



Radboud University



Coregistration of OPM-MEG data

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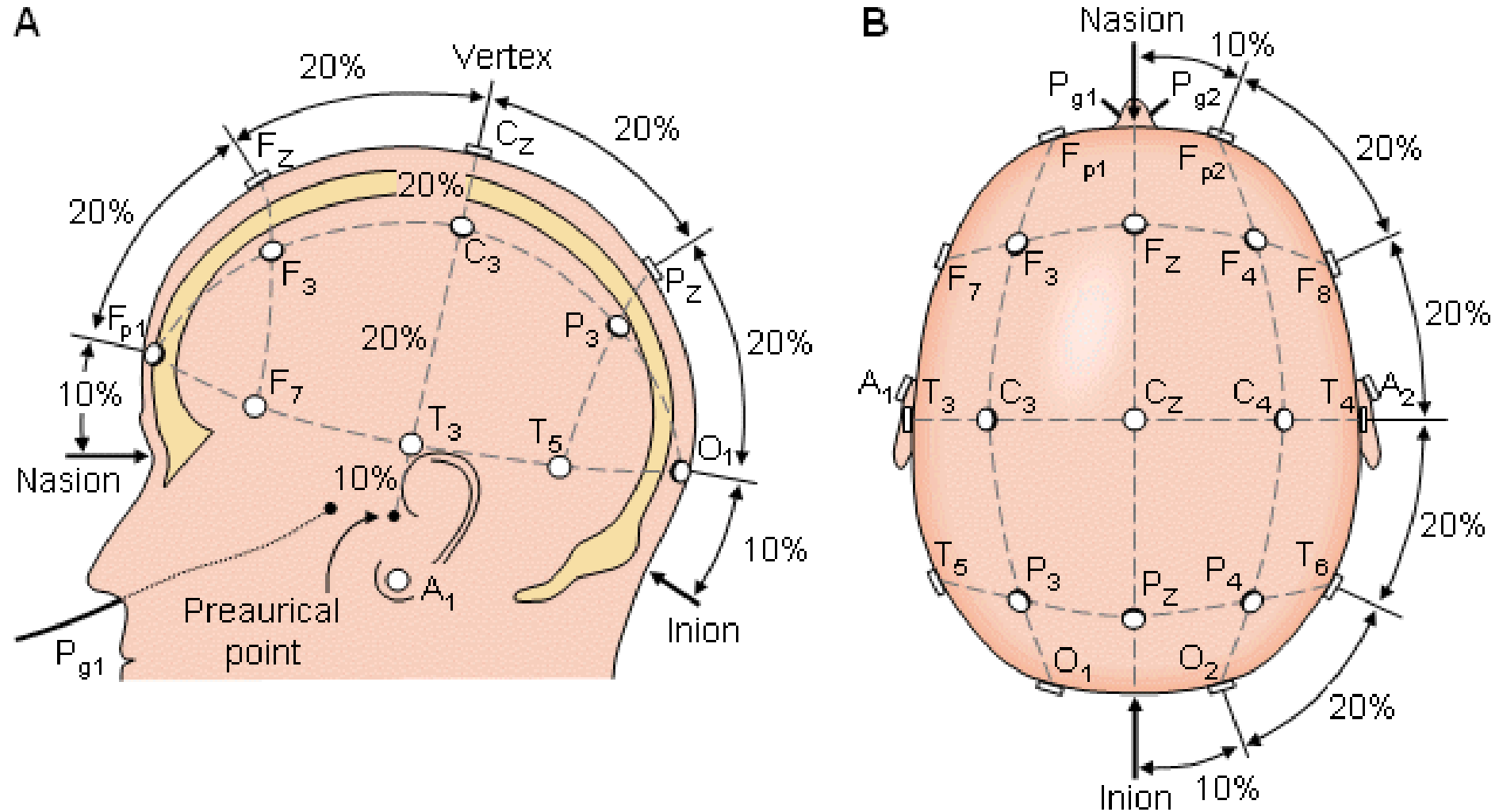
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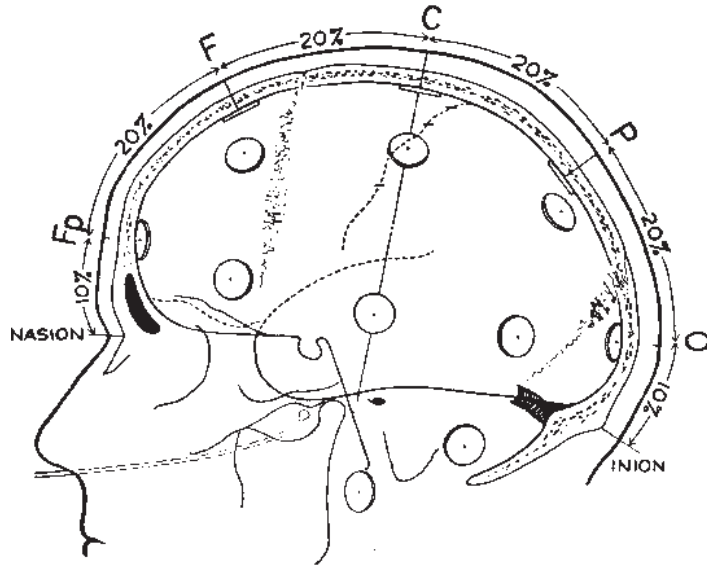
Karolinska
Institutet



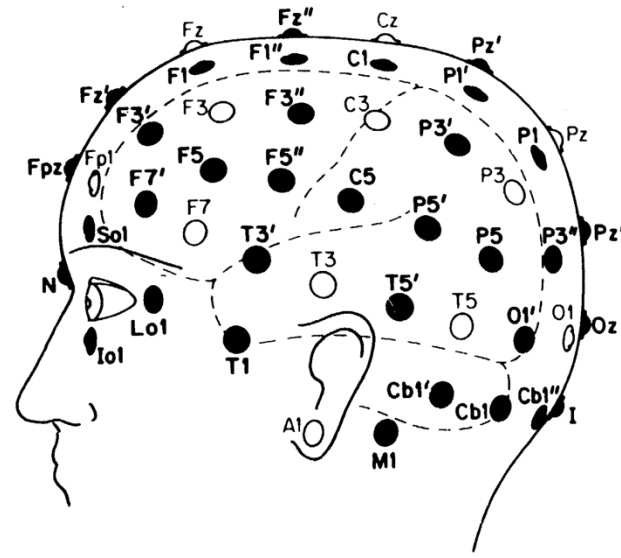
Coordinate systems for placing EEG electrodes



Coordinate systems for placing more EEG electrodes: 10-20, 10%, 5%



Jasper (1958)



Measuring the actual placement of EEG electrodes

The anatomical landmark-based 10-20 and derived placement schemes aim for consistent and comparable locations over **participants**, and consistent names over **labs**.

You slap an EEG cap on, and you are done ... right?

Still, heads differ and EEG experimenters are not always precise.

EEG caps speed up the placement, but make the placement less accurate.

Caps do not always fit our participant so well.

Caps differ between manufacturers.

Why is coregistration important for EEG?

Accurate source reconstruction of EEG activity benefits from individual anatomical MRIs (and headmodels) and/or from individually measured electrode positions.

You may or may not have an anatomical MRI available.

You may or may not have 3D electrode positions available.

... if so, they need to be coregistered.

	3D elec yes	3D elec no
MRI yes		?
MRI no	?	

But that is not the topic for today.

See <https://www.fieldtriptoolbox.org/tutorial/electrode/> and Homölle et al. (2019)

Why is coregistration (more) important for MEG?



SQUID (and some OPM) system helmets have a fixed size, whereas head sizes differ. Heads can be at different positions/angles in the helmet or relative to the sensors. The distance and relative location of the sensors to the brain varies.

We specifically rely on MEG for its high spatiotemporal resolution:
to learn about the “where” and “when” and “how” in the brain.
Comparing/combining over participants requires dealing with head size and anatomical differences.

Why is coregistration important for MEG?

It is required for “mapping” the channel-level data to the brain, aka source reconstruction.

Source reconstruction

- ... allows for correct interpretation of the activity (and derived measures such as connectivity).
- ... allows for mapping MEG results to anatomy and fMRI results.
- ... allows for comparing activity and networks over participants.

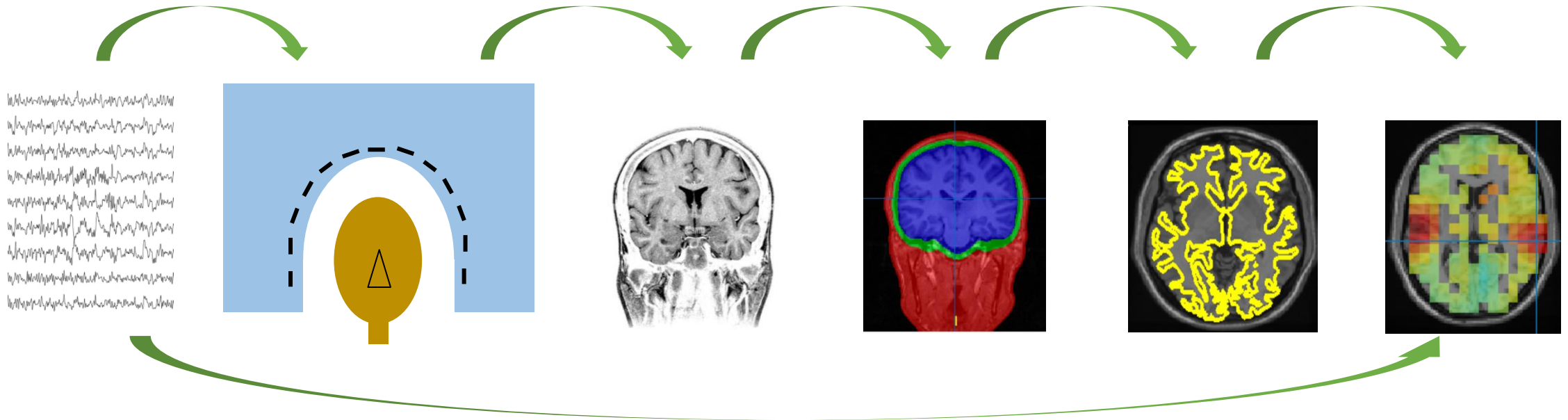
The more accurate your coregistration, the more accurate your interpretation of the brain activity.

What is it that we coregister?

