Spatial Distortions

MRI Physics for SPM

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MRI Physics for SPM – May 2026

Functional Imaging Laboratory
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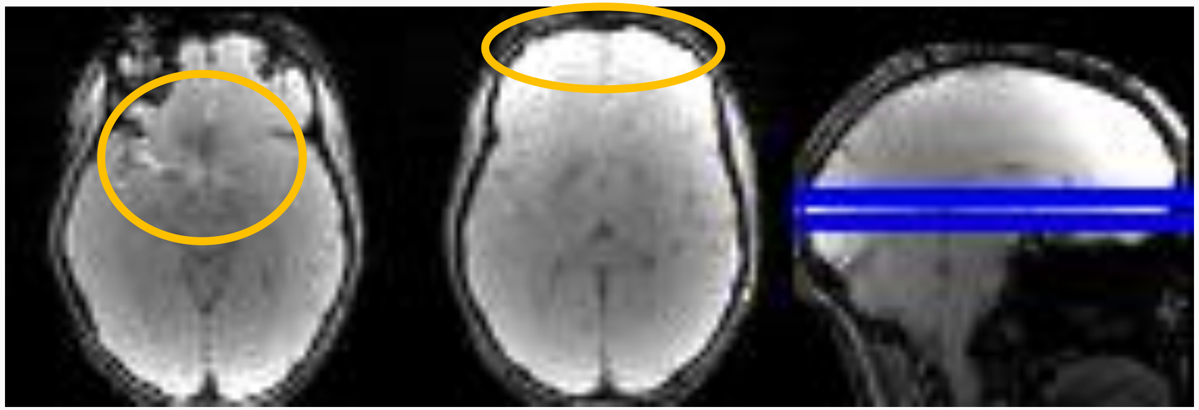
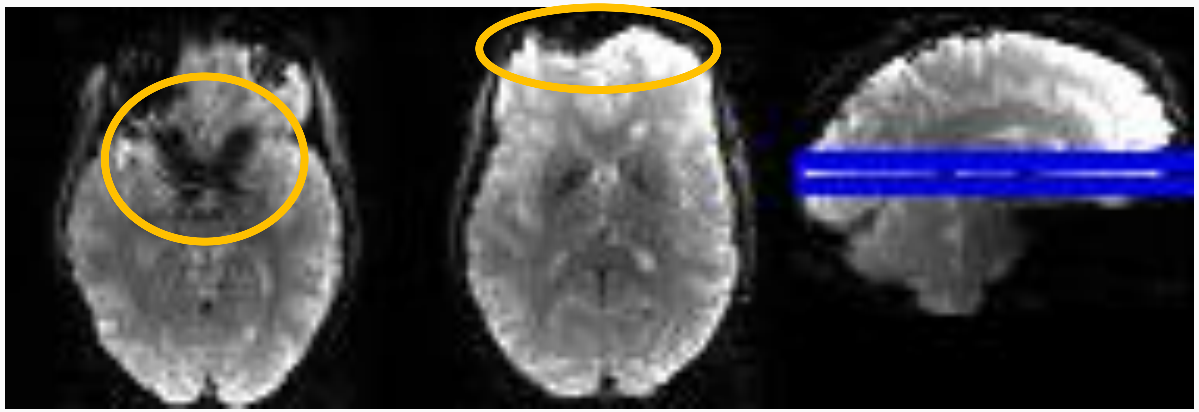
UCL

EPI artefacts

Multi-shot Gradient echo (slice in 2.4s)



Single Shot EPI (slice in 60 ms)



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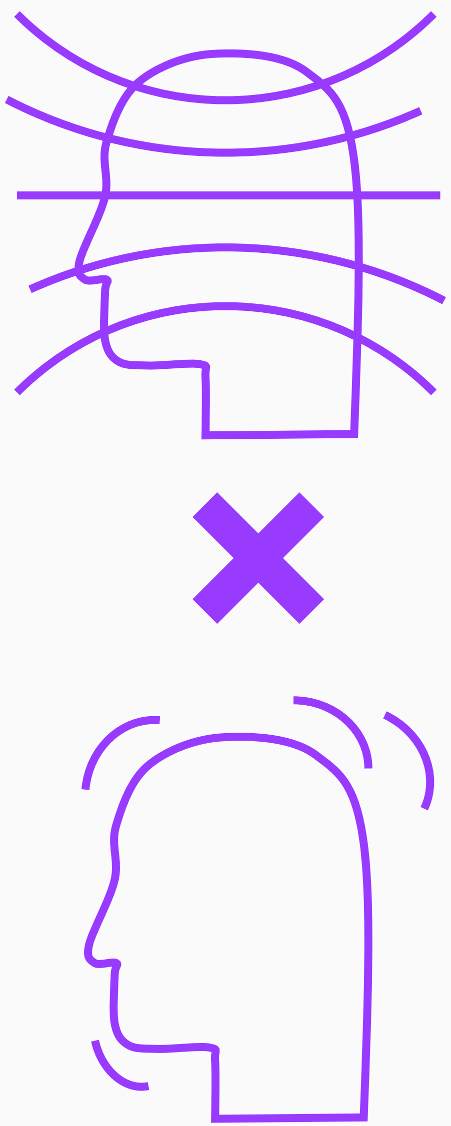


