Day 4 - Accelerating and Preprocessing fMRI

CBIC MRI Bootcamp 2025

Mike Tyszka
Caltech Brain Imaging Center

Caltech

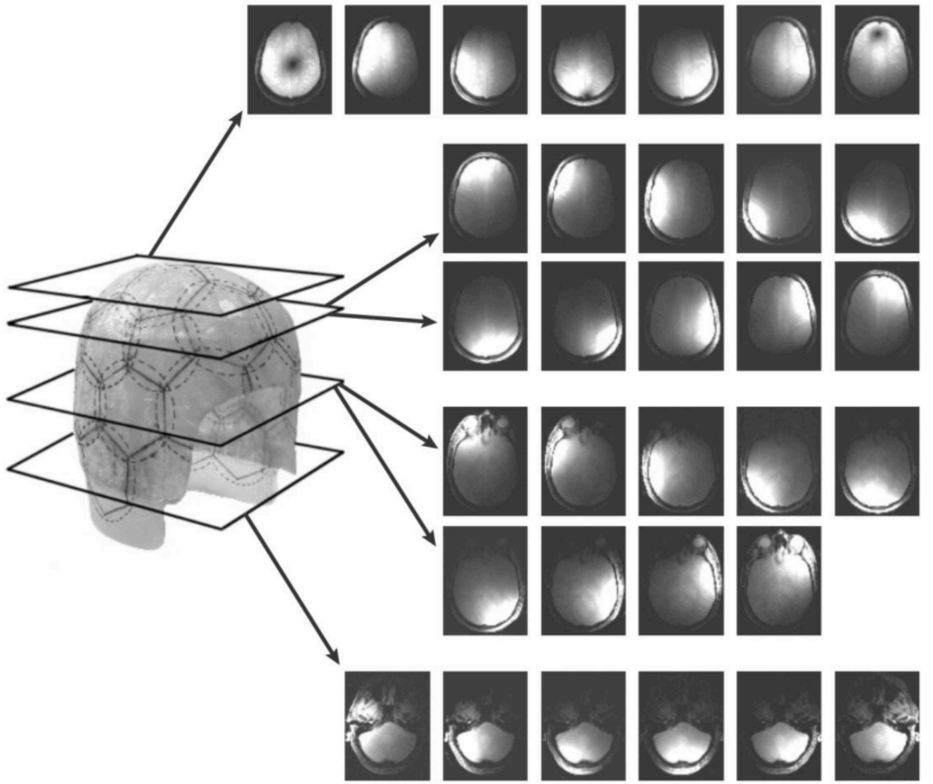
Review

- Noise is an unavoidable issue in MRI, which is intrinsically SNR starved.
- Noise sources include the participant’s body, RF coils and scanner electronics.
- Image artifacts happen when basic assumptions about the image acquisition are broken.
- MRI optimization should be driven by the science and balances resolution, sensitivity and time invested.

Accelerating MRI

Receive Coil Arrays

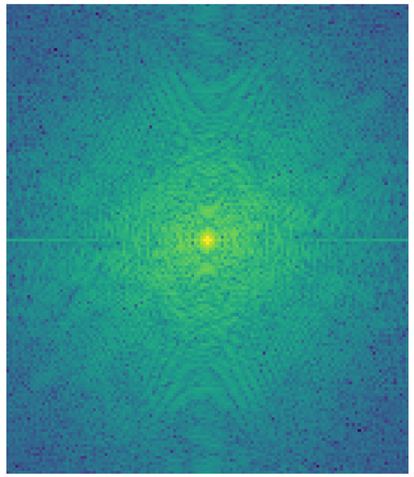
Array of small coils with minimal mutual inductance and independent signal reception from each coil

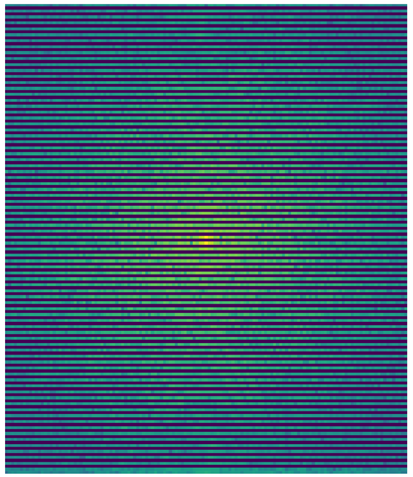


Wiggins, G. C., Triantafyllou, C., Potthast, A., Reykowski, A., Nittka, M., & Wald, L. L. (2006). 32-channel 3 Tesla receive-only phased-array head coil with soccer-ball element geometry. *Magnetic Resonance in Medicine: Official Journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine*, *56*(1), 216–223. https://doi.org/10.1002/mrm.20925

Undersampled k-space and fold-over

Full k-space





Sample every other row

Twice as fast, half the SNR

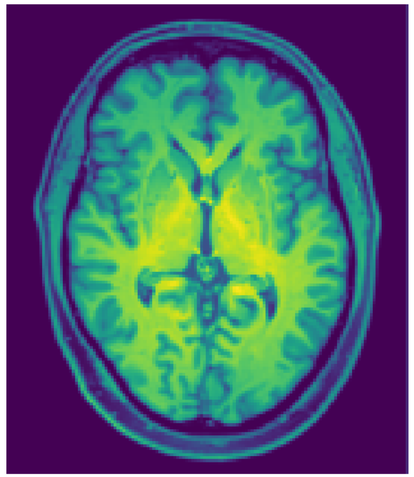
k-space FOV unchanged

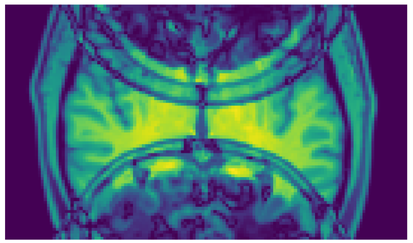
Image-space voxel size unchanged

Twice the k_y spacing

Half the image-space FOV

Full image





Half FOV with fold-over

SENSE Parallel Imaging

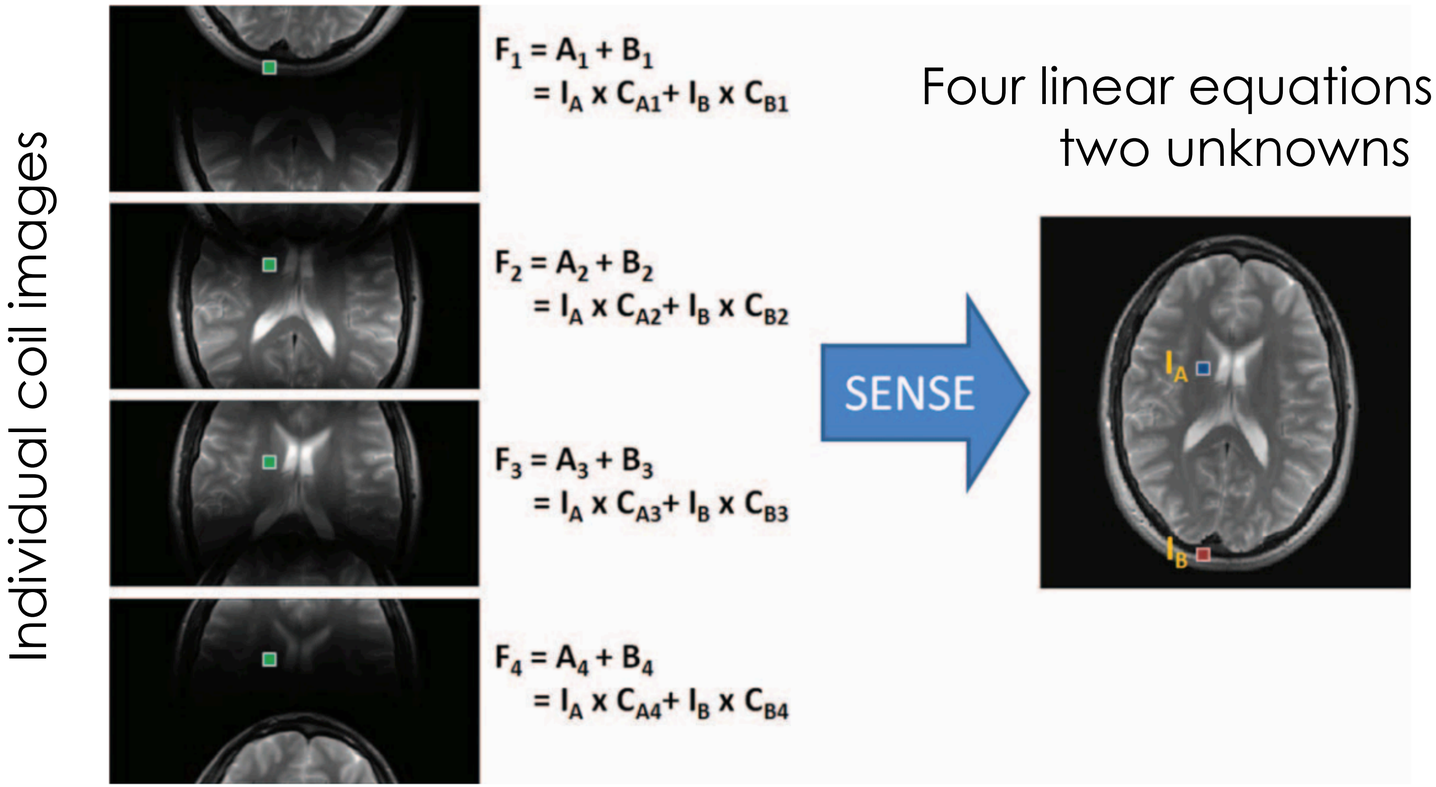
Reconstruction method that untangles fold-over using information multiple array coils

F = total signal in a coil image (known)

C = coil intensity weights (known)