The sensors (and thereby the fields that they record) relative to the head

The head relative to the MRI data, including

- the volume conduction model (or head model)
- the cortical sheet (or source model)



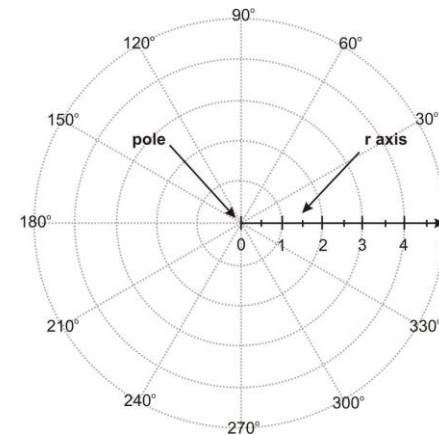
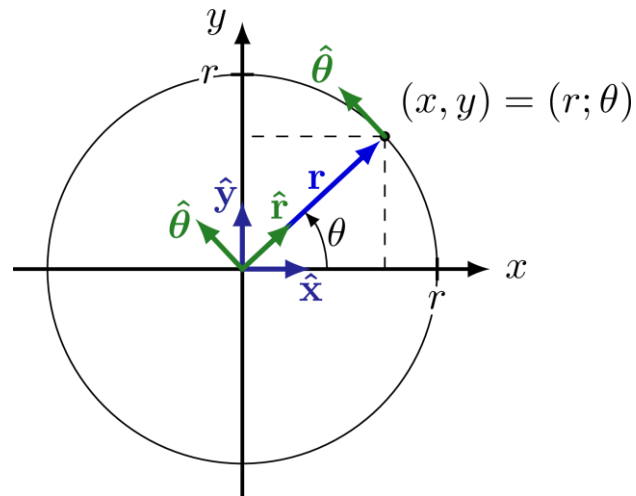
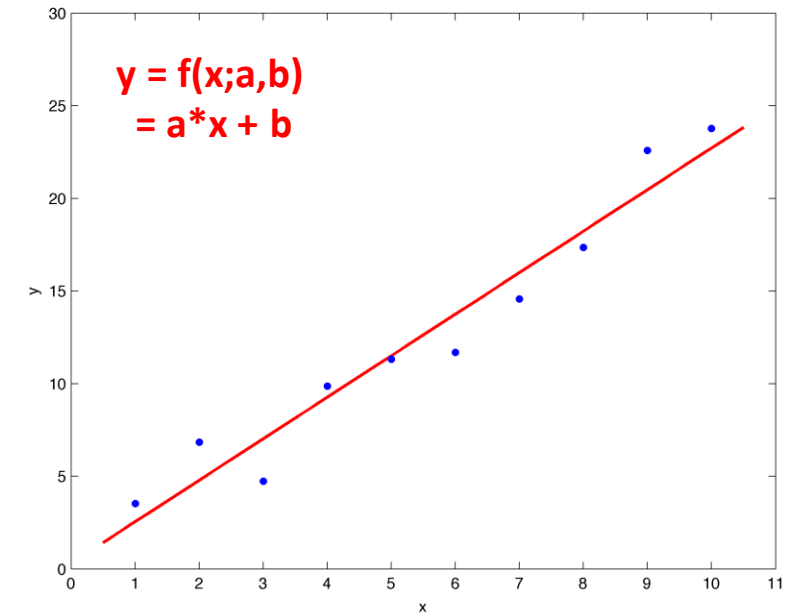
Some basics

Coordinate systems

X along the horizontal axis, Y along the vertical axis

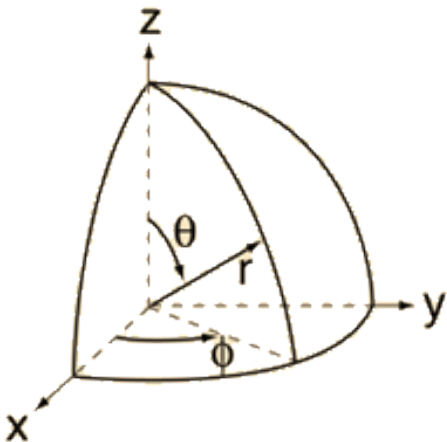
Cartesian coordinates use a pair (or triplet) of numbers along perpendicular axes, like $[x, y, z]$

Radial or polar coordinates use a pair that describe the radius and angle

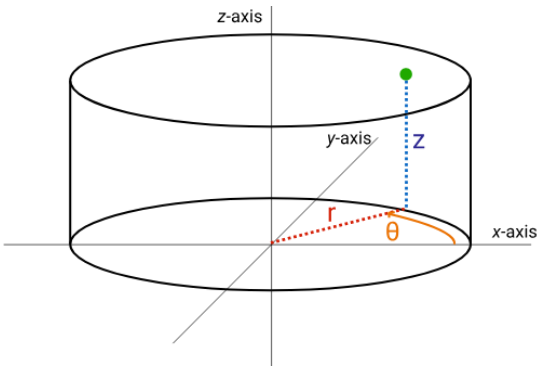


Coordinate systems

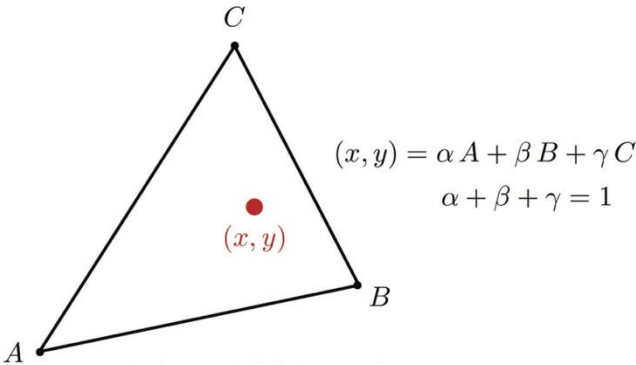
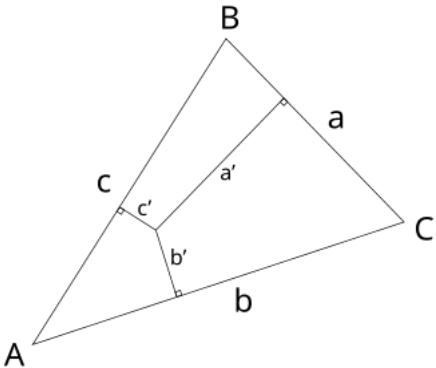
Cartesian $[x, y]$ or $[x, y, z]$
Radial or polar $[r, \theta]$



Spherical $[r, \theta, \phi]$ or in MATLAB [azimuth, elevation, radius]
Cylindrical $[r, \theta, z]$



Trilinear or Barycentric coordinates on a triangle



Cartographic mapping – spheres and projections

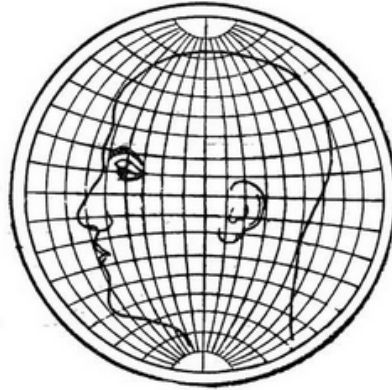


FIG. 42.—Man's head drawn on globular projection.

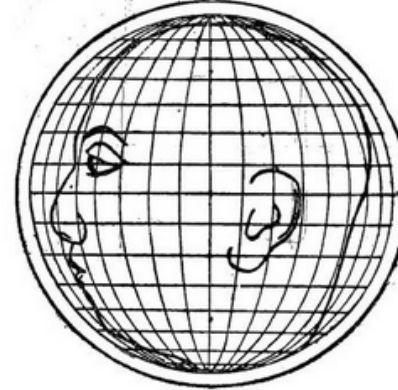


FIG. 43.—Man's head plotted on orthographic projection.

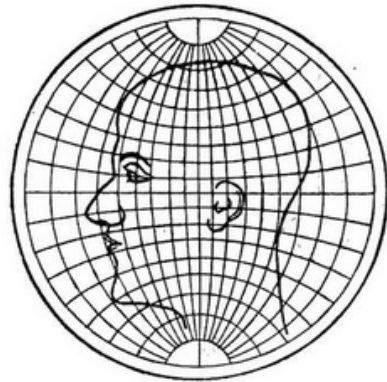


FIG. 44.—Man's head plotted on stereographic projection.

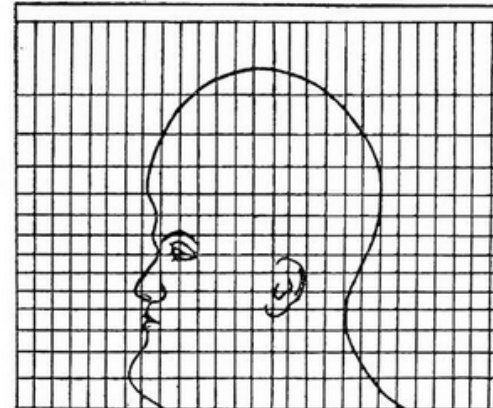


FIG. 45.—Man's head plotted on Mercator projection.

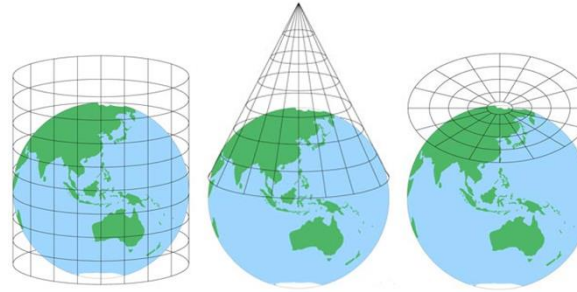
Cartographic mapping

The earth is approximately a sphere

Magnetic north and south pole

Axis around which the sphere rotates

Where is $[0, 0]$ defined?



