

Community survey of iEEG data usage

An important step in adopting community standards for data storage is deciding what *format* to use for the data itself. In choosing the data formats "officially" supported in BIDS-iEEG, the community attempted to cover as many possible iEEG data use-cases with as few unique formats as possible. To help guide this process, we conducted an informal survey of the human electrophysiology community to determine which formats were most suitable as "first class citizens" in the BIDS-iEEG specification.

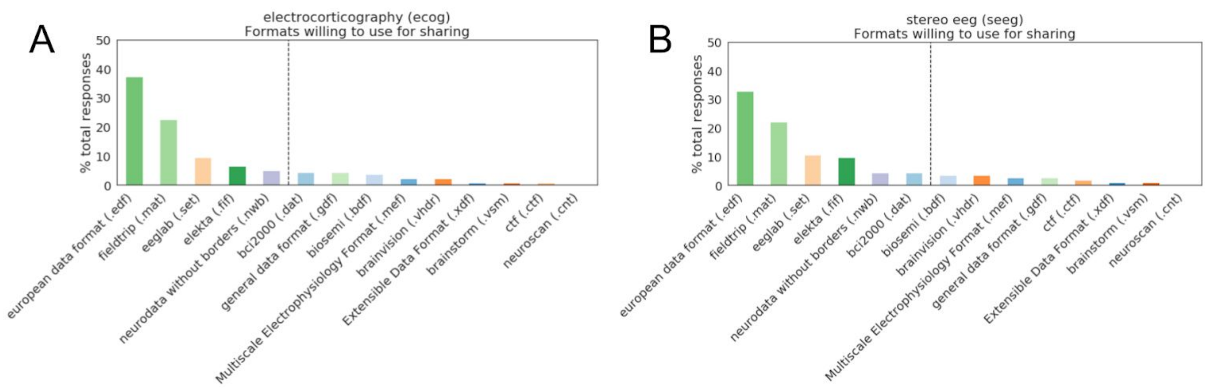

Figure 3. Distribution of data format usage in the electrocorticography community. To assist in choosing a subset of data formats to "officially" support, the BIDS-iEEG community conducted an informal survey of its community members. There were 450 total responses. Of this total, 108 reported using Electrocorticography and 86 reported using Stereo EEG data (both considered iEEG data). Pictured above is the percentage of total responses for that modality that reported using a given data format. In both cases, EDF was the most commonly-used data format. This figure originally appeared in (Holdgraf, 2018) and was modified with permission.

The BIDS-iEEG survey was sent out to a number of scientific software mailing lists (e.g., the FieldTrip, EEGlab and MNE mailing lists), academic mailing lists (e.g., departmental lists), and social media (e.g., Twitter). A description of this process, the survey, and the results was originally published in (Holdgraf, 2018). We briefly summarize the results relevant to BIDS-iEEG below.

There were 450 total responses. Of this total, 108 (24%) reported using ECoG and 86 (19.1%) reported using sEEG data (both considered iEEG data), for a total of 129 responses using iEEG data. We asked respondents to indicate which data formats they would be willing to use in order to share their data with others (both between labs and within a lab). This included formats that were not well-specified (e.g., arbitrary Matlab files). The following table summarizes the results.

Format	Total responses	Percent of responses
matlab custom files (.mat)	65	50.39%
european data format (.edf)	59	45.74%
fieldtrip (.mat)	35	27.13%
hdf5 custom files (.h5)	27	20.93%
eeglab (.set)	17	13.18%
elekta (.fif)	14	10.85%
neurodata without borders (.nwb)	8	6.20%
biosemi (.bdf)	7	5.43%
bci2000 (.dat)	7	5.43%
brainvision (.vhdr)	6	4.65%
general data format (.gdf)	6	4.65%
Multiscale Electrophysiology Format (.mef)	3	2.33%
ctf (.ctf)	2	1.55%
Extensible Data Format (.xdf)	2	1.55%
brainstorm (.vsm)	1	0.78%
neuroscan (.cnt)	0	0.00%

Table 1. Data formats participants would be willing to use to share their data (total responses: 129). This data was distributed as a part of (Holdgraf, 2018) and is displayed here with permission.

The BIDS-iEEG community selected a subset of formats to consider for adoption as “officially supported” for the specification. This subset is visualized in *Figure 3* (see methods for details on the process of selecting this subset of formats).