A, B = weighted intensities from aliased voxels

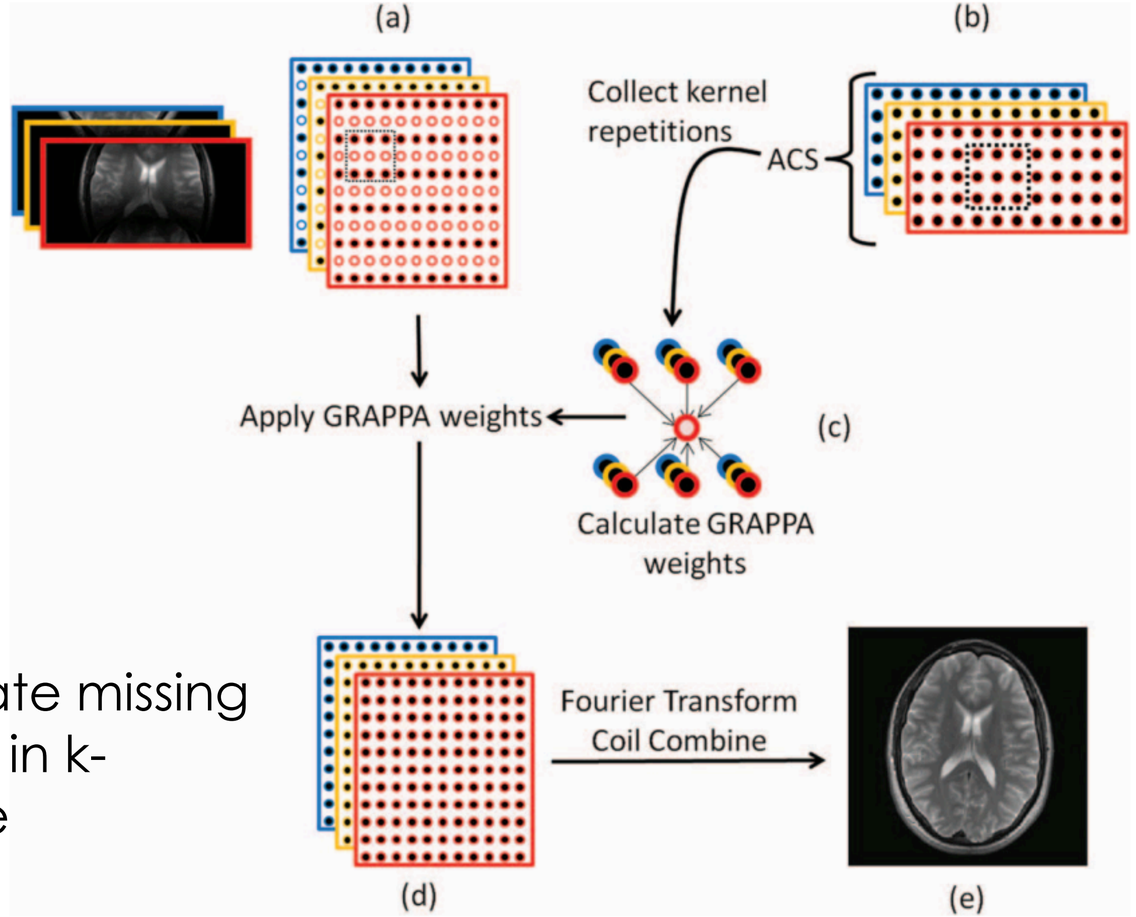
I = actual intensities (unknown)



Deshmane, A., Gulani, V., Griswold, M. A., & Seiberlich, N. (2012). Parallel MR imaging. *Journal of Magnetic Resonance Imaging*, *36*(1), 55–72. https://doi.org/10.1002/jmri.23639

GRAPPA Parallel Imaging

Undersampled k-space for each coil



Auto Calibration Signal (ACS) for each coil acquired in advance

Estimate missing signal in k-space

Reconstructed full image

Pros and Cons of GRAPPA

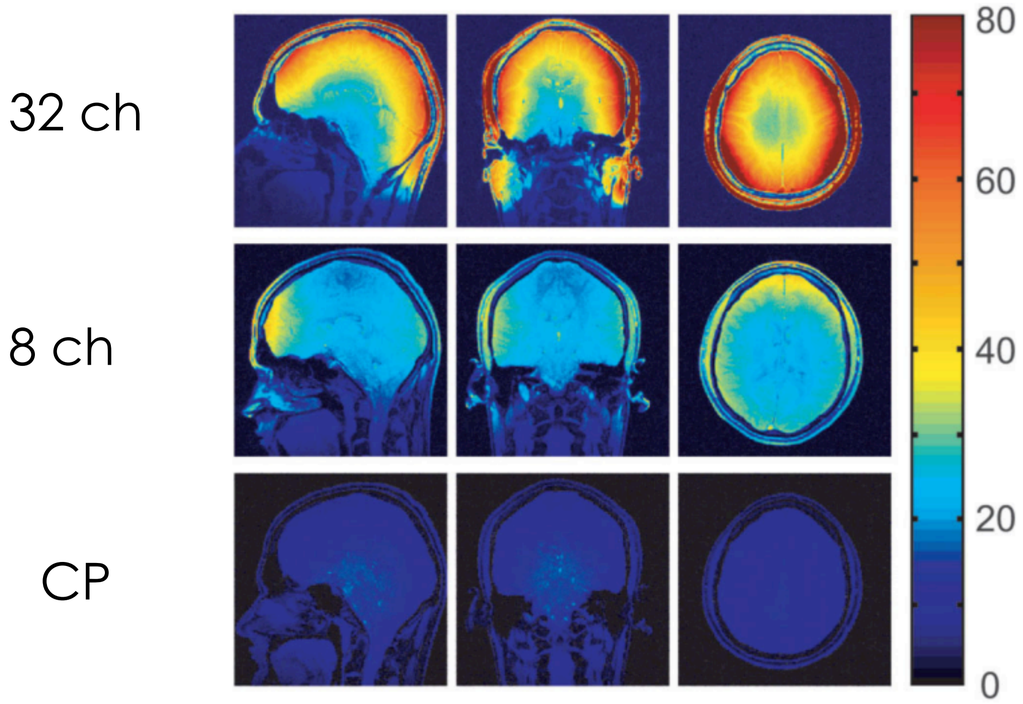
- As the acceleration factor, R, increases:
  - EPI echo train shortens
  - Geometric distortion reduces
  - Minimum TR and TE reduce
  - SNR drops