Mercator projection

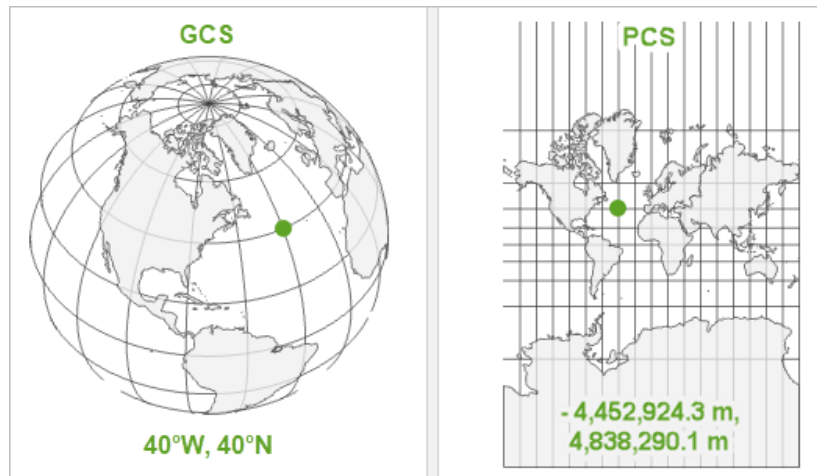


Equal-earth projection

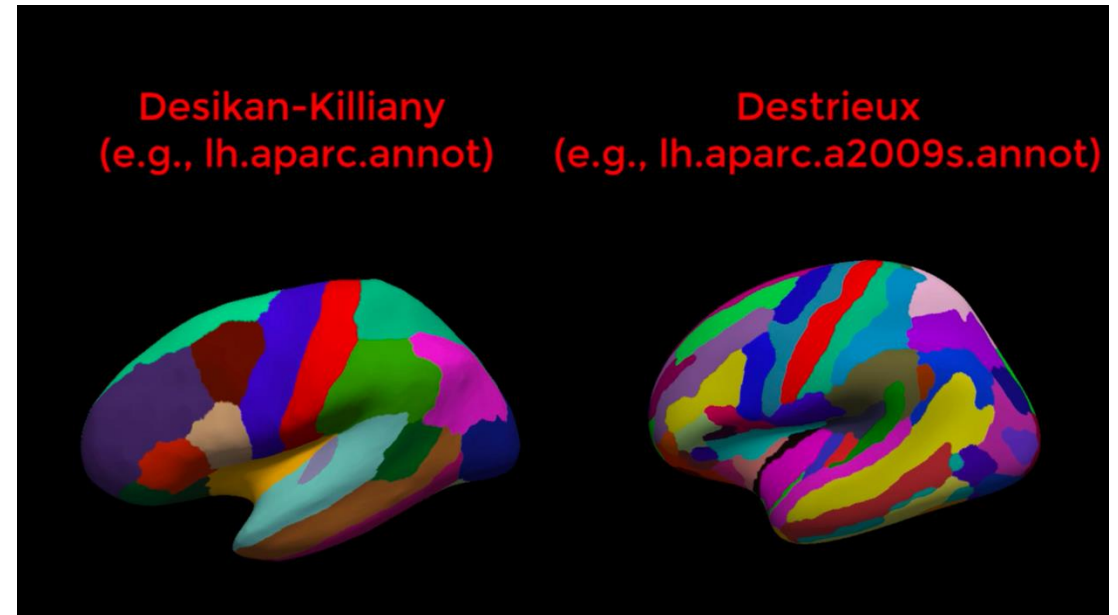
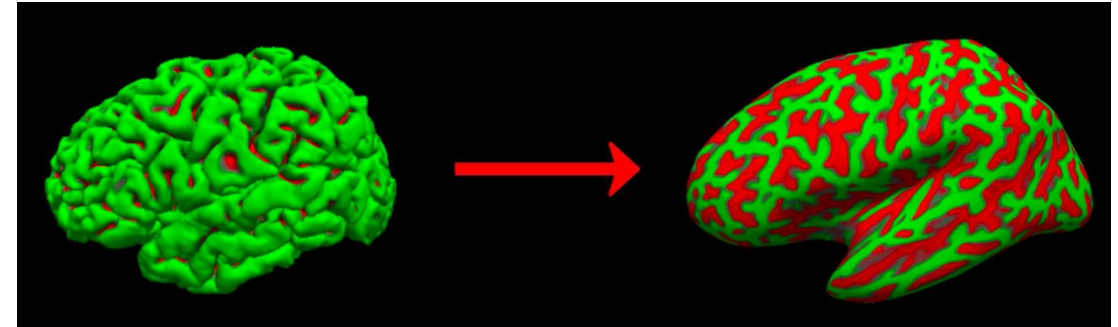
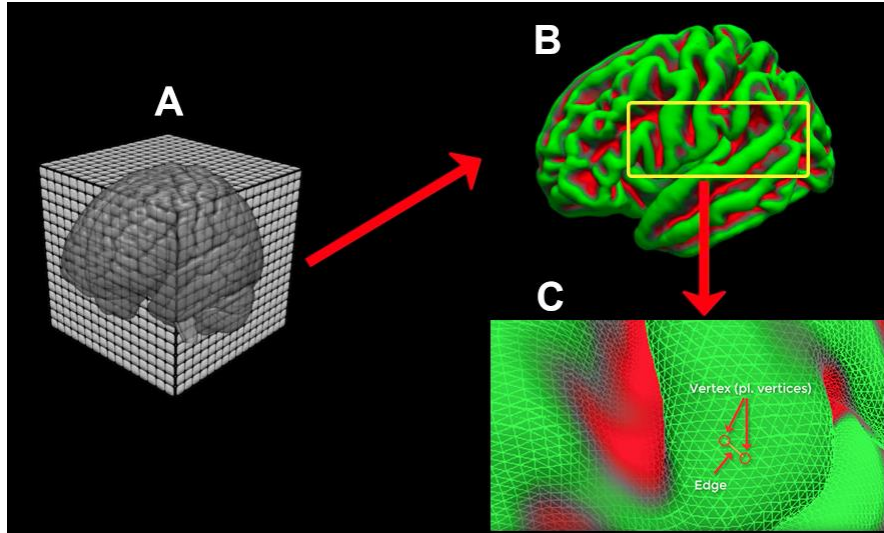


What if the earth is projected on a 2D surface (like paper)?

“All maps are wrong, but some are useful.”



Cartographic mapping in Freesurfer



Inflated representation of the cortex.
Values expressed at surface coordinates.
Mapping of an atlas onto the individual
cortical sheet.

Mapping between neuroimaging data and atlases

How can we map our estimated activity on volumetric or surface-based atlases?

How can we use atlases in the analysis (for example as parcellations)?

How can we use templates (if we don't have individual MRIs)?

But those are not the topics for today.

See <https://www.fieldtriptoolbox.org/template/atlas/> and elsewhere on the FieldTrip website.

Coordinate systems for the (human) body

Anterior: In front of; toward the face
Posterior: Behind; toward the back
Superior: Above; toward the head
Inferior: Below; toward the feet

Medial: Toward the middle

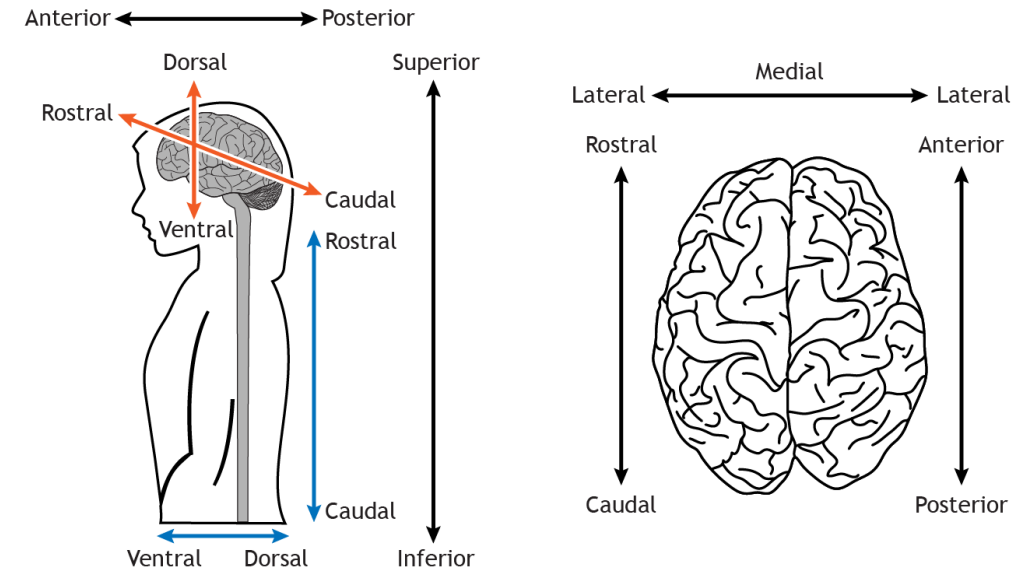
Lateral: Toward the edge

Dorsal: Toward the top of the brain or the back of the spinal cord

Ventral: Toward the bottom of the brain or the front of the spinal cord

Rostral: Toward the front of the brain or the top of the spinal cord

Caudal: Toward the back of the brain or the bottom of the spinal cord



Coordinate system naming
ALS, RAS, etc.

ALS = Anterior Left Superior

X-axis goes to anterior

Y-axis goes to left

Z-axis goes to superior

Coordinate systems for the (human) body

These body coordinate systems describe the orientations,
but not the origin that we define as $[0, 0, 0]$

For MRI scanners the origin is exactly at the middle of the bore.
For SQUID-MEG systems the origin is somewhere
in the middle of the dewar or helmet.

Data acquisition starts in device (or scanner) coordinates

Coordinate system naming
ALS, RAS, etc.

ALS = Anterior Left Superior

X-axis goes to anterior

Y-axis goes to left

Z-axis goes to superior

Cartesian coordinate systems (for the head)

MEG or MRI **device coordinates**, relative to the machine

Head coordinates:

CTF

Neuromag/Elekta/MEGIN

AC/PC

<https://www.fieldtriptoolbox.org/faq/coordsys/>

Talairach-Tournoux coordinates

MNI coordinates

MNI152 aka SPM

MNI305

MNI152 NLIN 2009a, 2009b, 2009c

Colin27

fsaverage, etc.

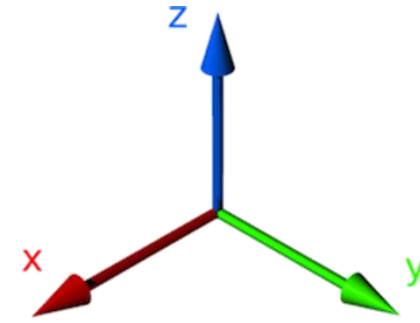
These are all methods to make the group analyses and reporting of coordinates consistent by making use of a **template space**. Often combined with a delineation of regions, aka an **atlas**.

<https://www.fieldtriptoolbox.org/template/>

Cartesian coordinate systems (for the head)

Specification of the **origin**, the direction of the **axes**, and sometimes the **units**

We often use Red/Green/Blue colors for XYZ.

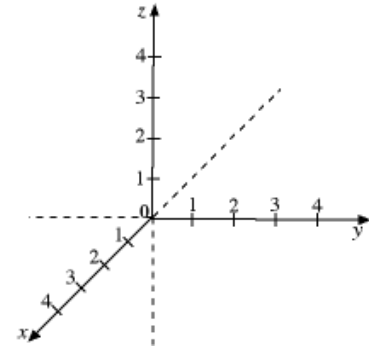


Based on external landmarks for non-imaging methods like EEG (and MEG)

- nasion

- left pre-auricular point

- right pre-auricular point



Based on internal landmarks visible in the image(s) for methods like MRI, CT, PET, X-ray

- anterior commissure (AC)

- posterior commissure (PC)

LPA and RPA, or the “points around the ear”