The results of this survey directly informed the decision of formats to be supported in the BIDS-iEEG specification. These formats are described in the section below. For more information about the BIDS survey, see its associated blog post and github repository (Holdgraf, 2018).

Data formats for iEEG

A challenge in extending the BIDS format to iEEG data was handling the diversity of data formats used in recording raw iEEG data. There are many different amplifier systems to record iEEG data and each stores data in a different raw format. BIDS requires data to be accessible by open source software tools in Python, Matlab/Octave, Javascript, Julia, R and C/C++. Moreover, the BIDS validator needs to do a rough check on the folder contents.

After pooling input from the iEEG community and collaborating with the EEG extension (see methods), the BIDS-iEEG community decided to support two classes of data formats: officially supported formats, and unofficially-supported formats.

Officially supported formats.

There are two “official” data formats for the BIDS-iEEG extensions: European Data Format (.edf) files, and BrainVision (.vhdr, .vmrk, and .eeg) data formats. These two formats are transparent and open standards and have support in a number of open languages. EDF is already a prolific format in the iEEG community (see Figure 3), and BrainVision is quickly growing in electrophysiology, including EEG, and makes up for some technical shortcomings of EDF (such as being able to store data to a higher level of numerical precision of up to 32 bits). Officially-supported formats in BIDS-iEEG will continue to be supported in the future, and will have the majority of community effort and development in creating tooling.

Unofficially supported formats.

There are three “unofficially-supported” formats. Their use is discouraged, though allowed, due to their prevalence in the iEEG community and to respect the fact that many labs may require time to shift their workflows into other data formats. Currently, the unofficially-supported formats are Neurodata Without Borders (.nwb) due to its shared goals in facilitating sharable and reproducible neurophysiology datasets, EEGLab (.set) due to its prevalent use in the iEEG community, and Multiscale Electrophysiology Format version 3 (MEF3) due to its suitability and future potential for clinical iEEG recordings and device-related applications (such as HIPAA-compliant multi-layer encryption, efficient data compression, and robustness to corruption and data stream interruptions). Efforts from the community will be made to ensure basic compatibility with these formats, and the BIDS data validator will accept them as viable formats for a BIDS data structure. However, unofficially-supported formats are not guaranteed to become supported in the future. In order to be supported, the data format has to have an openly accessible specification, it has to be possible to validate the content of the data file with the BIDS validator, which is written in JavaScript, and there have to be software readers in recent versions of at least Matlab and Python with a diverse community around the format.

Example iEEG datasets organized according to iEEG-BIDS

As a part of creating the BIDS-iEEG specification, four datasets were converted to BIDS format and added to the BIDS-examples github repository (https://github.com/bids-standard/bids-examples). These examples are meant to demonstrate how the BIDS structure maps onto different scientific use-cases. These datasets include: an auditory filtered speech experiment, a motor-movement dataset, a visual stimulus dataset, seizure sEEG recordings from a focal epilepsy of the left temporo-occipital junction, and a multimodal dataset with fMRI and ECoG in the same subject.

Format name	Open standard	Well-defined structure	Python I/O	Matlab I/O	Supports >16-bit precision	Established tool / community	HIPAA compliant encryption
brainvision (.vhdr)	✓	✓	✓	✓	✓	✓	✘
european data format (.edf)	✓	✓	✓	✓	✘	✓	✘
fieldtrip (.mat)	✓	✓	✘	✓	✓	✓	✘
eeglab (.set)	✓	✓	✘	✓	✓	✓	✘
elekta (.fif)	✓	✓	✓	✓	✓	✓	✘
neurodata without borders (.nwb)	✓	✓	✓	✓	✓	✘	✘
MEF3 (.mef)	✓	✓	✓	✘	✓	✘	✓
hdf5 custom files (.h5)	✘	✘	✓	✓	✓	✓	✘
bci2000 (.dat)	✓	✓	✘	✓	✓	✓	✘
matlab custom files (.mat)	✘	✘	✓	✓	✓	✓	✘
biosemi (.bdf)	✓	✓	✓	✓	✓	✓	✘

Table 2: A summary of data format qualities. The table above is an informal summary of several data formats considered for official use with BIDS-iEEG. Each format was given a check in case it met several factors of importance to the BIDS-iEEG community. This centered around topics such as openness, standardized data structures, and use within the iEEG community as well as the broader electrophysiology community. Listed formats are the top-ten formats respondents expressed their willingness to use, they are ranked with an aggregated score summarizing their suitability for BIDS-iEEG, and a minimal number of formats that satisfied the necessary constraints of BIDS-iEEG were chosen for the specification.