$$\mathrm{SNR} \propto \frac{1}{\sqrt{R}\, g}$$

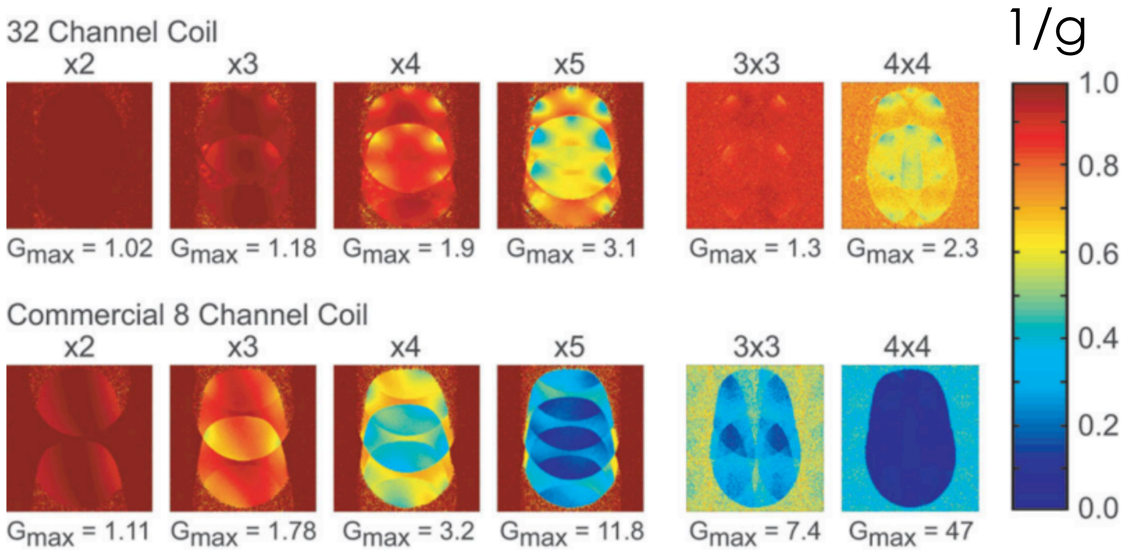
g-factor and noise amplification

Measure of noise amplification due to parallel reconstruction

Spatial SNR



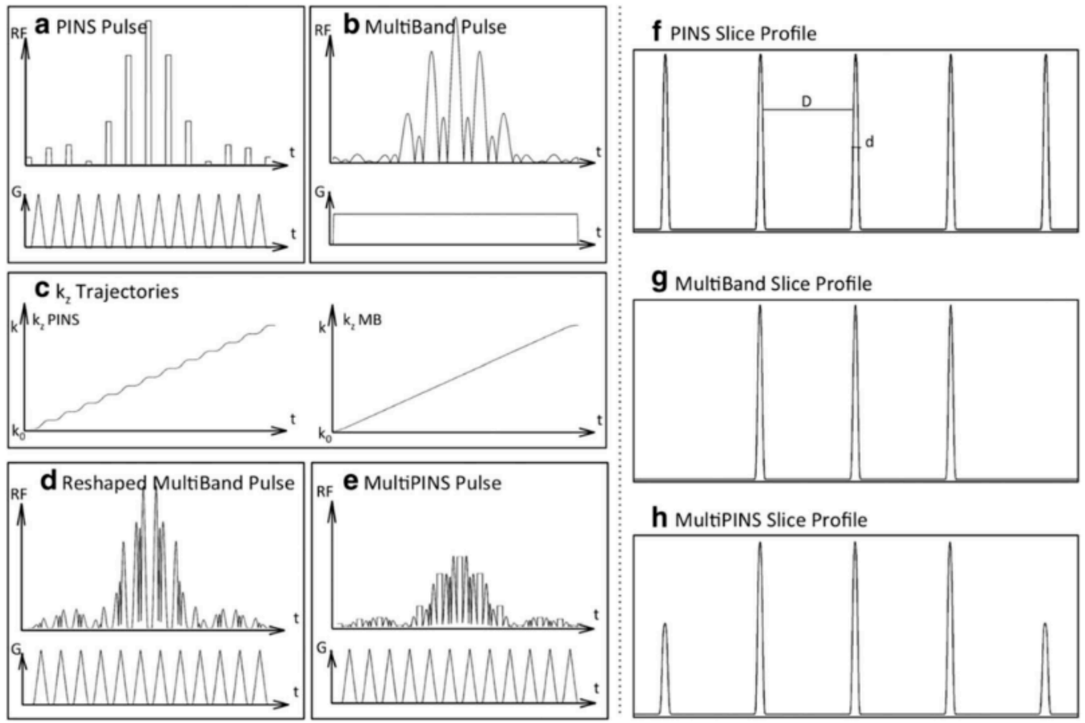
g-factor maps



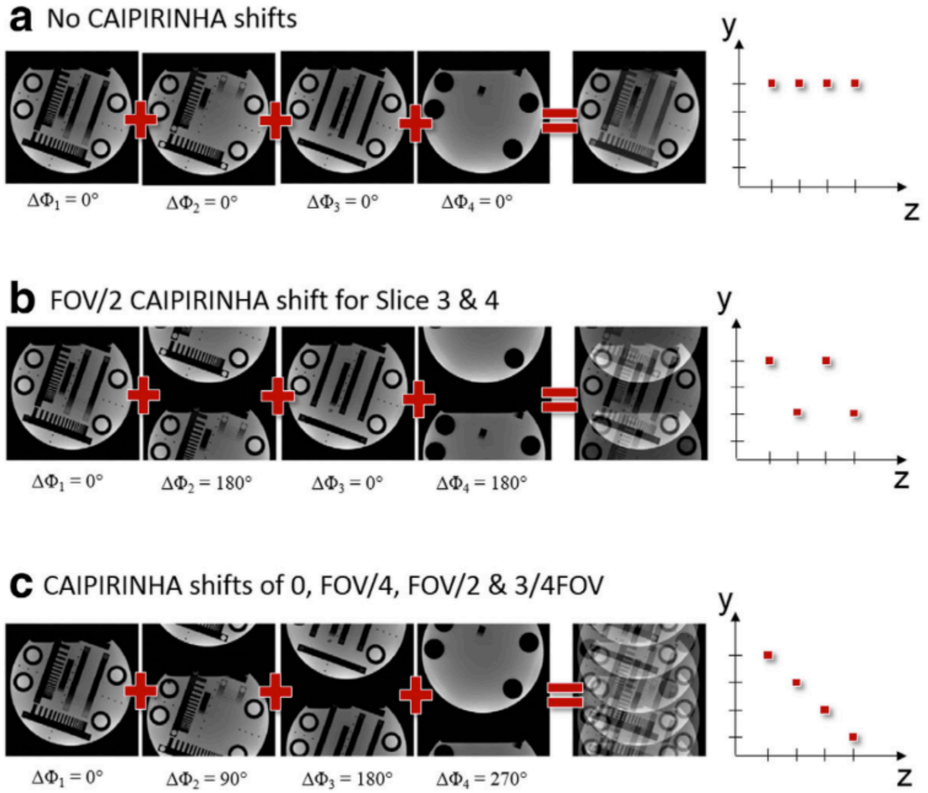
Wiggins, G. C., Triantafyllou, C., Potthast, A., Reykowski, A., Nittka, M., & Wald, L. L. (2006). 32-channel 3 Tesla receive-only phased-array head coil with soccer-ball element geometry. *Magnetic Resonance in Medicine: Official Journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine*, *56*(1), 216–223. https://doi.org/10.1002/mrm.20925

Multiband Slice Acceleration

RF pulses designed to excite multiple locations simultaneously



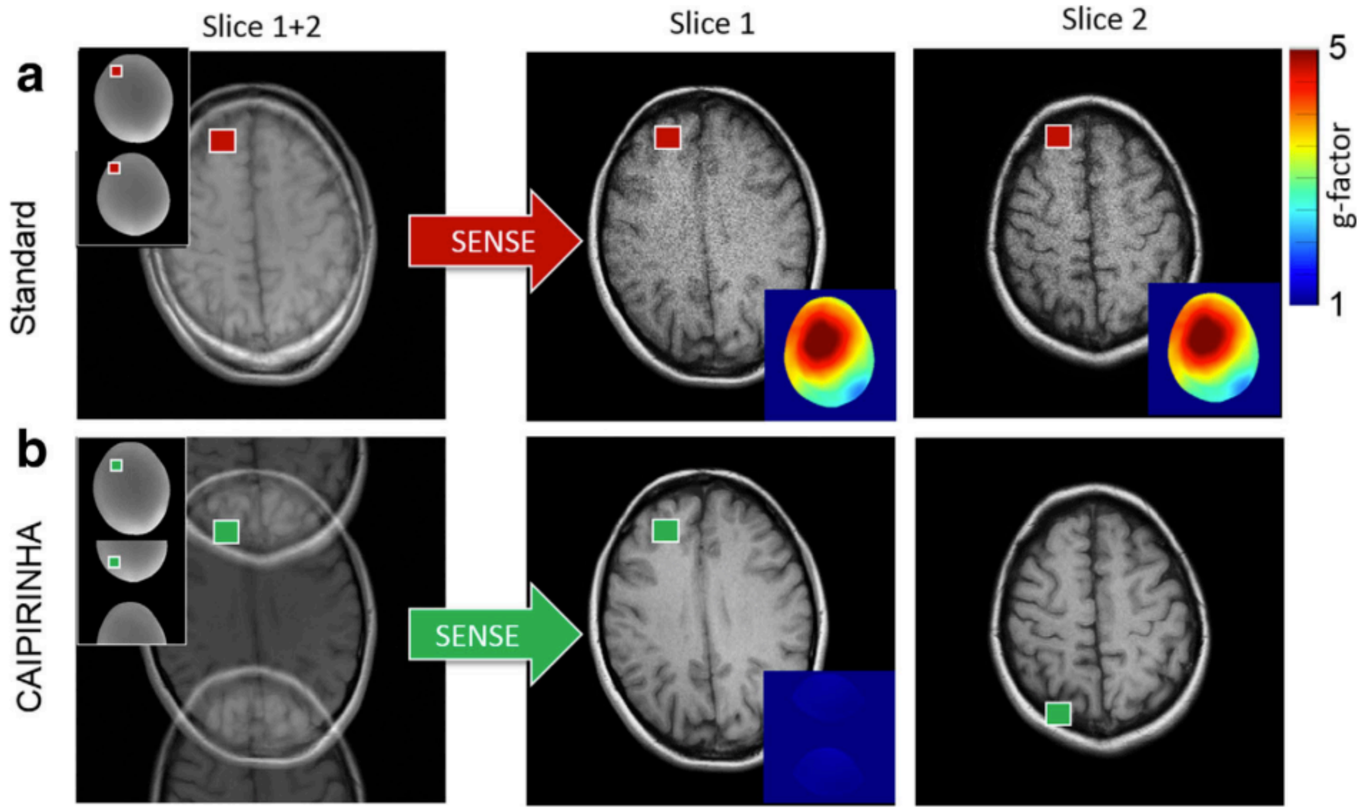
Excited slices combined in single image



Multiband Slice Acceleration

Slice SENSE untangles overlapping slice images using information from individual array coils

[Can similarly use slice GRAPPA for k-space]



Very small g-factor and no 1/sqrt(R) penalty

Barth, M., Breuer, F., Koopmans, P. J., Norris, D. G., & Poser, B. A. (2016). Simultaneous multislice (SMS) imaging techniques. *Magnetic Resonance in Medicine: Official Journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine*, *75*(1), 63–81. https://doi.org/10.1002/mrm.25897

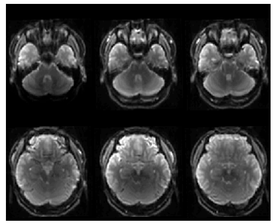
fMRI Preprocessing

Purpose of Preprocessing

- Bridges the gap between raw images straight from the scanner and the needs of subsequent image analysis
- Minimize, mitigated or compensate noise, artifacts and non-neuronal signals in a **principled manner**
- Condition data to meet **assumptions of analysis models**

Typical Preprocessing Workflow

Raw DICOM



BIDS Conversion

Slice Timing Correction

Head Motion Correction

Susceptibility Distortion Correction

Align and Resample to Other Spaces

Signal Extraction

Confound Estimation

Cleanup

Motion Correction

EPI Distortion Estimation

Alignment to Functional EPI

B1 Bias Correction

Individual Templates

Registration to Standard Spaces

Cortical Surface Extraction

DICOM - Digital Imaging and Communications in Medicine

ACR/NEMA standard for medical image transfer and storage

DICOM File Header Metadata

Meta-Data: /Users/jmt/Documents/Horos Data/DATABASE.noindex/10000/3.dcm (243 KB)

Edit Add Apply | Image Series Study Patient | search string

Export XML Export Text Expand All Collapse All | DICOM Editing | Sort Images Validator | Search

Field Name	Tag	Content
BodyPartExamined	0018,0015	BRAIN
ScanningSequence	0018,0020	SE
SequenceVariant	0018,0021	SK\SP\OSP
ScanOptions	0018,0022	PFP
MRAcquisitionType	0018,0023	3D
SequenceName	0018,0024	*spc_314ns
AngioFlag	0018,0025	N
SliceThickness	0018,0050	0.89999997615814
RepetitionTime	0018,0080	3200
EchoTime	0018,0081	564
NumberofAverages	0018,0083	1
ImagingFrequency	0018,0084	123.250022
ImagedNucleus	0018,0085	1H
EchoNumbers	0018,0086	1
MagneticFieldStrength	0018,0087	3
NumberofPhaseEncodingSteps	0018,0089	274
EchoTrainLength	0018,0091	314
PercentSampling	0018,0093	100
PercentPhaseFieldofView	0018,0094	100
PixelBandwidth	0018,0095	750
DeviceSerialNumber	0018,1000	167050
SoftwareVersions	0018,1020	syngo MR E11
ProtocolName	0018,1030	anat-T2w
TransmitCoilName	0018,1251	Body
AcquisitionMatrix	0018,1310	0\256\256\0
In-planePhaseEncodingDirection	0018,1312	ROW
FlipAngle	0018,1314	120
VariableFlipAngleFlag	0018,1315	Y
SAR	0018,1316	0.1821525192099
dB_dt	0018,1318	0
PatientPosition	0018,5100	HFS
StudyInstanceUID	0020,000d	1.3.12.2.1107.5.2.43.167050.30000022111602111597700000046
SeriesInstanceUID	0020,000e	1.3.12.2.1107.5.2.43.167050.20221122153301440219917 2.0.0.0
StudyID	0020,0010	1
SeriesNumber	0020,0011	14
AcquisitionNumber	0020,0012	1

One 2D Slice per file*

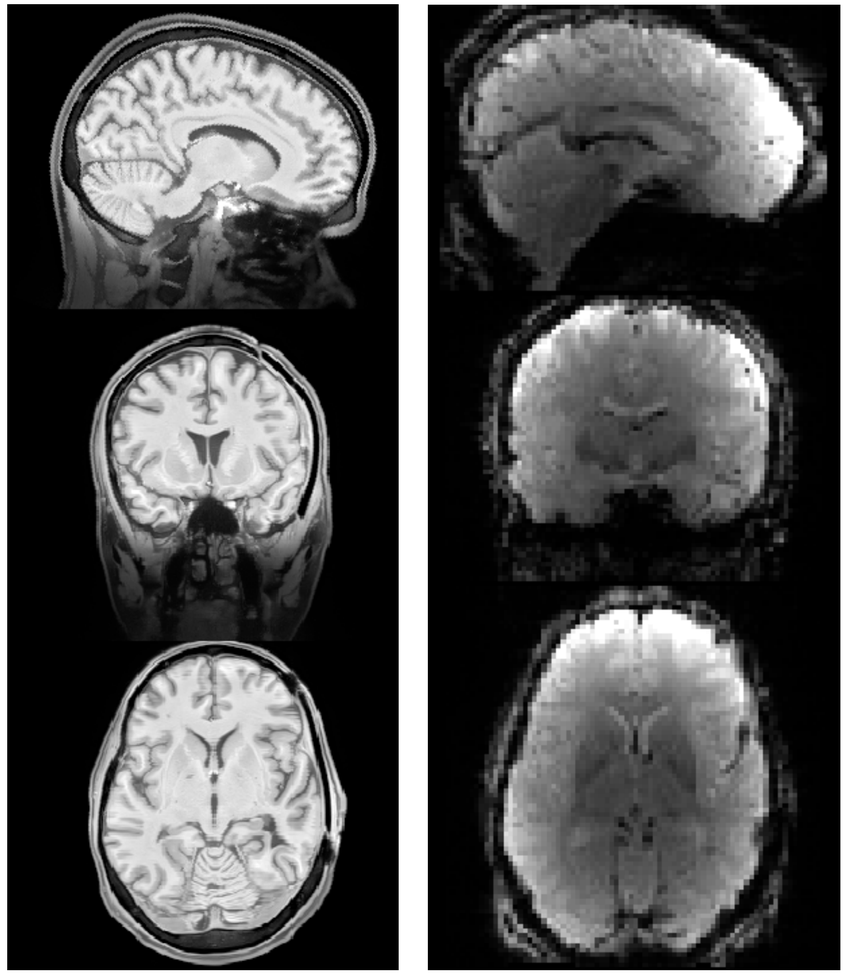
*Exceptions for Siemens EPI montages and Enhanced DICOM (up to 4D images)