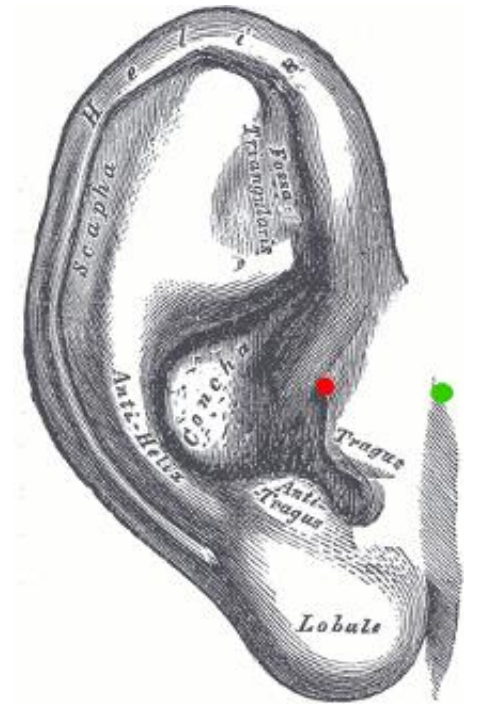
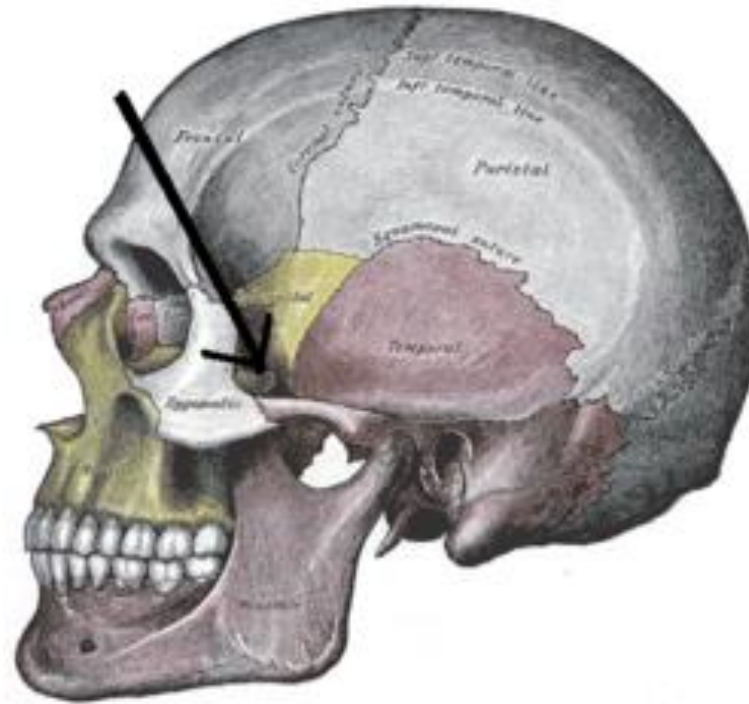
Pre-auricular points

Tragus, or the point above the tragus

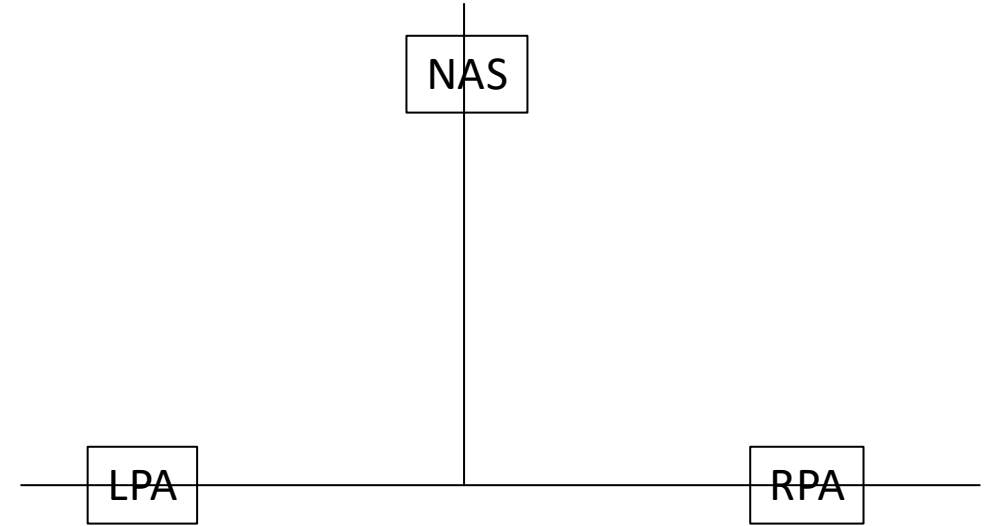
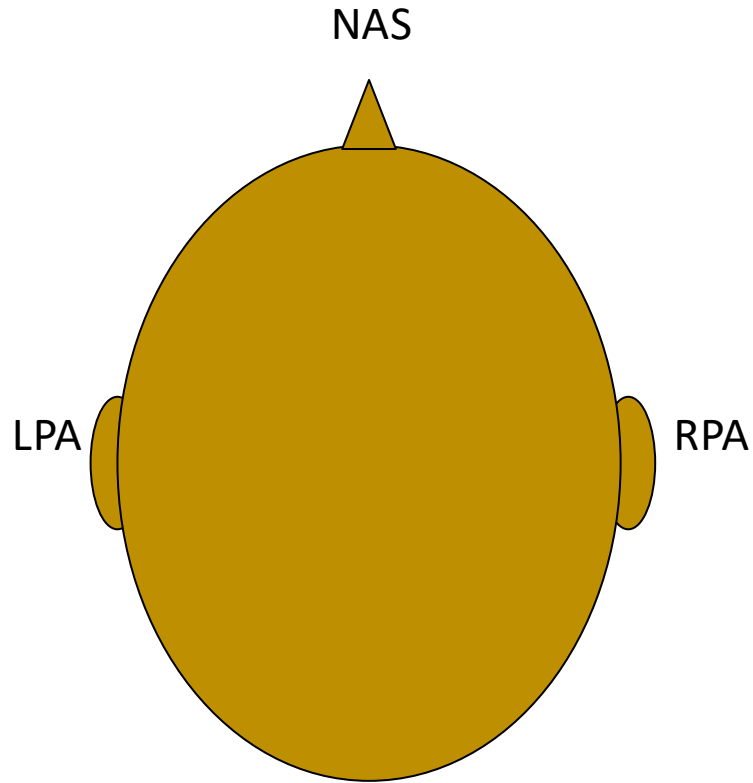
The ear canal

Ear lobes

Mastoids



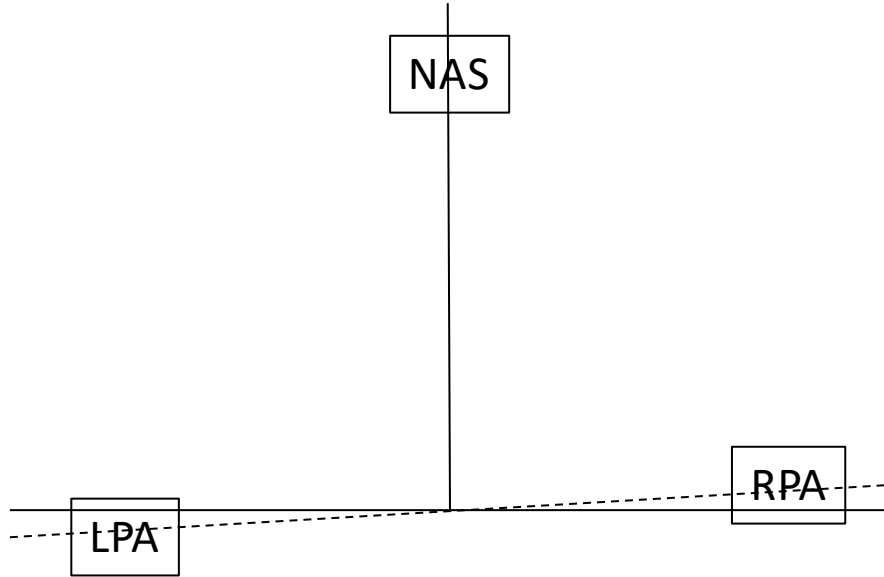
The NAS/LPA/RPA head coordinate system(s)



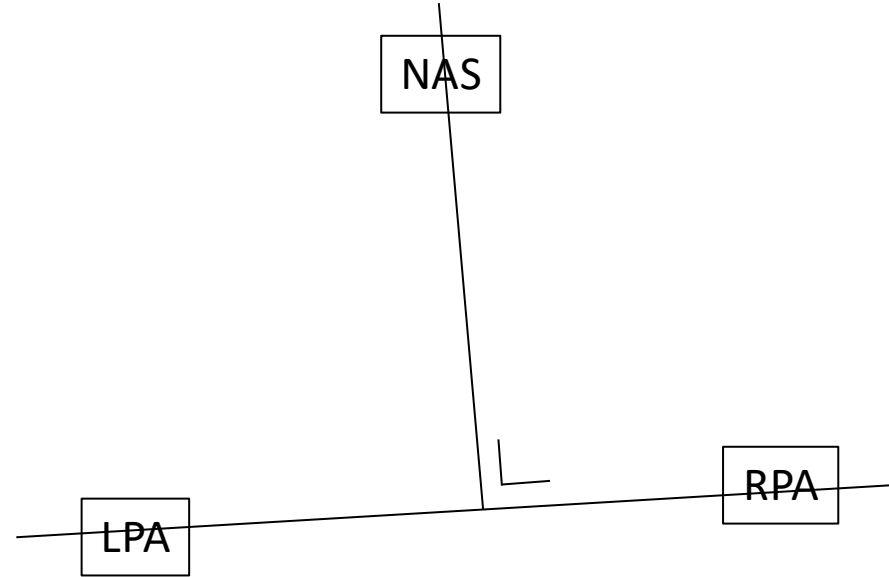
For CTF, the axis going to the nose is the x-axis (aka ALS).

For Neuromag, the axis going from L to R is the x-axis (aka RAS).