An example dataset of the BIDS structure is shown in *Figure 1*. It shows how amplifier information, electrode hardware information, position and coordinate system, event and stimulus information, and other metadata can be stored along with a visual stimulus dataset. In addition, *Figure 2* shows more in-depth information for how different BIDS metadata files map onto various aspects of the experiment and neural data.

Community software and adoption

BIDS is a community project with two primary products: a specification for organizing neuroscience data, and a collection of software and tooling that facilitates the use of BIDS data structures. Creating the BIDS-iEEG specification involved the development of several new community tools. Below we list those that required the most new development for BIDS-iEEG.

The BIDS Validator

Defining a specification is only useful if one can *validate* whether a given dataset matches the specification or not. In BIDS, this is accomplished with a Javascript validator that is maintained by the BIDS community. The validator parses a folder, checks whether its hierarchy and naming structure conform to BIDS, and checks text files for the proper metadata and file types needed for the BIDS specification. This validator can also be deployed as a web-app so that researchers can validate their datasets without running any code locally (bids-standard.github.io/bids-validator/). For the BIDS-iEEG specification, modifications were made to the BIDS validator, ensuring that new datasets conforming to BIDS-iEEG can be validated properly (https://github.com/bids-standard/bids-validator).

pybv and pyedf

One of the requirements for any BIDS data structure is that the data formats are described in a freely accessible form, are interoperable with existing analysis software and can be implemented as open-source software in programming languages, such as Python, C/C++, and Matlab. While many neuroscience toolboxes exist for the Matlab language, there are relatively fewer for Python. In particular, there was no community-managed package for writing BrainVision or EDF files[1], the two "primary" data formats used with BIDS-iEEG. In finalizing this specification for BIDS-iEEG, two new Python packages were created for reading and writing which will be maintained and developed by the BIDS community (https://github.com/bids-standard/pybv and https://github.com/bids-standard/pyedf).

MNE-BIDS and MNE-Python

The MNE-Python package is an open-source tool for electrophysiology analysis, visualization, and data representation in Python. (Gramfort et al., 2013) This package has recently been extended to include functionality for intracranial EEG. Alongside the creation of the BIDS-iEEG specification, the community worked alongside those in the EEG and MEG communities to create a new package for moving between MNE-Python and the BIDS specifications in electrophysiology: MNE-BIDS (https://github.com/mne-tools/mne-bids). MNE-BIDS will be

[1] importing and exporting in Python was supported with https://pypi.org/project/pyEDFlib/ using binary CPython bindings, but not in pure Python code. The is also a package with I/O as a part of a more complex analysis/visualization pipeline (https://github.com/wonambi-python/wonambi).

maintained and supported by the MNE community and will facilitate converting electrophysiology workflows in MNE-Python into the BIDS dataset framework.

FieldTrip

FieldTrip (www.fieldtriptoolbox.org) is an open source Matlab toolbox for the analysis of electrophysiological data (Oostenveld, Fries, Maris, & Schoffelen, 2011). Although primarily documented for MEG and EEG data, FieldTrip has been developed and used for intracranial data since its initiation (Bosman et al., 2012; Rubehn, Bosman, Oostenveld, Fries, & Stieglitz, 2009; Stolk et al., 2018). It supports importing data from a large number of iEEG formats and can export data to BIDS recommended formats. Furthermore, FieldTrip includes the *data2bids.m* function to help users to organize their iEEG and MRI data and to provide proper metadata annotation. Tutorial documentation for BIDS can be found on www.fieldtriptoolbox.org/example/bids.

iElvis

iELVis (https://github.com/iELVis/iELVis) is an open source package for localizing iEEG electrodes and visualizing their data overlaid on neuroimaging (Groppe et al., 2017). It contains Matlab code and bash scripts that build on BioimageSuite's GUI for electrode tagging (Joshi et al., 2011) and FreeSurfer's automatic MRI parcellation and cortical surface reconstruction (www.freesurfer.net). Specifically, it implements multiple algorithms for correcting electrode locations for post-implant brain shift, provides several interactive visualizations of iEEG data overlaid on a variety of neuroimaging data, and maps electrode locations to five FreeSurfer anatomical atlases and the FreeSurfer average brain. iELVis is currently being made compatible with the iEEG-BIDS standard (http://ielvis.pbworks.com/w/page/130759893/iEEG-BIDS%20Compatibility).