Neuroimaging Informatics Technology Initiative (Nifti) Format

Research N-D imaging format. Variants Nifti-1, Nifti-2, Gifti, Cifti

Example Nifti-1 header from a 4D BOLD image

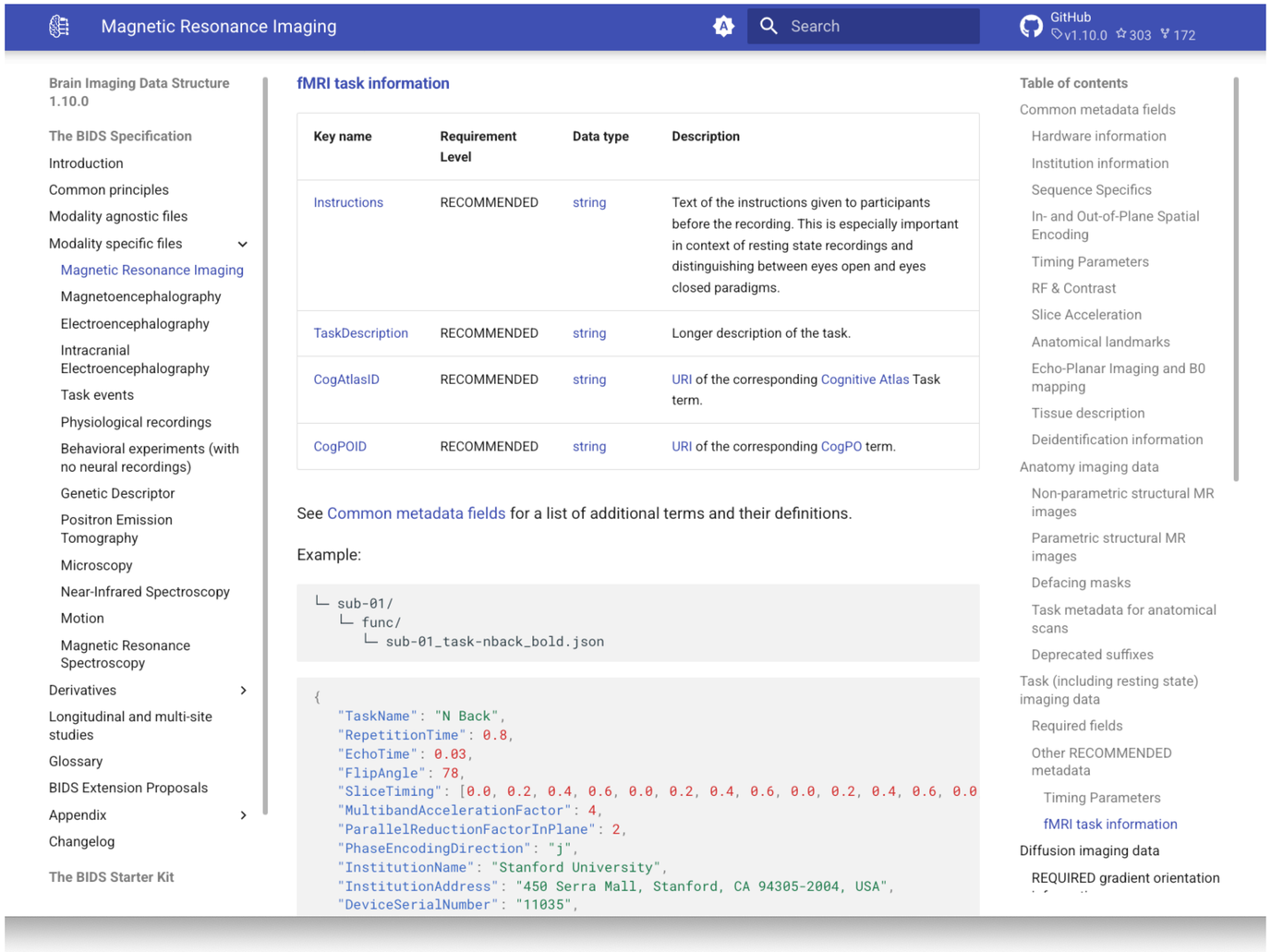
```
sizeof_hdr      : 348
data_type       : b''
db_name         : b''
extents         : 0
session_error   : 0
regular         : b'r'
dim_info        : 57
dim             : [  4  96  96  28 549   1   1   1]
intent_p1       : 0.0
intent_p2       : 0.0
intent_p3       : 0.0
intent_code     : none
datatype        : uint16
bitpix          : 16
slice_start     : 0
pixdim          : [-1.     2.     2.     2.     0.556  0.     0.     0.   ]
vox_offset      : 0.0
scl_slope       : nan
scl_inter       : nan
slice_end       : 0
slice_code      : unknown
xyzt_units      : 10
cal_max         : 0.0
cal_min         : 0.0
slice_duration  : 0.0
toffset         : 0.0
glmax           : 0
glmin           : 0
descrip         : b'TE=30;Time=143907.237;phase=1;mb=4'
aux_file        : b'Unaliased MB4/PE3/LB'
qform_code      : scanner
sform_code      : scanner
quatern_b       : 0.0
quatern_c       : 0.98939943
quatern_d       : 0.14521967
qoffset_x       : 96.0
qoffset_y       : -78.983635
qoffset_z       : -73.84162
srow_x          : [-2.  0. -0. 96.]
srow_y          : [ -0.          1.915645    -0.57472104 -78.983635  ]
srow_z          : [  0.          0.57472104   1.915645   -73.84162   ]
intent_name     : b''
magic           : b'n+1'
```



BIDS - Brain Imaging Data Structure

Hierarchical specification for neuroimaging data organization

https://github.com/bids-standard




```
BreathHold
├── CHANGES
├── README
├── code
│   ├── 1_populate_sourcedata.sh
│   ├── 2_bidskit.job
│   ├── 3_slabpreproc.job
│   ├── Protocol_Translator.json
│   ├── logs
│   └── subj_sess_list.txt
├── dataset_description.json
├── derivatives
│   ├── amy_ics
│   │   └── amy_IC_overlap.ipynb
│   └── slabpreproc
│       ├── sub-Damy001
│       │   ├── ses-20220303
│       │   ├── ...
│       ├── sub-Damy002
│       │   ├── ses-20220301
│       │   ├── ...
│       └── sub-Damy003
│           ├── ses-20220301
│           ├── ...
├── participants.json
├── participants.tsv
├── sub-Damy001
│   └── ses-20220303
│       ├── anat
│       │   ├── sub-Damy001_ses-20220303_acq-mezrms_rec-bias_run-1_part-mag_T1w.json
│       │   ├── sub-Damy001_ses-20220303_acq-mezrms_rec-bias_run-1_part-mag_T1w.nii.gz
│       │   ├── ...
│       ├── fmap
│       │   ├── sub-Damy001_ses-20220303_acq-amybh_dir-AP_part-mag_epi.json
│       │   ├── sub-Damy001_ses-20220303_acq-amybh_dir-AP_part-mag_epi.nii.gz
│       │   ├── ...
│       └── func
│           ├── sub-Damy001_ses-20220303_task-amybh_dir-AP_events.tsv
│           ├── sub-Damy001_ses-20220303_task-amybh_dir-AP_part-mag_bold.json
│           ├── sub-Damy001_ses-20220303_task-amybh_dir-AP_part-mag_bold.nii.gz
│           ├── sub-Damy001_ses-20220303_task-amybh_dir-AP_part-mag_sbref.json
│           ├── sub-Damy001_ses-20220303_task-amybh_dir-AP_part-mag_sbref.nii.gz
│           ├── ...
├── sub-Damy002
│   └── ses-20220301
│       ├── anat
│       │   ├── ...
│       ├── fmap
│       │   ├── ...
│       └── func
│           ├── ...
└── ...
```

DICOM to BIDS Conversion

Common basic need in neuroimaging so lots of software solutions

https://bids.neuroimaging.io/tools/converters.html

Name	Expected input	Language
BIDScoin	DICOM PAR/REC physiological PET Nifti	Python
BIDSconvertR	DICOM	R
BIDSme	DICOM Nifti Brain Vision	Python
BMAT	DICOM	Python
BrkRaw	Bruker MRI scanner data	Python
Clinica	ADNI AIBL GENFI HABS IXI NIFD OASIS OASIS-3 UKB	Python
Data2Bids	not DICOM	Python
Dcm2Bids	DICOM	Python
Explore ASL	DICOM Nifti	MATLAB
FieldTrip - data2bids	any EEG or MEG file format NBS Presentation logfiles DICOM	MATLAB
HeuDiConv	**DICOM**	**Python**
Horos (Osirix) export plugin	???	objective C
OpenfMRI2BIDS	openfMRI datasets	???
ReproIn	DICOM	Python
SAMRI	Bruker ParaVision NIfTI	Python
XNAT2BIDS	DICOM	shell
bidskit	**DICOM**	**Python**
dac2bids	DICOM	Python
ezBIDS	DICOM NIfTI/JSON events (tsv, csv, txt, out, xlsx)	Vue TypeScript Javascript Python shell
mercure-dcm2bids	DICOM	Python
niix2bids	Nifti converted from DICOM using dcm2niix	Python

ReproIn Series Descriptions

- Naming imaging series on the console can help with DICOM to BIDS conversion
- Developed at Dartmouth Brain Imaging Center
- Series Description Template. Use for console protocol series names.