The NAS/LPA/RPA head coordinate system(s) considering asymmetric ears

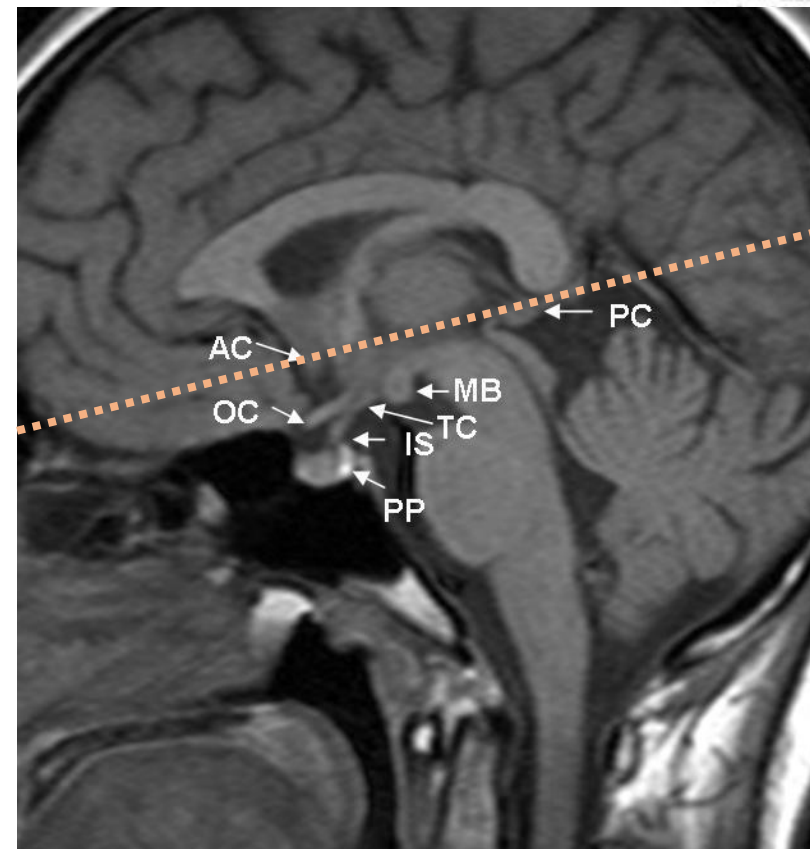
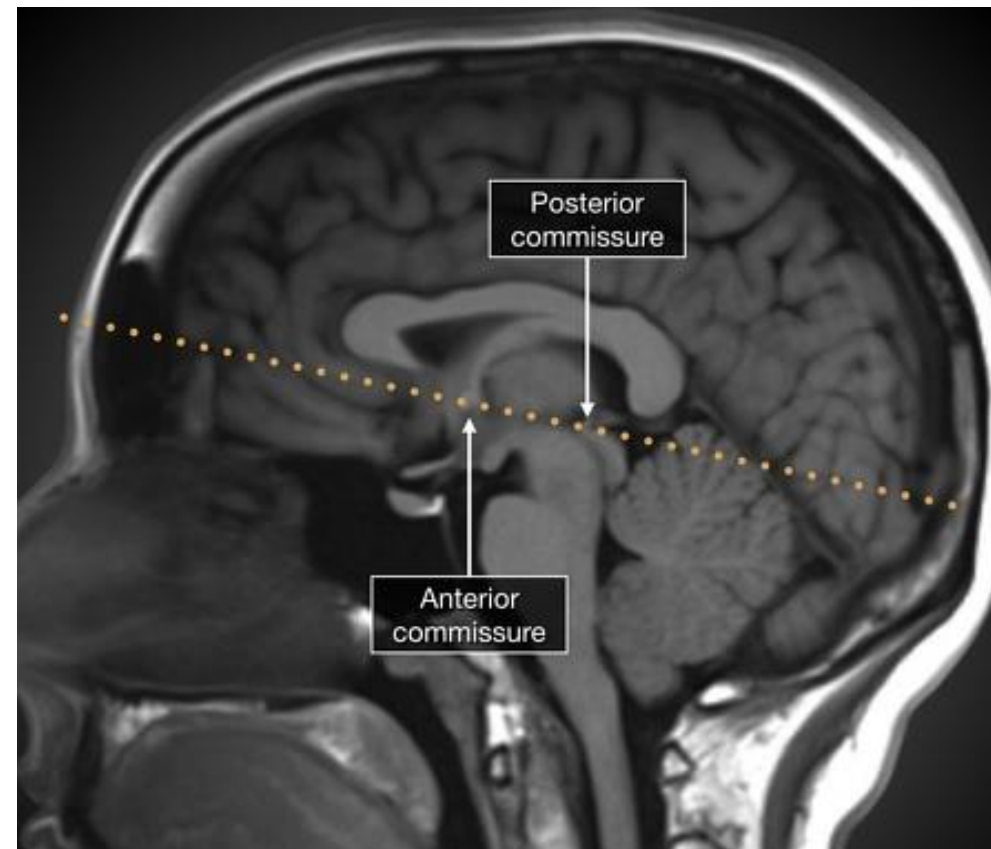
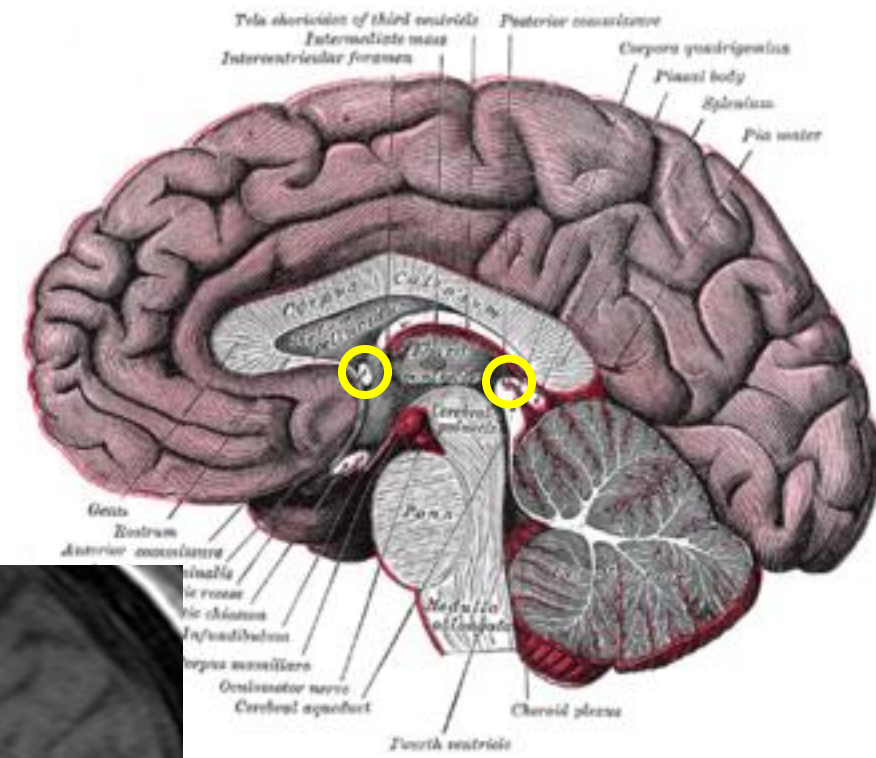


The origin can be the **midpoint**
on the helper line
between LPA and RPA.

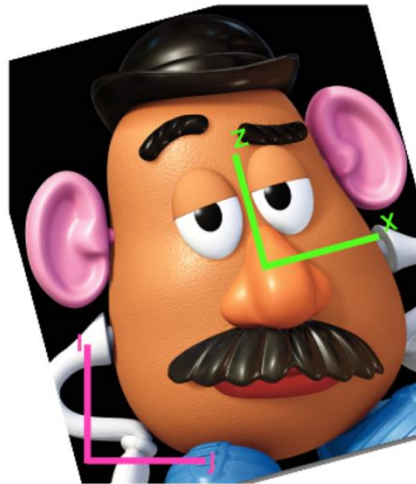
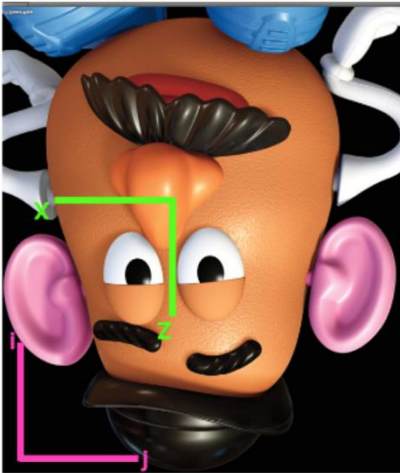
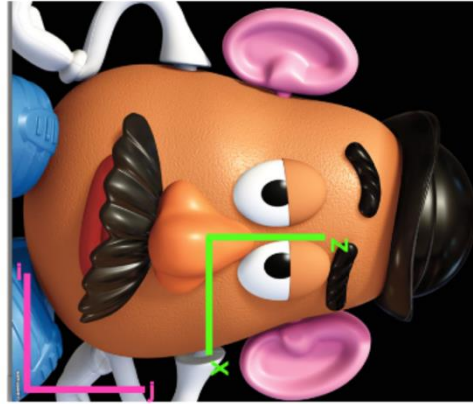
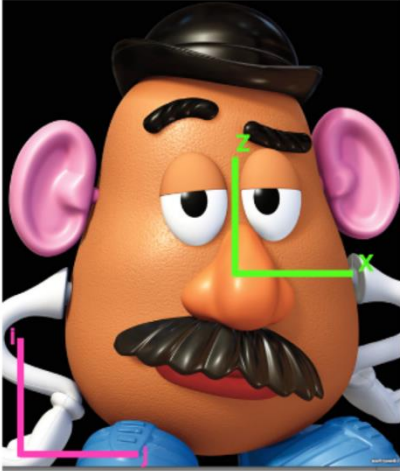


The origin can be the point
where the line from the nasion
is **orthogonal** to the LPA-RPA line.

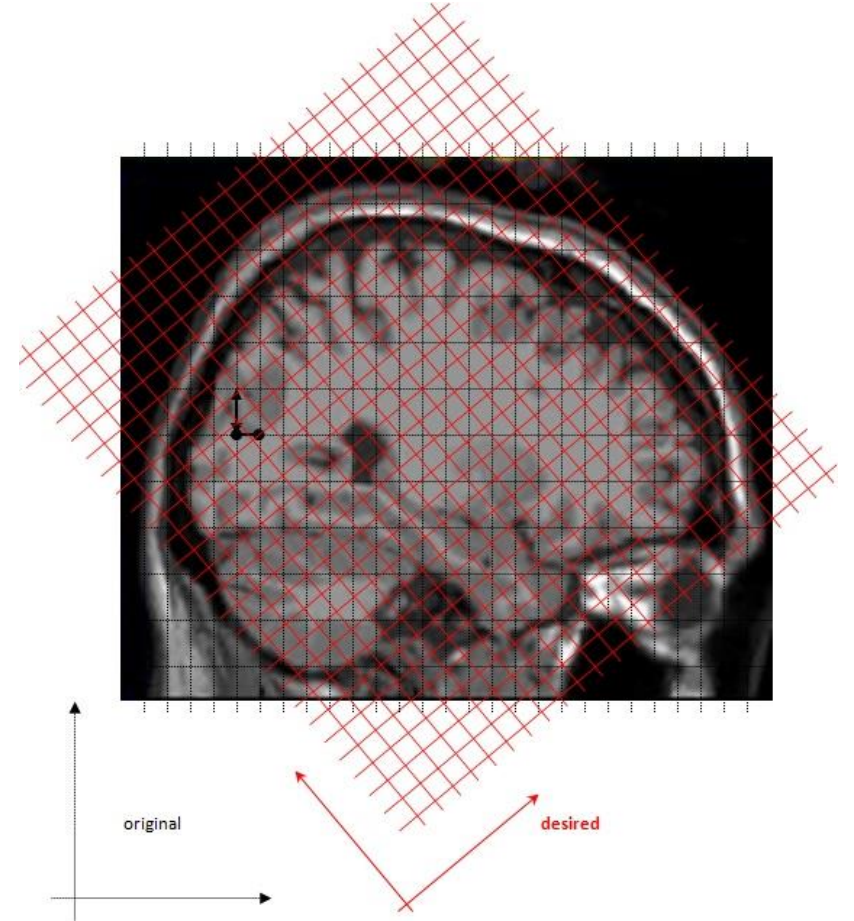
The AC/PC coordinate system



The point-of-view and image orientation are not the same as the coordinates



```
cfg = [];  
cfg.method = 'flip';  
mri_flipped = ft_volumereslice(cfg, mri)
```



```
cfg = [];  
cfg.method = 'linear';  
mri_resliced = ft_volumereslice(cfg, mri)
```

Radiological versus Neurological convention

Radiological convention

Viewed from the patient's feet looking up toward the head
(as if standing at the end of the bed or the scanner).

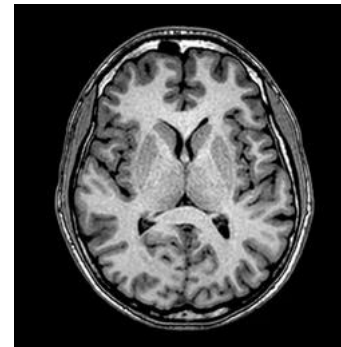
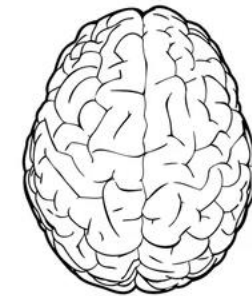
Patient's **right** is on the viewer's **left**; patient's **left** is on the viewer's **right**.