The BIDS starter kit

Finally, while the tools above allow researchers to do more with the BIDS data specification, there is still a learning curve to understanding the specification itself, as well as the collection of tools around it. To help bring more members in the BIDS community, we launched the BIDS Starter Kit in collaboration with others in the BIDS community (https://github.com/bids-standard/bids-starter-kit). This is a collection of community-driven guides, tutorials, helper scripts, and wiki resources to help researchers get started with the BIDS data structure.

Brainstorm

Brainstorm (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011) is an open-source Matlab-based application dedicated to the analysis of multimodal neurophysiology data: MEG, EEG, fNIRS, ECoG, depth electrodes and animal electrophysiology (Tadel et al., 2011). Its rich user interface features specific tools for positioning electrode contacts in post-implantation CT or T1 scans and reviewing/annotating efficiently long data records, such as clinical iEEG signals (https://neuroimage.usc.edu/brainstorm/Tutorials/Epileptogenicity). It supports natively most file formats commonly used in iEEG and can convert them into BrainVision or EDF files. Studies in Brainstorm's database can be imported and exported automatically as BIDS-formatted datasets.

OpenNeuro

OpenNeuro.org is a repository for public neuroimaging data, currently supporting MR and MEG. It heavily capitalizes on the BIDS standard - each dataset is validated prior to upload using the bids-validator. OpenNeuro already uses the bids-validator version that features optional support for iEEG BIDS extension. When the extension will be merged into the main specification OpenNeuro will start accepting iEEG datasets. This will allow researchers that adopted BIDS in their labs to easily archive and share their iEEG datasets online.

Discussion

Benefits of a shared data structure

iEEG-BIDS is a structure for storing raw, unprocessed human intracranial electrophysiology data, spanning stereo EEG, ECoG, and DBS. While this paper has thus far focused on describing BIDS-iEEG specification and the process around it, we will now discuss the benefits that come with adopting a community-driven specification such as BIDS. A well-defined structure for storing intracranial and experimental data, along with their metadata, will help in several aspects of the scientific process. Below we list several key aspects of modern-day scientific work, and the ways in which the BIDS-iEEG (and broader BIDS ecosystem) enables them.

Data analysis within a lab.

While many consider best-practices in "open science" as beneficial towards other groups, the key beneficiary of best-practices in computational research is core collaborators on a given project. It is often said that "your most important collaborator is yourself in four months," and keeping a sensible structure to one's raw data is a key step in ensuring that it is easy to get oriented to a dataset and perform subsequent analyses over time. The adoption of *any* standard that follows best-practices will result in a significant increase in personal productivity, and the fact that BIDS-iEEG is designed specifically with iEEG data in mind means that it will be particularly useful for this community.

Collaboration between labs.

Most researchers have experienced a collaboration in which the two groups used different fundamental structures for representing their raw data. Needing to learn a "new way of doing things" with each new collaborator serves as a barrier to collaboration and an impediment to effective teamwork. BIDS-iEEG creates a community standard across the diverse field of iEEG research. As this field is young and diverse, these standards are particularly useful in standardizing the representation of data and experiments. This will make it easier to work with others, and increase the efficiency with which iEEG data can be shared between research groups.

Replication of results.

Science is replicable when a different team of people can reproduce the same result following the same scientific process (here, a data analysis) (Plesser, 2018). Science must be replicable in order to be trusted, but replicating results between labs (or repeating results within a lab) is often an arduous process. This is particularly true when each result has a different starting point and basic structure of data and metadata. BIDS-iEEG provides a standard that the community can use to facilitate both repeating and replicating scientific results. By assuming that the "starting point" of an analysis is a BIDS data structure, it becomes much easier to step through subsequent analyses and understand the work that was done.

Combining with other modalities.

Each recording modality has its own pros and cons. For example, fMRI has superior spatial resolution whereas iEEG has superior temporal resolution. As a result, it is becoming more common to record *multiple* kinds of brain activity in the same session or task. How should one organize these very different kinds of raw data? The BIDS ecosystem provides a common structure that flexibly handles these modalities in cognitive neuroscience. By adopting this common structure, BIDS-iEEG makes it easier to combine intracranial work with data collected in MEG, EEG, and MRI. This will facilitate more complex, cross-domain analyses.