  <seqtype[-label]>[_ses-<SESID>][_task-<TASKID>][_acq-<ACQLABEL>][_run-<RUNID>][_dir-<DIR>][<more BIDS>][__<custom>]

- Examples (ReproIn -> BIDS)

  anat-T1w_ses-1_acq-highres -> sub-ABC/ses-1/anat/sub-ABC_ses-1_acq-highres_T1w.[nii.gz | json]

  fmap-epi_ses-2_acq-trailer_run-2_dir-AP -> sub-ABC/ses-2/fmap/sub-ABC_ses-2_acq-trailer_run-2_dir-AP_epi.[nii.gz | json]

  func-bold_ses-3_task-faces_run-1-> sub-ABC/ses-3/func/sub-ABC_ses-3_task-faces_run-1_bold.[nii.gz | json]

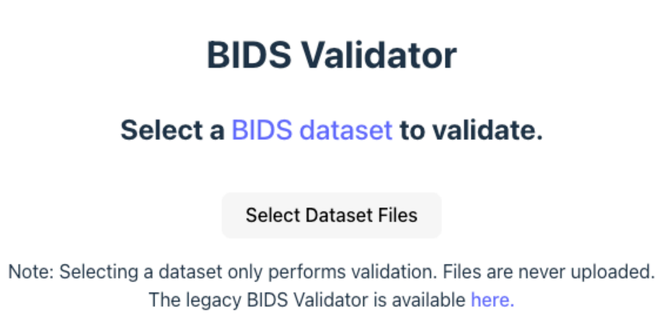
BIDS Validation

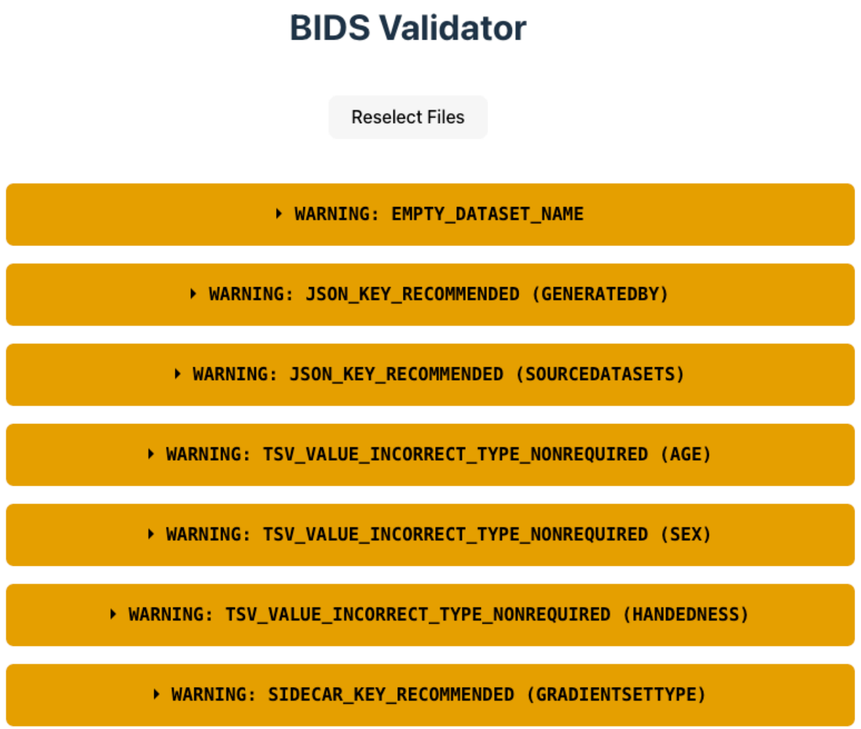
Complex, generalized format with a lot of rules

Local BIDS datasets can be validated online using the latest specification

Useful for curation prior to upload to OpenNeuro and similar repositories

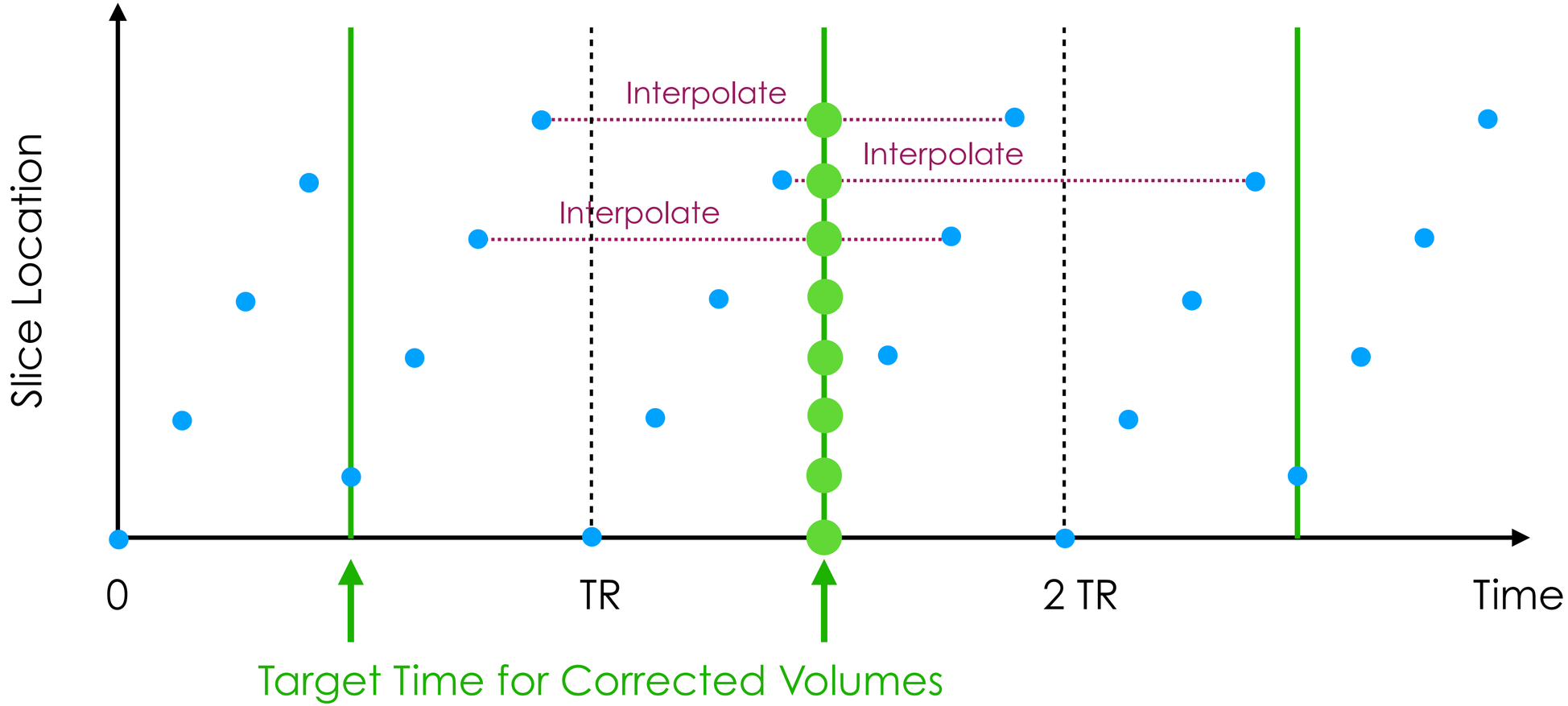
https://bids-standard.github.io/bids-validator/