Neurological convention

Viewed from above the head looking down toward the feet
(a bird's-eye view, as if standing behind the patient who is sitting on a chair).

Patient's **right** is on the viewer's **right**; patient's **left** is on the viewer's **left**.

These are obvious when you look from the outside and can recognize details on the surface, but not if you look at an axial MRI image.



Coordinates and transformations

MEG and EEG coordinate systems

EEG electrodes and MEG sensor positions are expressed as an Nx3 list of numbers.
Changing the coordinates in which they are expressed means changing the numbers.

Translations means that we add a number.

Rotations require dealing with sin and cos.

Scaling requires that we multiply:

scaling from cm to mm means 10 x

scaling from mm to cm means 0.1 x

```
>> xyz = randn(5,3)
```

```
xyz =
```

0.8884	1.4384	-0.1022
-1.1471	0.3252	-0.2414
-1.0689	-0.7549	0.3192
-0.8095	1.3703	0.3129
-2.9443	-1.7115	-0.8649

```
>> xyz(:,3) = xyz(:,3) + 100
```

```
xyz =
```

0.8884	1.4384	99.8978
-1.1471	0.3252	99.7586
-1.0689	-0.7549	100.3192
-0.8095	1.3703	100.3129
-2.9443	-1.7115	99.1351

MRI coordinate systems and homogenous coordinates

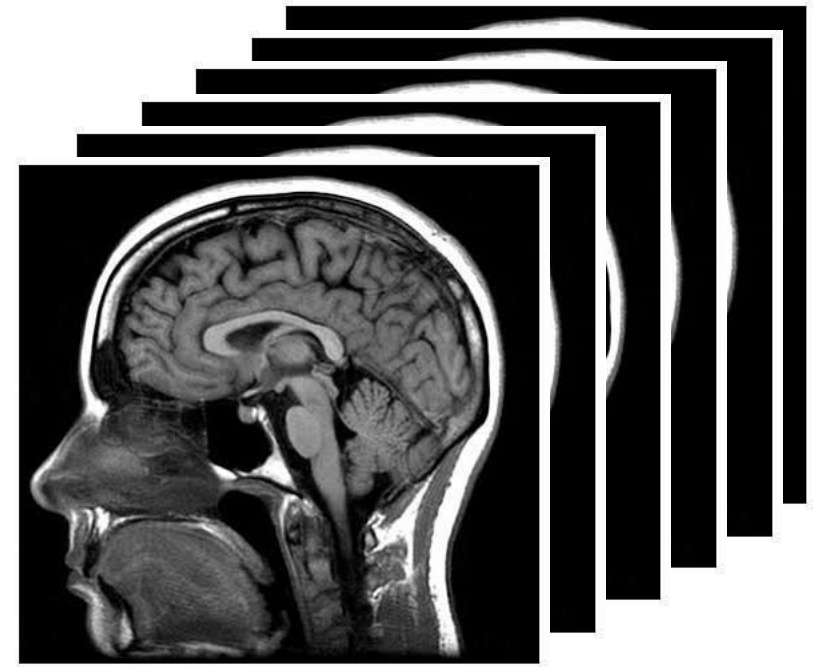
An MRI is a stack of images, or a 3D array in MATLAB.
Each pixel (in the image) or voxel (in the volume) has a grey-scale value.

We use homogenous transformations to map from
voxel indices to voxel coordinates:

$$[i, j, k] \rightarrow [x, y, z]$$

$[i, j, k]$ are expressed as dimensionless (integer) numbers

$[x, y, z]$ are expressed in units of distance, like mm



Homogenous coordinate transformations

$$\mathbf{M} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad \begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \mathbf{M} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

$$\mathbf{M} = \begin{pmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad \begin{pmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} v_x \\ v_y \\ v_z \\ 1 \end{pmatrix} = \begin{pmatrix} v_x + t_x \\ v_y + t_y \\ v_z + t_z \\ 1 \end{pmatrix}$$

Homogenous coordinate transformations

$$\mathbf{M} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \mathbf{M} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

$$\mathbf{M} = \begin{pmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} v_x \\ v_y \\ v_z \\ 1 \end{pmatrix} = \begin{pmatrix} s_x v_x \\ s_y v_y \\ s_z v_z \\ 1 \end{pmatrix}$$

Homogenous coordinate transformations

$$\mathbf{R}_x(\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta) & \sin(\theta) & 0 \\ 0 & -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{R}_y(\theta) = \begin{pmatrix} \cos(\theta) & 0 & -\sin(\theta) & 0 \\ 0 & 1 & 0 & 0 \\ \sin(\theta) & 0 & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{R}_z(\theta) = \begin{pmatrix} \cos(\theta) & -\sin(\theta) & 0 & 0 \\ \sin(\theta) & \cos(\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{R} = \mathbf{R}_x * \mathbf{R}_y * \mathbf{R}_z$$

*Note that the order of rotations and
hence multiplications matters*

Homogenous coordinate transformations

transforming voxel indices to head coordinates (in mm)

$$XYZ = M * IJK$$

transforming Cartesian positions from one coordinate system to another

$$XYZ_{\text{new}} = M * XYZ_{\text{old}}$$

M is the 4x4 homogenous coordinate transformation matrix
(in FieldTrip also called T, or H, or “transform”)

Homogenous coordinate transformations

transforming Cartesian positions from one coordinate system to another

$$XYZ_{\text{new}} = M * XYZ_{\text{old}}$$

combining or “chaining” multiple transformations

$$XYZ_{\text{new}} = M_T * M_S * M_R * XYZ_{\text{old}}$$

*Note that the order of transformations
and hence multiplications matters*

going back by inverting the transformation

$$\text{inv}(M) * XYZ_{\text{new}} = XYZ_{\text{old}}$$

Coregistration in the MEG lab

MEG coregistration using HPI coils

Place three HPI coils on Nasion, LPA and RPA.

At the DCCN we put them on Nasion, left ear-mold and right ear-mold.

The system passes a sinusoidal current through each of the coils, with different frequencies for each coil.

Record MEG, bandpassfilter, determine topography with PCA, fit a magnetic dipole.

This gives the HPI coil location relative to MEG device coordinates. We also know the HPI coil locations in head coordinates, so we can determine the 4x4 transform that maps between device and head coordinates.

This is done with a click of a button for all SQUID systems and stored with the MEG data.



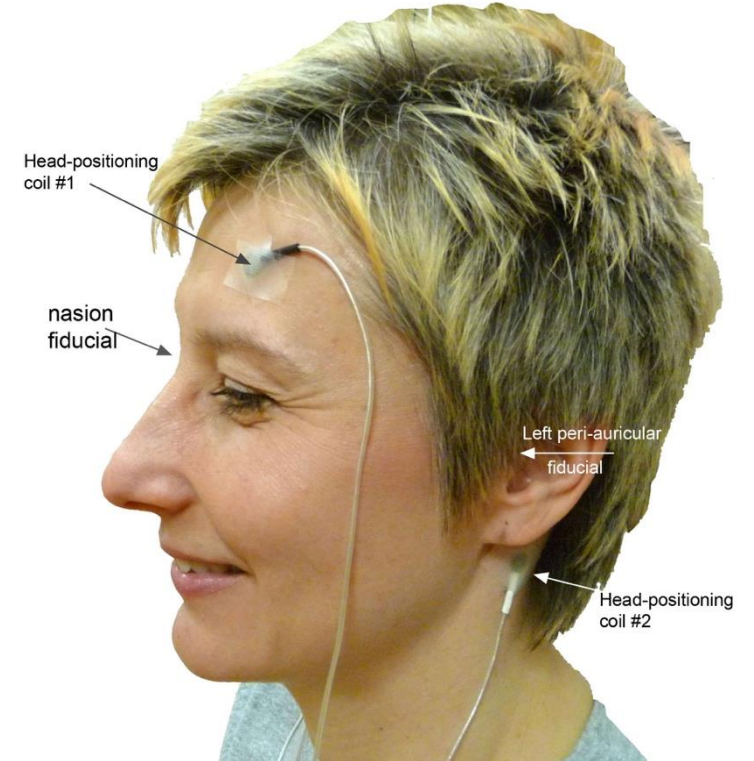
MEG coregistration using HPIs and a Polhemus for the landmarks

Putting a HPI coil on the nasion is not so convenient if the coil is large and/or the cable is stiff.

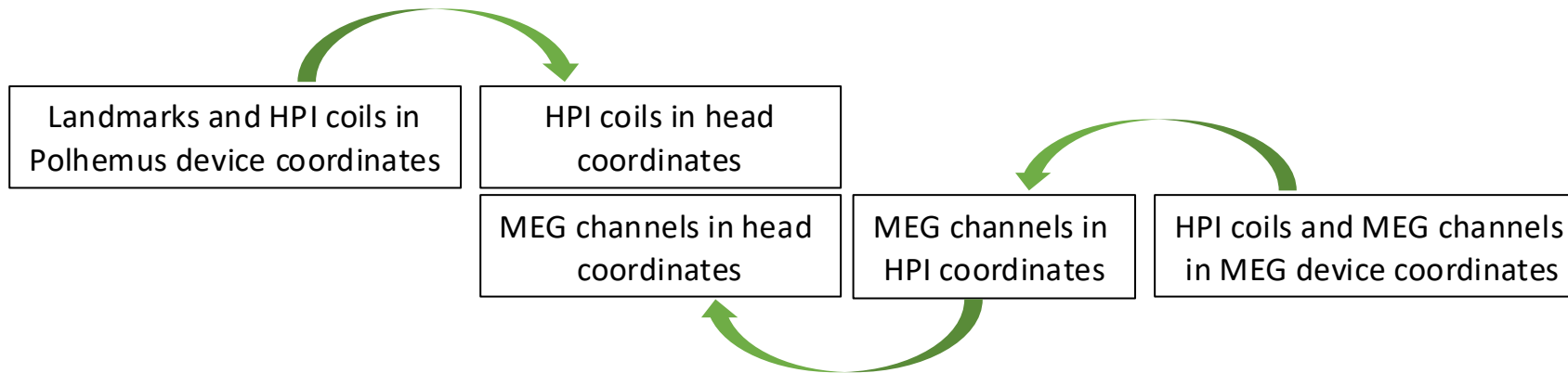
Putting the coils on the ear points is also not trivial.

Rather: place the coils wherever convenient and record both the coils *and* the anatomical landmarks (NAS/LPA/RPA). This also allows to place more than 3 coils.

Use the Polhemus to measure both the anatomical landmarks and the HPI coil positions.



MEG lab @ Medical College of Wisconsin



This is done with a click of a button for the Neuromag SQUID system - but not for CTF - and stored with the MEG data.