Data sharing and large datasets.

Publishing large, curated datasets is becoming more common in the scientific world. This is particularly useful in fields like iEEG, where access to data is limited or difficult to obtain. When publishing a large corpus of data, it is crucial that the information around each dataset be structured in a sensible and understandable manner. Because BIDS-iEEG extends the broader BIDS format, it fits nicely with a structure that has already proven useful in large-scale dataset sharing (Gorgolewski et al., 2016). BIDS was partially inspired by the format used internally by the OpenfMRI repository (openfmri.org/), and has proven useful in facilitating the dissemination of large imaging datasets. For this reason it is now the core data structure of OpenNeuro.org, a project of OpenfMRI. We expect BIDS-iEEG to similarly encourage and facilitate the sharing of large datasets in the iEEG community.

Data sharing, reproducibility, and quality control are one of the priority areas of large research consortia, such as the US Brain Research through Advancing Innovative Neurotechnologies (BRAIN) initiative (whitehouse.gov/share/brain-initiative) as well as the EU Commission's Future and Emerging Technologies (FET) flagship, the Human Brain Project (HBP). Within these efforts it has become clear that community-wide accepted data standards are essential (Ferguson, Nielson, Cragin, Bandrowski, & Martone, 2014). As more labs within these frameworks record/use iEEG, the BIDS-iEEG specification can facilitate these efforts. Within HBP, BIDS-iEEG has been adopted in the Medical Informatics Platform (MIP) and is intended to be deployed in several hospitals for conducting multicenter studies (humanbrainproject.eu/en/medicine/). Furthermore, BIDS (with all its extensions) is facilitating the data integration and curation process for the data sharing framework of the HBP Neuroinformatics Platform (NIP). In this context the NIP is planning on supporting an automatic transfer of metadata from BIDS to the HBP database (humanbrainproject.eu/en/explore-the-brain/search/). Moreover, several HBP-developed analysis and/or visualization tools will profit from BIDS-compliant data, such as the HBP interactive atlas viewer (humanbrainproject.eu/en/explore-the-brain/atlases/) and HiBoP, a Unity-based software for anatomical visualization of dynamic iEEG data developed within HBP.

Integration with scientific tools.

Finally, while accessing and understanding raw data is an important first step, it is then necessary to *analyze* these data in order to answer a scientific question. This is generally done with domain-specific software. By adopting a common starting point, it makes writing scientific analyses and software packages more efficient, as they can leverage the structure of the data in order to standardize workflows and make more assumptions about the data. The BIDS MRI community already has several projects to facilitate analyzing BIDS datasets (bids-apps.neuroimaging.io/), and the BIDS-iEEG community already has several projects moving in this direction (see Results section). Standard ways of storing derived BIDS data (e.g. results of statistical analysis) is a topic of ongoing development (bids-apps.neuroimaging.io/ lists several extension proposals).

Community standards and growth.

Finally, one of the core benefits of adopting community standards such as BIDS-iEEG is that it provides a common point around which researchers can focus their discussions and work. BIDS is a community-driven project, and the BIDS-iEEG structure was created after many months of open discussion with the broader iEEG community. Over time we anticipate and hope that BIDS will grow, bringing in more voices and ideas for how the specification can meet the iEEG community's needs. This will open up new conversations across research groups in iEEG research, and provide a common point that can be the basis for future collaborations.

Outstanding challenges for BIDS-iEEG

There are several outstanding questions regarding the BIDS-iEEG data specification. While the community came to agreement about most questions surrounding metadata and data structures, several points will require further community input and discussion. For example, there are still outstanding questions about describing coordinate systems, merging metadata across modalities, and handling derivatives of raw iEEG data. In addition, the BIDS-iEEG specification design process was primarily focused on *human* intracranial data. There are many non-human uses for iEEG (e.g., primates or rodents) that will have their own challenges in metadata and standards. These will be addressed by the community in subsequent BIDS Enhancement Proposals, and will be released in a future version of the BIDS specification.