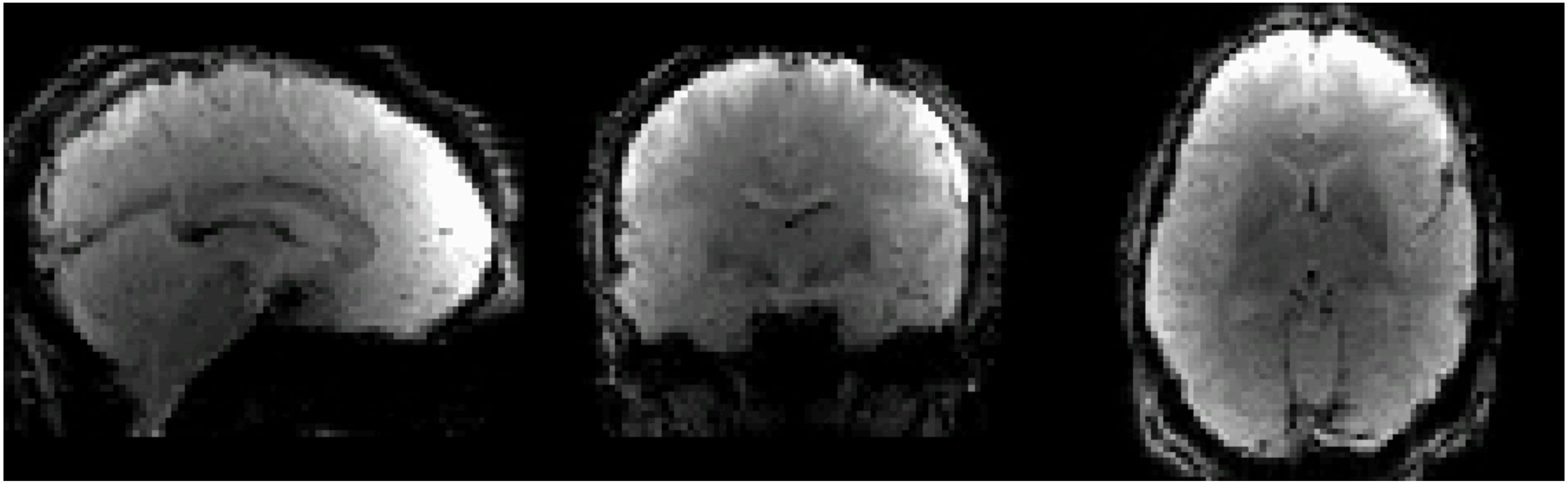
Slice Timing Correction

Eight 2D slices with interleaved slice ordering



Head Motion

Involuntary rigid body head motion during a breath hold task

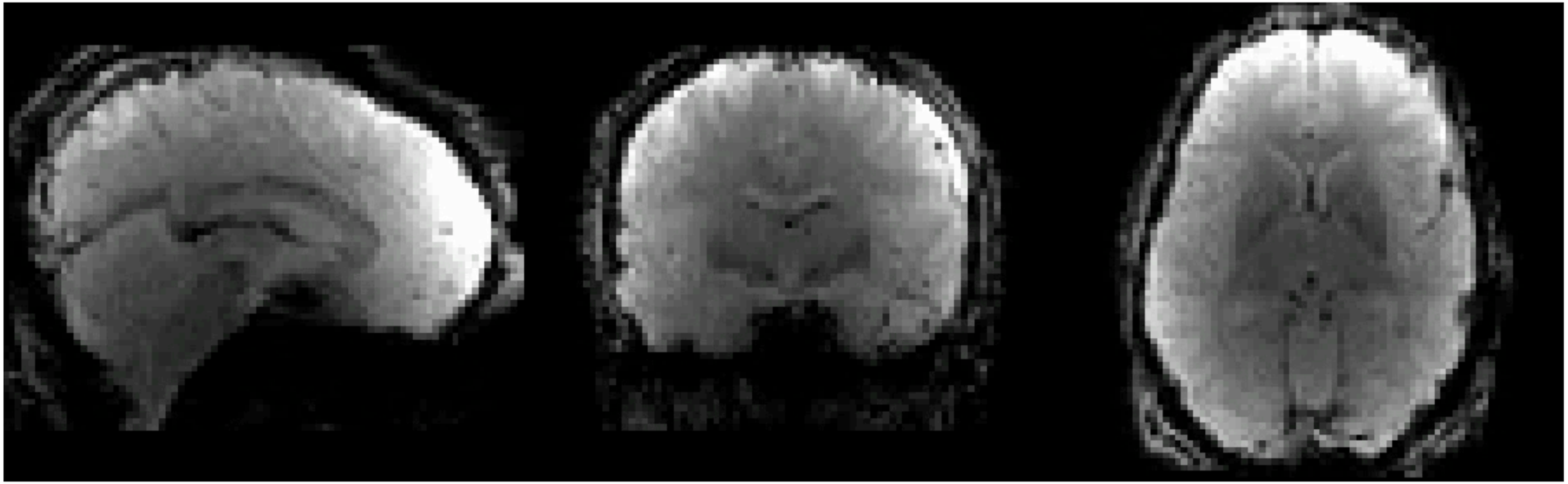


Breath Hold Task

TR 700 ms 2.5 mm isotropic voxels

Head Motion Correction

Rigid body (6-parameter) alignment of all volumes to a reference volume

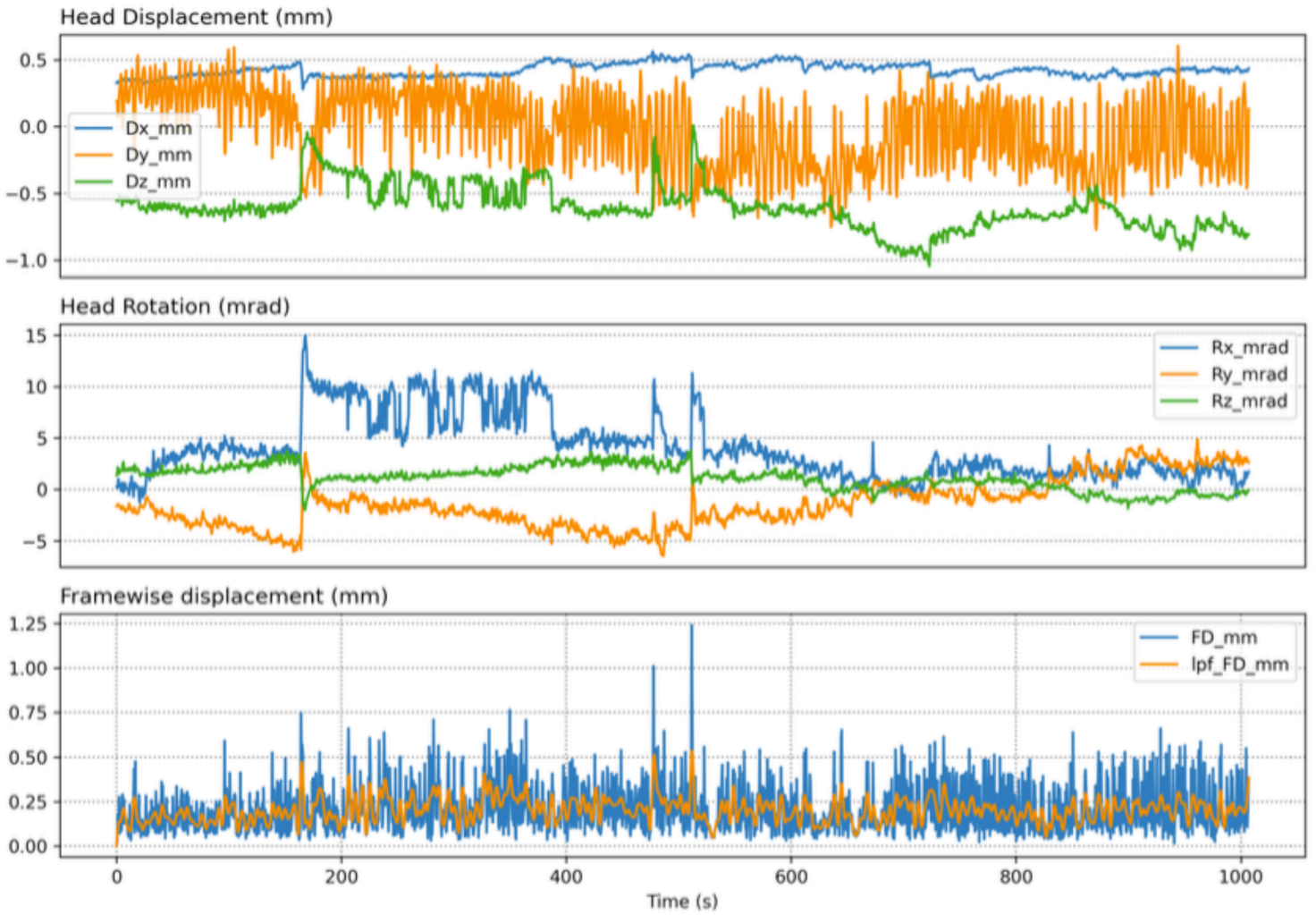


Breath Hold Task

fMRIPrep preprocessing including head motion correction

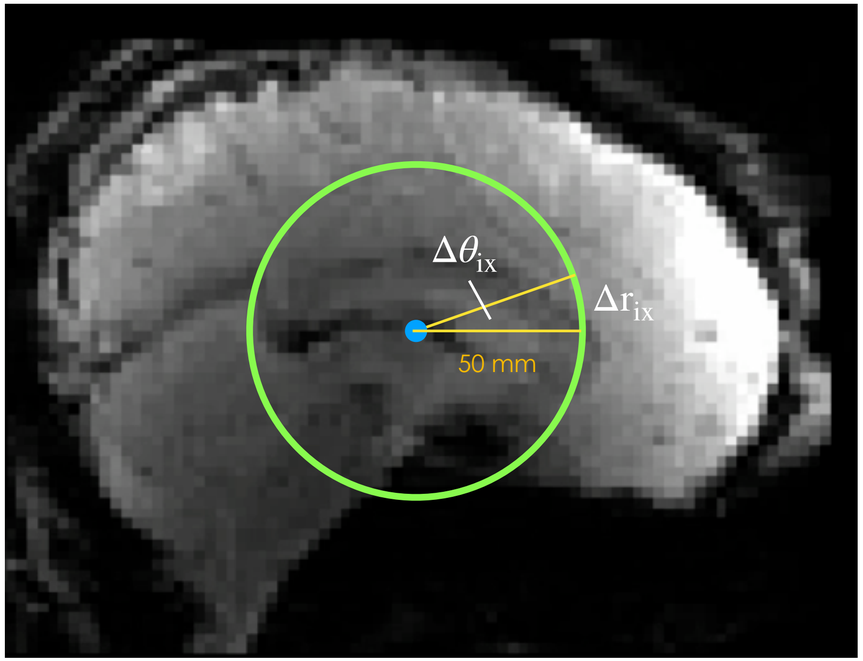
Motion Parameter Timeseries

Derived from the optimal rigid body transform from a volume at time t to the reference



Frame-wise Displacement

Weighted sum of rigid body displacement and rotations between volumes (frames)



$$FD_i = |\Delta d_{ix}| + |\Delta d_{iy}| + |\Delta d_{zi}| + |\Delta r_{ix}| + |\Delta r_{iy}| + |\Delta r_{iz}|$$

Rigid Body Registration Parameters

Δd_{xi} : linear displacement

$\Delta r_{ix} = 50\ \Delta\theta_{ix}$: rotation displacement on 50 mm sphere

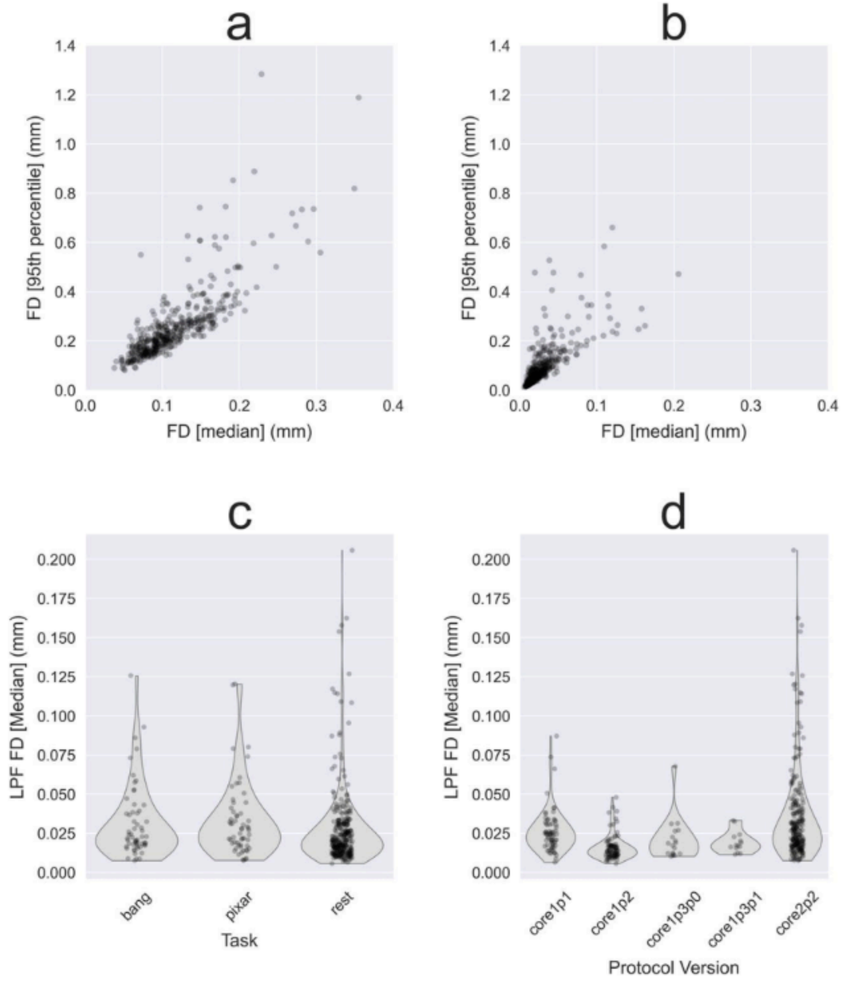
Power, J. D., Barnes, K. A., Snyder, A. Z., Schlaggar, B. L., & Petersen, S. E. (2012). Spurious but systematic correlations in functional connectivity MRI networks arise from subject motion. *NeuroImage*, *59*, 2142–2154. https://doi.org/10.1016/j.neuroimage.2011.10.018

Respiratory motion and FD

Apparent inter-frame motion is noticeable for sub-second TR EPI (typically multi band)

Mixture of true head motion from respiration and motion x field effects on EPI geometry