MEG coregistration using HPI and a Polhemus head scan

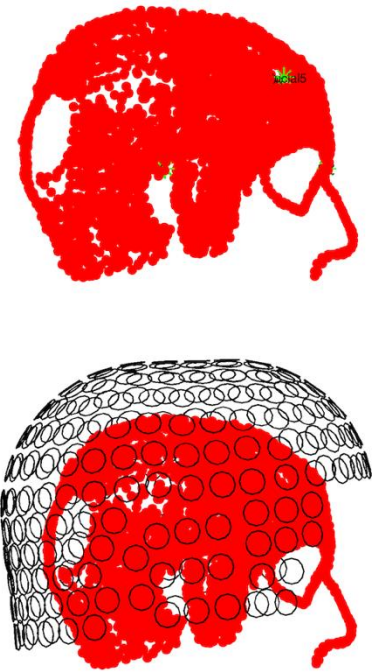
Acquisition is done with the same 3 HPI coils on the landmarks,
or 3 or more HPIs elsewhere combined with the Polhemus recording of both.

Also record the scalp surface by “scraping” with the tip of the Polhemus
stylus over the scalp, trying not to get tangled up in the hair.

Also track around the eyes and nose.

Coregistration initially starts with the same procedure as before
using the landmarks and the HPI coil positions.

Segment the MRI head surface, make a headshape mesh, and use the Iterative Closest Point (ICP)
method to align the MRI headshape to the Polhemus headshape.

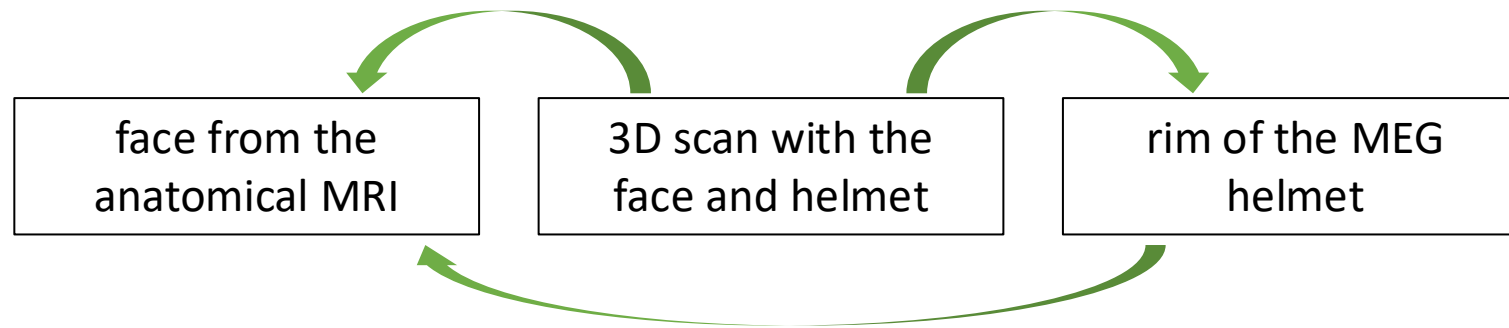


MEG coregistration using an optical 3D scanner

This basically skips the HPI points and Polhemus, but uses a very detailed 3D optical scan of the face in the helmet.

The 3D optical scan is then

- 1) aligned to the surface of the face extracted from the MRI
- 2) aligned to a model of the MEG helmet (with the sensors)

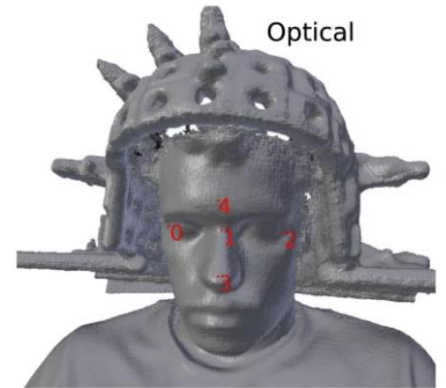


1. Initial alignment

MRI



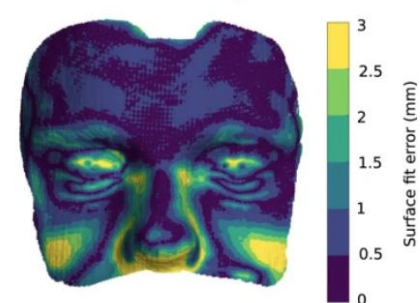
Optical



2. Area selection



3. ICP co-registration



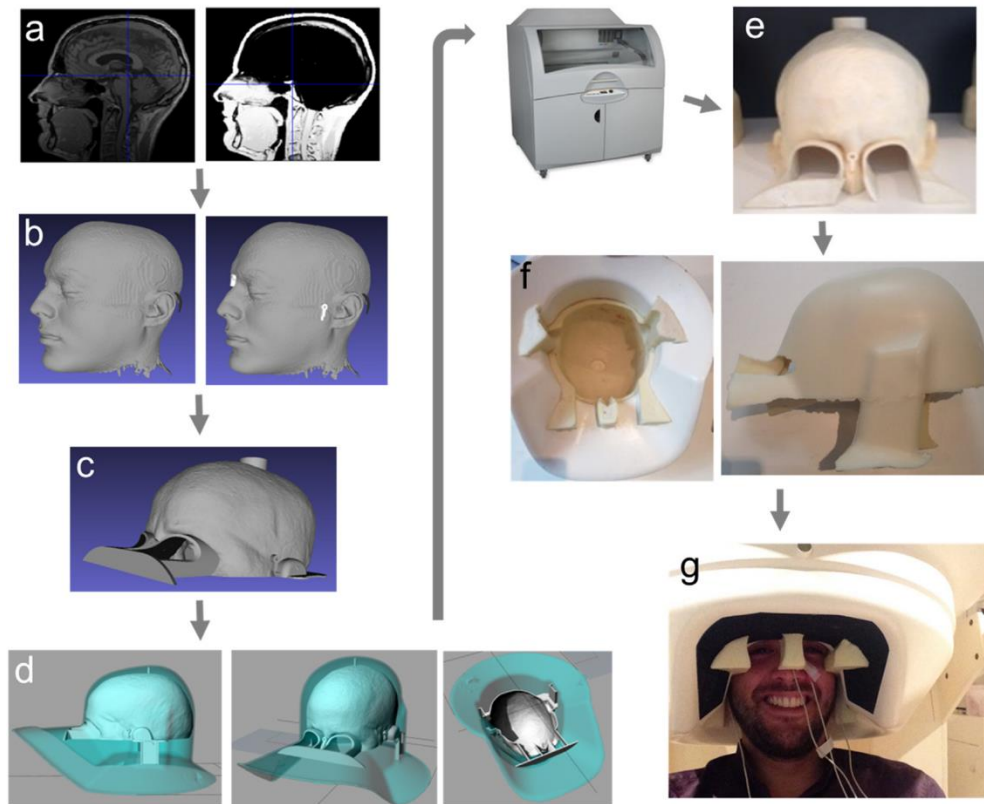
Zetter et al. (2019)

MEG coregistration using MRI-based headcasts/helmets

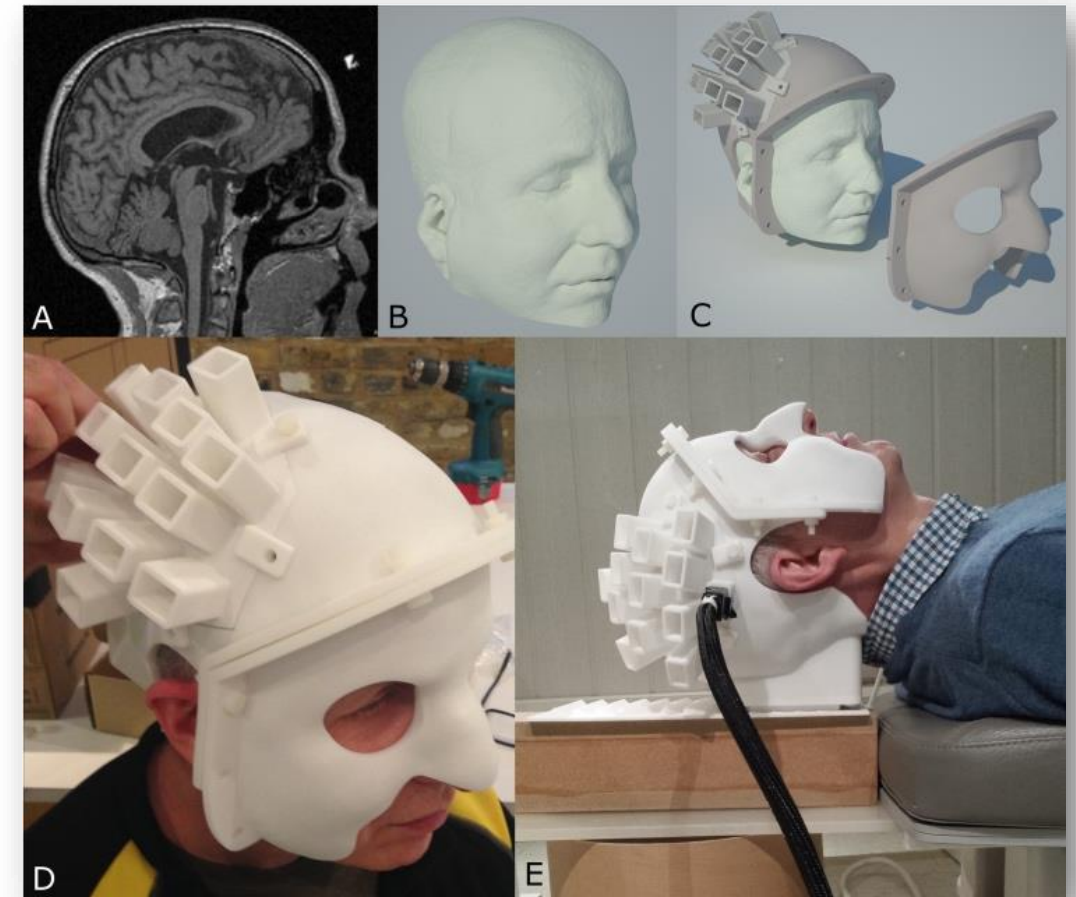
For SQUID MEG we can use headcasts to minimize movements and facilitate repositioning.

With the appropriate design process, the position of the sensors is known relative to the MRI.

For OPM MEG we can make individual MRI-based helmets in which the sensors are (by design) known relative to the MRI.



Meyer, Barnes et al. (2017) J Neurosci Methods



Boto, Barnes, Brookes, et al. (2017) Neuroimage

Why would you use one or the other coregistration method?

Ease of use
Accuracy
Practical reasons



effort and skills required in data processing

Sparse sampling with OPMs does not work well with the very focal spatial topography of HPI coils, hence optical 3D scanning.

What about individual OPM sensors?