In particular, the BIDS-iEEG specification will need further community input in order to be suitable for clinical use-cases. The BIDS structure was initially developed to describe MRI data collected with research purposes in mind. Therefore, future development will involve labeling and annotating clinical observations, such as data recorded during seizures or anesthesia. For behavioral tasks, BIDS follows the ontologies of cognitive terms such as the Cognitive Atlas (cognitiveatlas.org/ (Bilder et al., 2009)), which defines, for example, 'rest eyes open', 'rest eyes closed', 'sleep' and 'self talk'. The BIDS community will seek more input from those with clinical experience in order to develop new ontologies extend the current Hierarchical Event Descriptor (HED) tags (Bigdely-Shamlo et al., 2016) to describe clinical observations related to neurological diseases such as epilepsy. Finally, the BIDS community does not currently have any explicit standards around anonymization of subject data. This is of particular interest to the iEEG community as all data, by definition, is sensitive patient data. Future BIDS Enhancement Proposals should define community standards around this.

Conclusion

BIDS-iEEG specifies a structured way of storing BIDS-iEEG data and metadata. It facilitates reproducibility and cross-modal integration across datasets, experiments and recording sites.

Methods

Process for community feedback on BIDS-iEEG

The BIDS standard requires input from the community in order to drive decision-making around community standards. Since BIDS is a multi-modal specification, the decision-making process must also occur *between* communities. When creating the BIDS-iEEG extension, the BIDS-iEEG community regularly consulted with several members of the BIDS-EEG and BIDS-MEG communities, and even shared several core members. Several issues that were unique to each modality were re-shaped such that their solutions were shared across modalities. This also led to more community tooling that spanned modalities (e.g., pybv and mne-bids). Finally, the BIDS-iEEG extension process preserved as much overlap as possible with the pre-existing BIDS specification - additional metadata files and fields were only defined when it was necessary.

Within the iEEG community, the BIDS-iEEG extension process followed an inclusive and participatory governance model, in order to get feedback from as many stakeholders as possible. The preparation of the iEEG-BIDS specification was done in several stages. First, an early draft of the BIDS-iEEG specification was created in a public Google Doc and an example dataset was created in the BIDS-examples repository. These were shared broadly with the iEEG community via emails, social media links, and advertisement on the BIDS website. Collaborators were invited to comment on the specification via comments and suggested edits, and early adjustments were made by the core BIDS-iEEG team. Next, a poster was presented at SfN 2017 asking for comments and participation from the community. This resulted in another round of iteration for the BIDS-iEEG specification. Once new changes to the specification became relatively minor, additional feedback was sought from maintainers of analysis software packages (Fieldtrip, MNE-Python) in order to find and address technological gaps that would make it difficult for users to utilize the BIDS-iEEG structure. For example, this uncovered the fact that there was no “BrainVision” export functionality in Python, which led to the creation of the pybv package. At this point, two additional datasets were converted to iEEG-BIDS as well. Once the specification was relatively stable, the BIDS validator was extended to incorporate new rules added by the iEEG specification. This made it possible to “verify” a dataset as adhering to the BIDS-iEEG structure. At this point, we identified an open question regarding the allowed data formats for BIDS-iEEG. To address this, we conducted a survey that asked scientists two primary questions: “which data formats do you currently use in your work”, and “which would you be *willing* to use for sharing data in the future”. The results of this informal questionnaire were used to decide which formats to “officially” support in BIDS-iEEG. Finally, we requested comments and feedback for the BIDS-iEEG specification one final time before “freezing” it and incorporating it into the broader BIDS specification.

Community input survey on data formats

Participating in the BIDS-iEEG specification design is a relatively involved process that requires a high level of interaction. For certain specific questions, we felt that it would be better to get a quick “straw poll” of the broader iEEG community to reduce the personal bias of the core BIDS-iEEG contributors. To decide which data formats BIDS-iEEG should “officially” support, we conducted an informal survey of iEEG practitioners asking which kinds of data formats they would be willing to use in their work. The questions of the survey were created along with input from the BIDS-EEG community. These were the two primary questions of interest:

1. What data formats do you currently use for storing raw cognitive electrophysiology data?
2. Which open formats below do you consider the most suitable for sharing data for others to (re)analyze (select 4 at most. If None select "Other" and say why).

Each question was followed by a list of data formats that at least one BIDS community remember had reported using before (along with one field for respondents to give a format not listed).

The survey was sent out to the BIDS-iEEG, -MEG, and -EEG communities. Respondents were also asked which modalities they use in their own work. This allowed the results to be broken down by modality and used in the decision-making for allowed formats in BIDS-EEG as well.