Low pass filter FD time series (< 0.2 Hz) if used for motion confound control



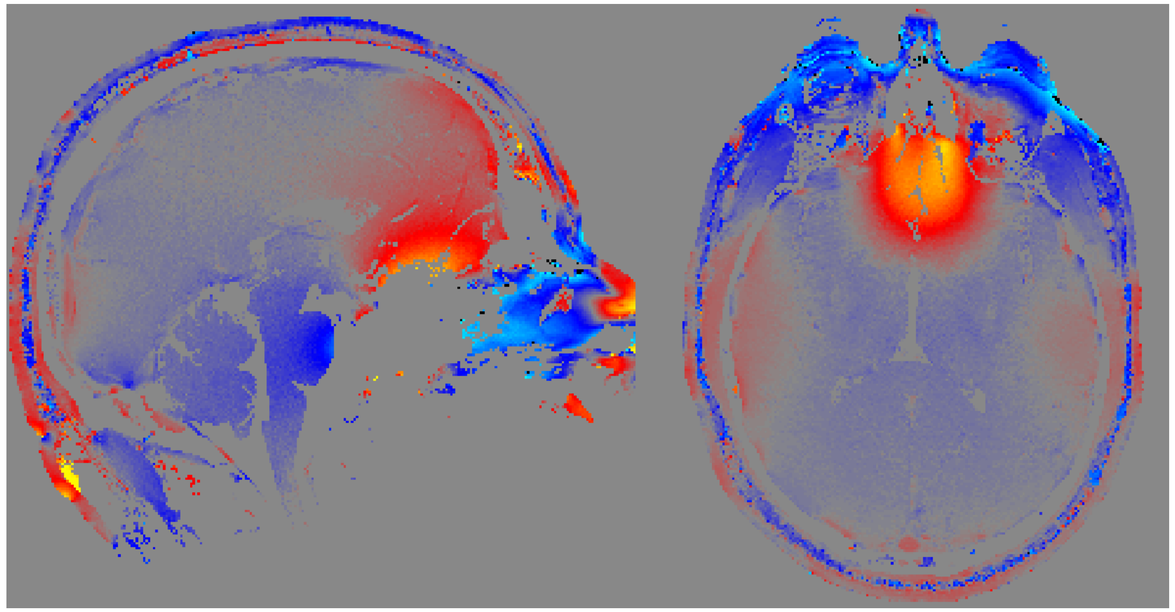
Power, J. D., Lynch, C. J., Silver, B. M., Dubin, M. J., Martin, A., & Jones, R. M. (2019). Distinctions among real and apparent respiratory motions in human fMRI data. *NeuroImage*, *201*, 116041. https://doi.org/10.1016/j.neuroimage.2019.116041

Kliemann, D., Adolphs, R., Armstrong, T., Galdi, P., Kahn, D. A., Rusch, T., Enkavi, A. Z., Liang, D., Lograsso, S., Zhu, W., Yu, R., Nair, R., Paul, L. K., & Tyszka, J. M. (2022). Caltech Conte Center, a multimodal data resource for exploring social cognition and decision-making. *Scientific Data*, *9*(1), 138. https://doi.org/10.1038/s41597-022-01171-2

B_0 Field Mapping

Multiecho GRE

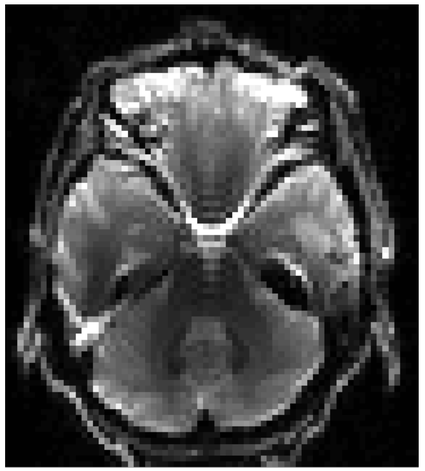
No geometric distortion
Complex-valued signal
Slow
High resolution
Different space from BOLD EPI



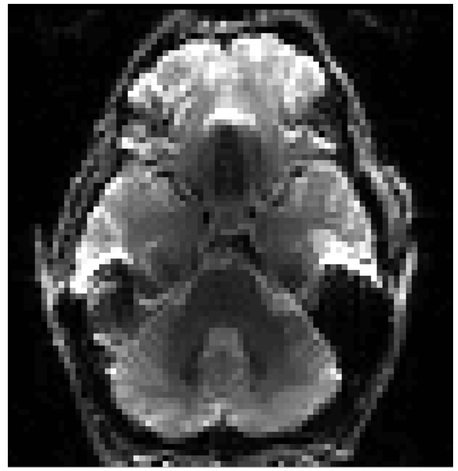
PEPOLAR SE-EPI

Phase-encoding polarity reversal
Fieldmap derived from distortion
Fast
Lower resolution
Same space as BOLD EPI

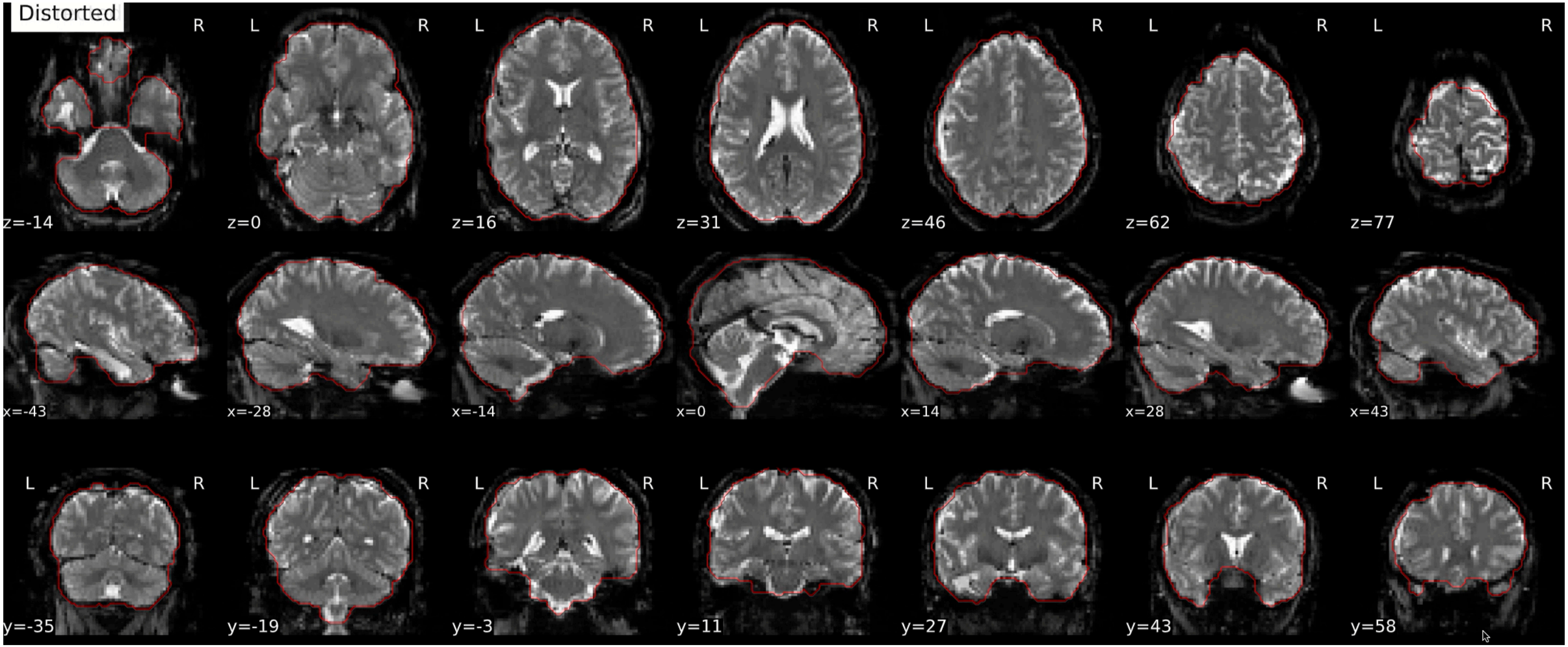
AP Encoded



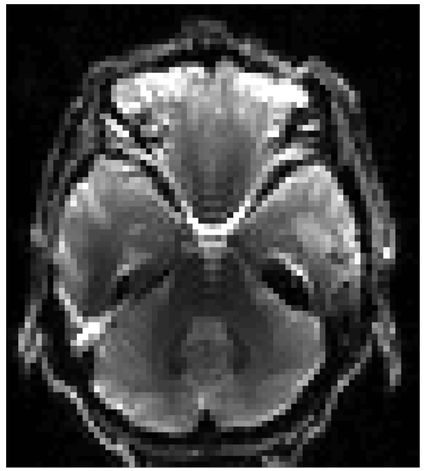
PA Encoded

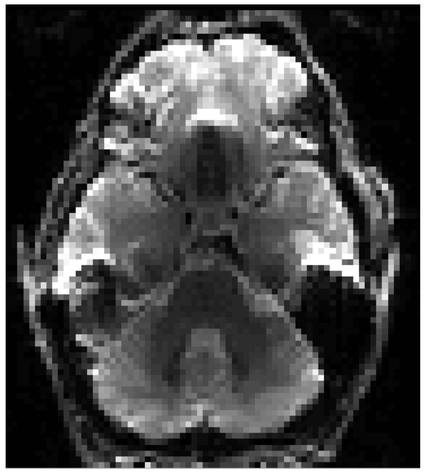


Susceptibility Distortion Correction



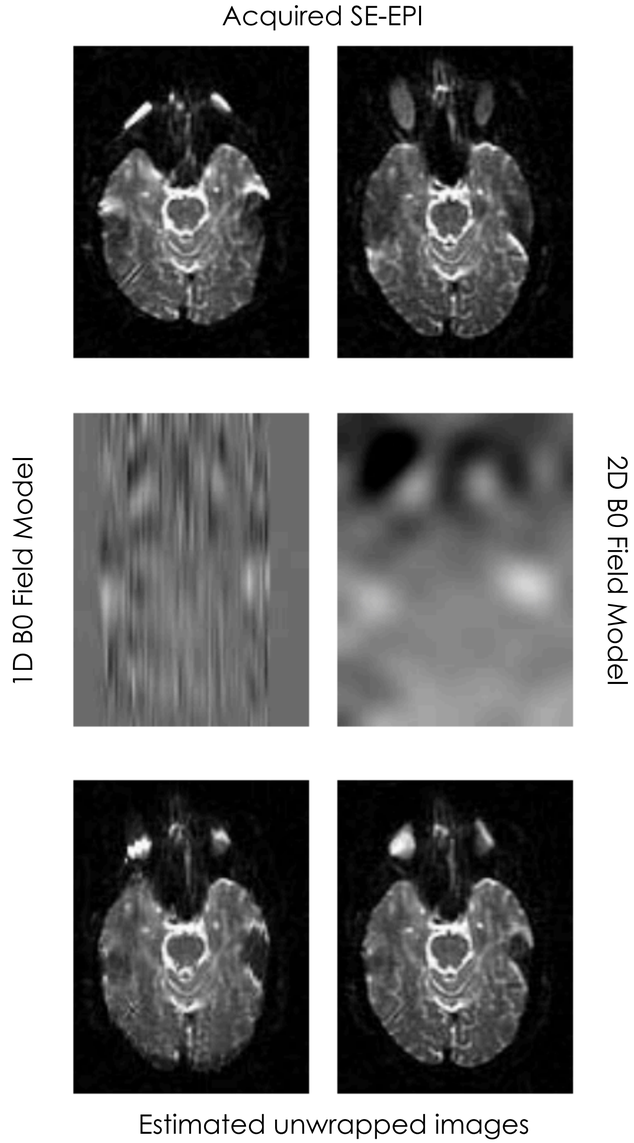
TOPUP B_0 field estimation





EPI signal model based on knowledge of imaging parameters for each encoding and a constrained B_0 field estimate

$$\hat{\boldsymbol{\rho}} = \left(\begin{bmatrix} \mathbf{K}_+^T & \mathbf{K}_-^T \end{bmatrix} \begin{bmatrix} \mathbf{K}_+ \\ \mathbf{K}_- \end{bmatrix} \right)^{-1} \begin{bmatrix} \mathbf{K}_+^T & \mathbf{K}_-^T \end{bmatrix} \begin{bmatrix} \mathbf{f}_+ \\ \mathbf{f}_- \end{bmatrix}$$