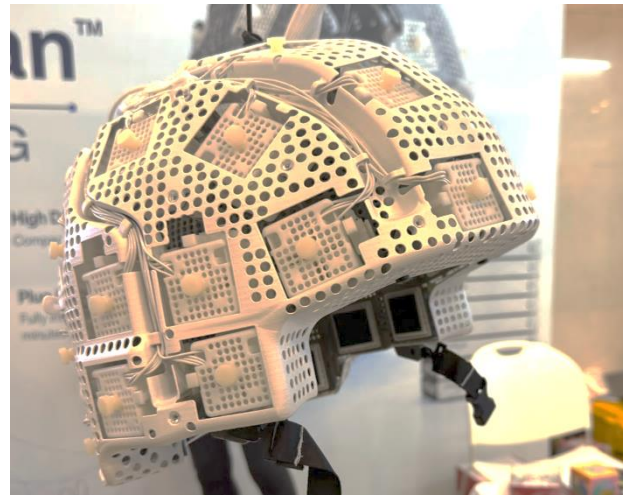
OPMs allow for flexible placement, sometimes allowing movement (sliding in a slot), sometimes used in semi-flexible helmets or soft EEG-like caps.

In that case you (also) need to determine the position and orientation of all OPMs relative to each other, relative to the helmet, and/or relative to the head.

Position/orientation of sensors must be known for some OPM denoising methods, like HFC and AMM (but not for SSP).



FieldLine “beta2” smart helmet



Upcoming FieldLine smart helmet



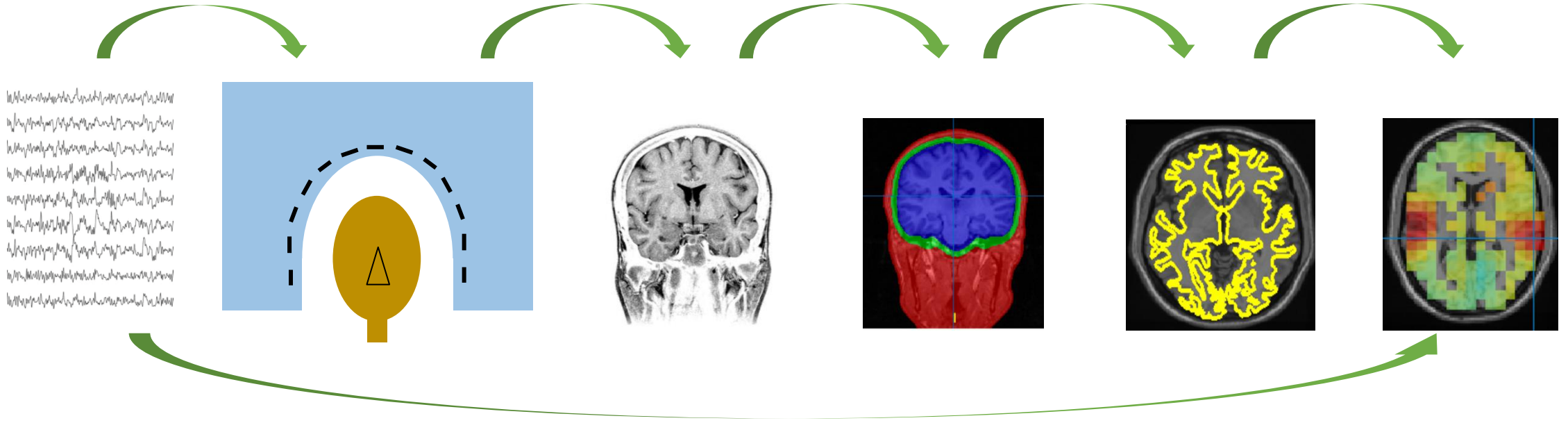
QuSpin Halo



Mag4Health

Back to the conceptual idea

Why are we coregistering again?



In the end we don't really care in which coordinates everything is expressed, as long as it is expressed consistently.

Note that the units also have to be consistent

- CTF expresses sensor positions in cm

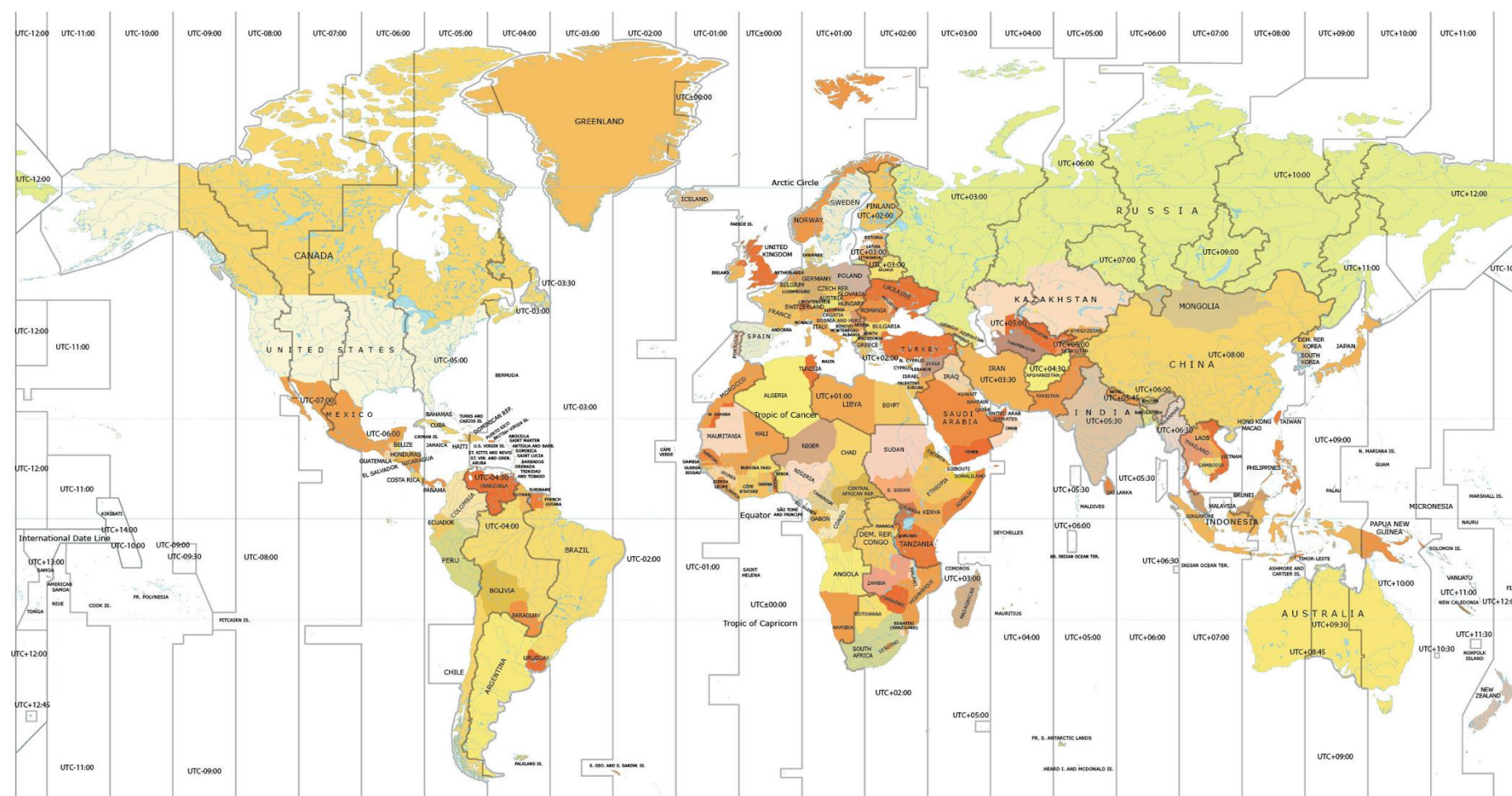
- Anatomical MRIs are often in mm

- Correct biophysical computations require everything to be in SI units, hence meter, Tesla, Volt, Ohm, etc.

Coregistration or (re)alignment, just like timezones

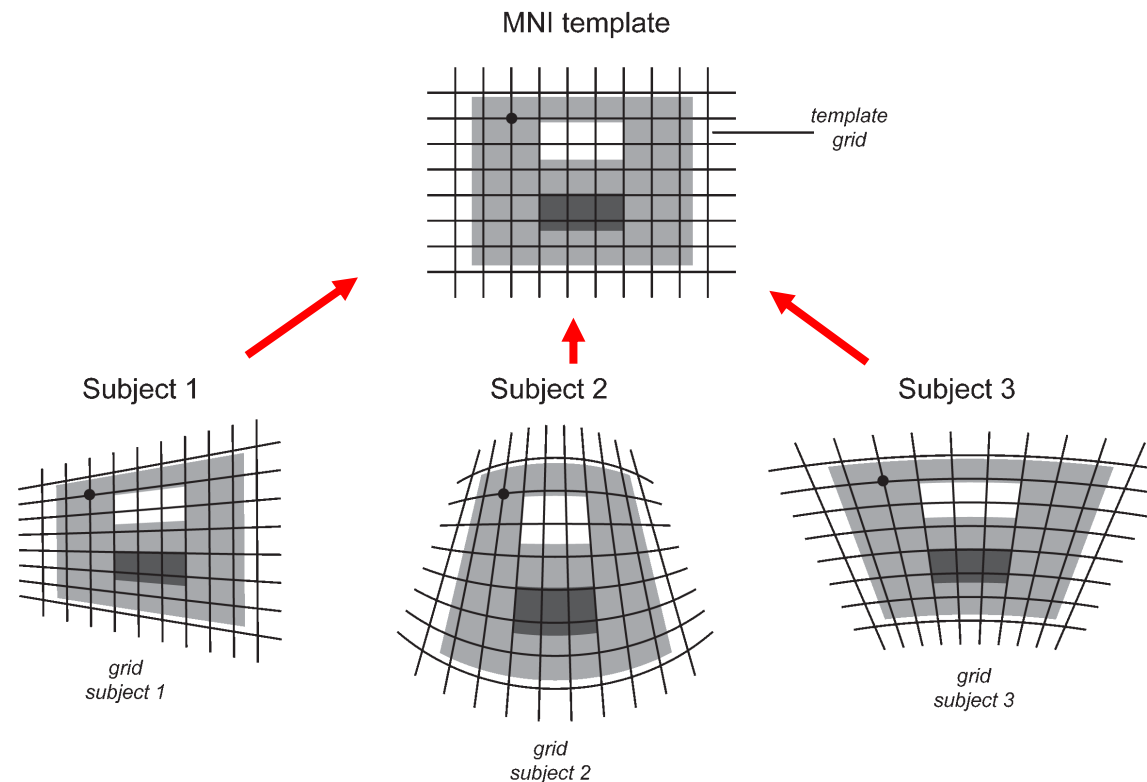
An appointment in *my agenda* would show up at 16:00 (4pm), whereas in the agenda of *my colleague* in New York it would be at 10:00 (10am).

Same appointment, different numbers.



Coregistration differs from spatial normalization

Coregistration only involves “rigid body” transformations (translation+rotation).
Spatial normalization involves rescaling and deformations.



FieldTrip functions for coregistration

`ft_electroderealign`, `ft_volumerealign`, `ft_meshrealign`, `ft_SOMETHINGrealign` takes SOMETHING and changes its coordinate system so that it is aligned with something else.

`ft_interactiverealign` is a shared helper function that interactively (with a GUI) can align anything to anything.

`ft_transform_geometry` takes any geometry and applies a (homogenous) transformation to it.

`ft_headcoordinates` takes NAS/LPA/RPA coordinates and computes the homogenous transformation to the desired coordinate system.



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Coregistration of OPM-MEG data

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