The survey was primarily distributed via a combination of online methods: members of the BIDS communities shared the survey with their collaborators via email, via departmental mailing lists, via communities of electrophysiology software communities, and finally via social media. The responses were collected after several weeks, and analyzed for simple statistics. As this was not a hypothesis-driven scientific study (and an admittedly biased sample), no statistical inference was performed on this data, we merely calculated statistics of the dataset and used it to help guide decision-making for allowed formats.

The decision to allow specific formats went as follows. First, for the iEEG modality, we took the list of formats that respondents reported using as a base set. We then threw out any formats that did not adhere to open principles (e.g., formats that were not well-specified, not well-utilized, or depended solely on proprietary software). We next used the second survey question, which asked about the willingness to use a data format for sharing. We used the formats with the highest rating in this question to choose from the formats remaining from step 1. Finally, we then asked the BIDS-iEEG community whether at least one of the chosen formats could satisfy their particular use-case. From this process, we discovered that several more specialized formats needed to be included in order to be used with specific iEEG use-cases (such as privacy-minded clinical data or high-precision data). Finally, to avoid making opinionated decisions without all the information needed to decide properly, we chose to create two groups of data formats: “officially” supported formats and “allowed” formats. Former have a special status in the BIDS-iEEG specification, and support will continue for the foreseeable future. Latter are supported currently but may be dropped in the future. As the BIDS-iEEG specification evolves, we can incorporate new community experience to decide which formats to “officially” support.

A summary of the process surrounding the survey, as well as a light analysis of all results (not only those related to BIDS-iEEG) was originally posted in (Holdgraf, 2018).

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Competing interests

- Gorgolewski, K: is a part-time Kaggle Research Consultant for Google LLC

Author contributions

CRH: managing process for specification, writing the paper, creating survey and analyzing results, coordinating with working group throughout process, updating the validator, adding filtered speech dataset, development of BIDS tooling (pybv and mne-bids).
DH: managing process for specification, writing the paper, development of bids tools: creating bids-starter-kit, coordinating with working group throughout process, adding visual and motor dataset.

Working group:
SA: ensure compatibility with BIDS-EEG and collaboratively write software code in MNE-BIDS, pybv, and the BIDS-validator. Been involved in discussions on suitable data formats and actively participated in shaping the extension via the forums and the google doc.
SB: verify specification for ECoG and electrical stimulation data
KB: verify specification for compatibility with NWB
SDA: verify specification for electrical stimulation data
OD1: verify specification for electrical stimulation data and usability within EU Human Brain Project; contribute SEEG epilepsy dataset
OD2: contribute dataset and verify specification for Brain Initiative data
BD: verify specification for compatibility with NWB
AF: contribute dataset and verify specification for ECoG
BLF: verify specification for ECoG data
KJG: mentorship and guidance throughout the specification process
IG: contribute dataset and verify specification for ECoG
DG: verify specification of electrode positions and compatibility with iElvis
AG: verify specification for DBS data
LH: verify specification for ECoG data
CJH: verify specification for ECoG data
MJ: writing software for the validator and MNE-Python
RTK: contribute dataset and verify specification for ECoG data
JPL: verify specification for use within EU Human Brain Project
JCL: verify specification for ECoG, DBS, sEEG data, intraoperative and post-operative photos
BNL: verify specification for clinical iEEG data and large datasets
CLM: verify specification for clinical iEEG data
KJM: contribute dataset and verify specification for DBS and ECoG data
JO: contribute dataset
RO: contribute to specification, contribute to validator, review of examples, verify compatibility with BIDS-EEG and BIDS-MEG, implemented support in FieldTrip, outreach and support adoption of draft specification
NP verify specification for usability for Brain Initiative data
AP: verify specification for ECoG data
AP: verify specification for electrical stimulation data
NP verify specification for Brain Initiative data
NFR: verify specification for ECoG and Brain Initiative data
AS: assistance with FieldTrip compatibility with BIDS and other Matlab tools
NCS: verify specification for ECoG, sEEG and DBS data
FT: Contribute SEEG epilepsy dataset, verify specification for SEEG, implemented support in Brainstorm
BV: verify specification for ECoG data
BW: verify specification for machine readability in a data archive
JW: contributed dataset and verify specification for Brain Initiative data
LZ: verify specification for use within EU Human Brain Project

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