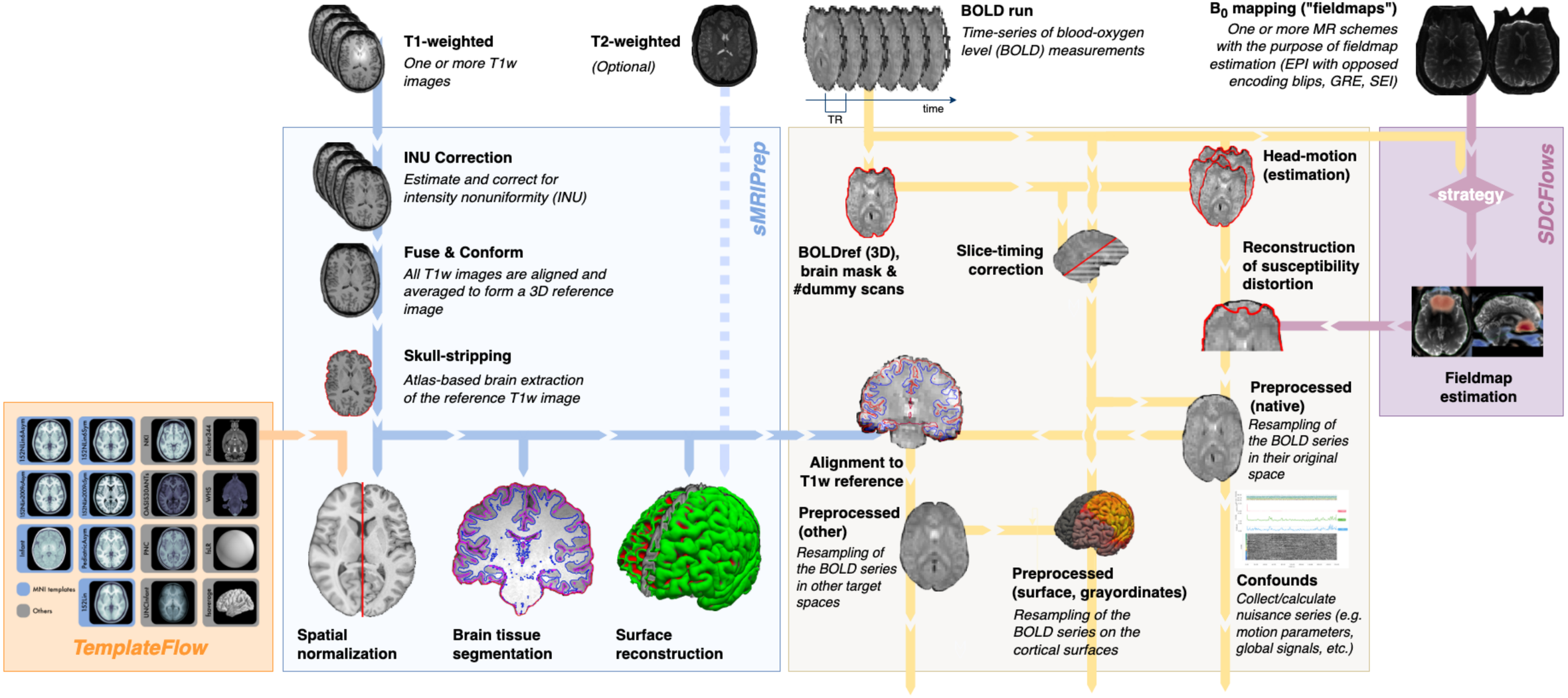


Andersson, J. L. R., Skare, S., & Ashburner, J. (2003). How to correct susceptibility distortions in spin-echo echo-planar images: application to diffusion tensor imaging. *NeuroImage*, *20*(2), 870–888. https://doi.org/10.1016/S1053-8119(03)00336-7

fMRIPrep

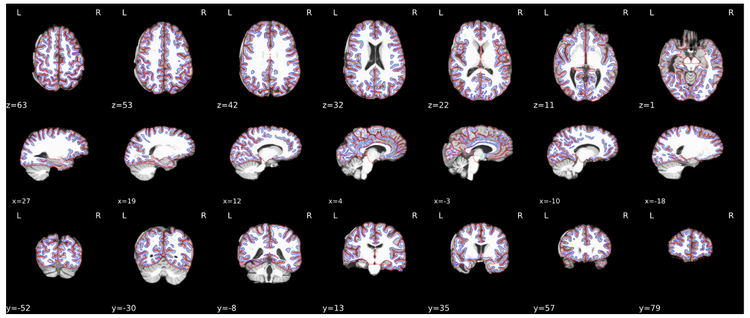
- **Current standard for whole-brain fMRI preprocessing**
- Built on nipype, templateflow, sdcflow
- Containerized and HPC compatible
- Highly parallelized workflow
- Requires BIDS-format data
- State-of-the-art spatial resampling
- Designed for whole-brain MRI
- Current latest version 25.0.0 (fmriprep.org)
- Source available (github.com/nipreps/fmriprep)

fMRIPrep Overview

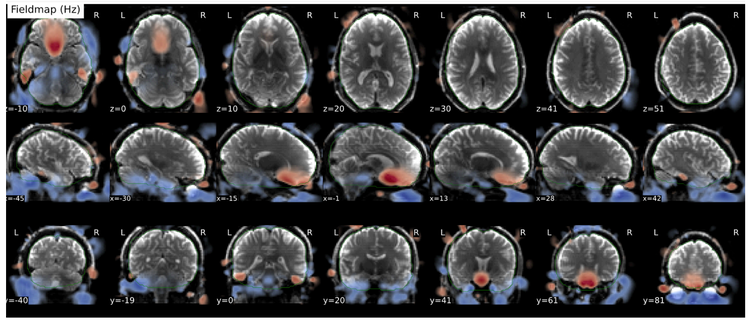


fMRIPrep Quality Control

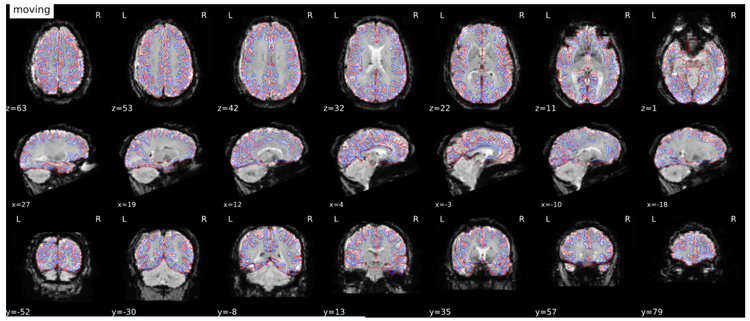
Structural segmentation



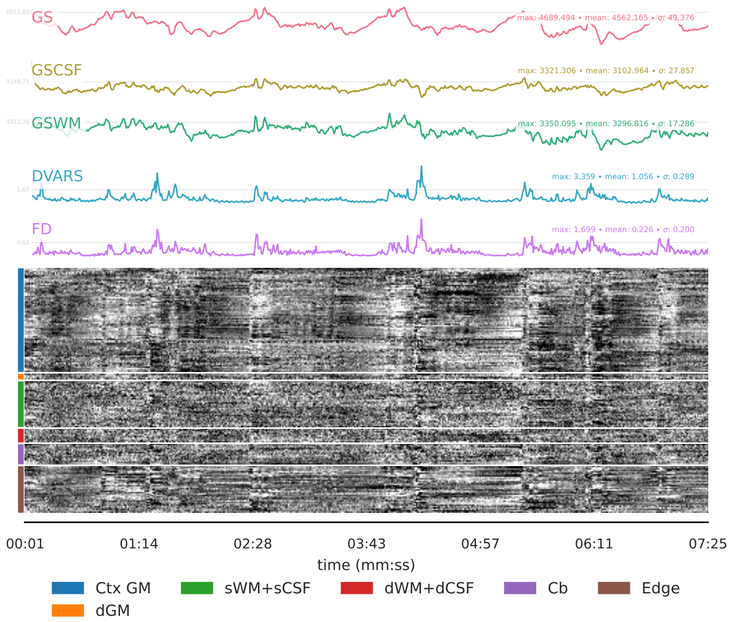
SDC Fieldmap Estimate



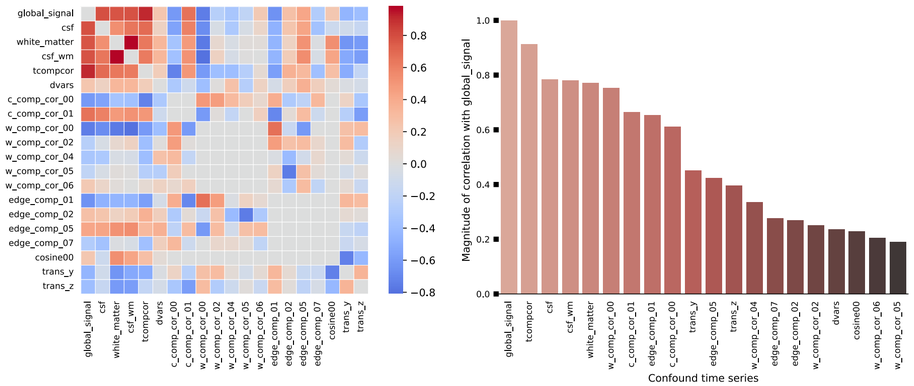
EPI to Structural Registration



Global signal and motion



Confound correlations



Epilogue

- **2025 CBIC fMRI Bootcamp Slides**
  - https://evendim.sites.caltech.edu/teaching
- **Topics not covered**
  - BOLD physiology and neurovascular coupling
  - Non-BOLD fMRI methods
  - fMRI analysis