- ❑ **Understand the causes of magnetic field inhomogeneity**
  - ➢ Hardware
  - ➢ Magnetic susceptibility
  - ➢ Eddy currents
- ❑ **Understand image distortions in EPI**
  - ➢ Linear vs Planar readout
  - ➢ Local gradients
  - ➢ Impact on the acquired signal
- ❑ **Understand the different types of field mapping**
  - ➢ Phase-based (multi echo)
  - ➢ Magnitude-based (reversed polarity)
- ❑ **Understand how to correction distortions in SPM**
  - ➢ SCOPE
  - ➢ Realign & Unwarp

Magnetic field inhomogeneity

Static field homogeneity

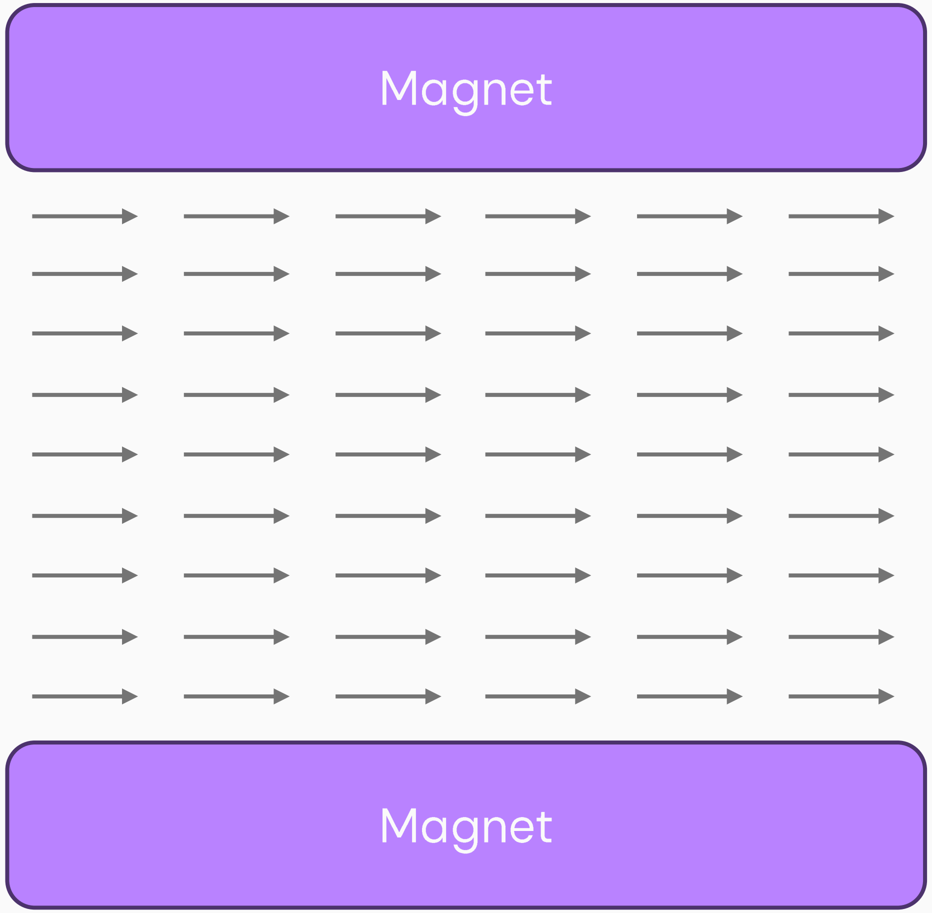
Main magnetic field: B_0

Derivative of the main magnetic field: $\partial B_0/\partial z$

Passive shimming

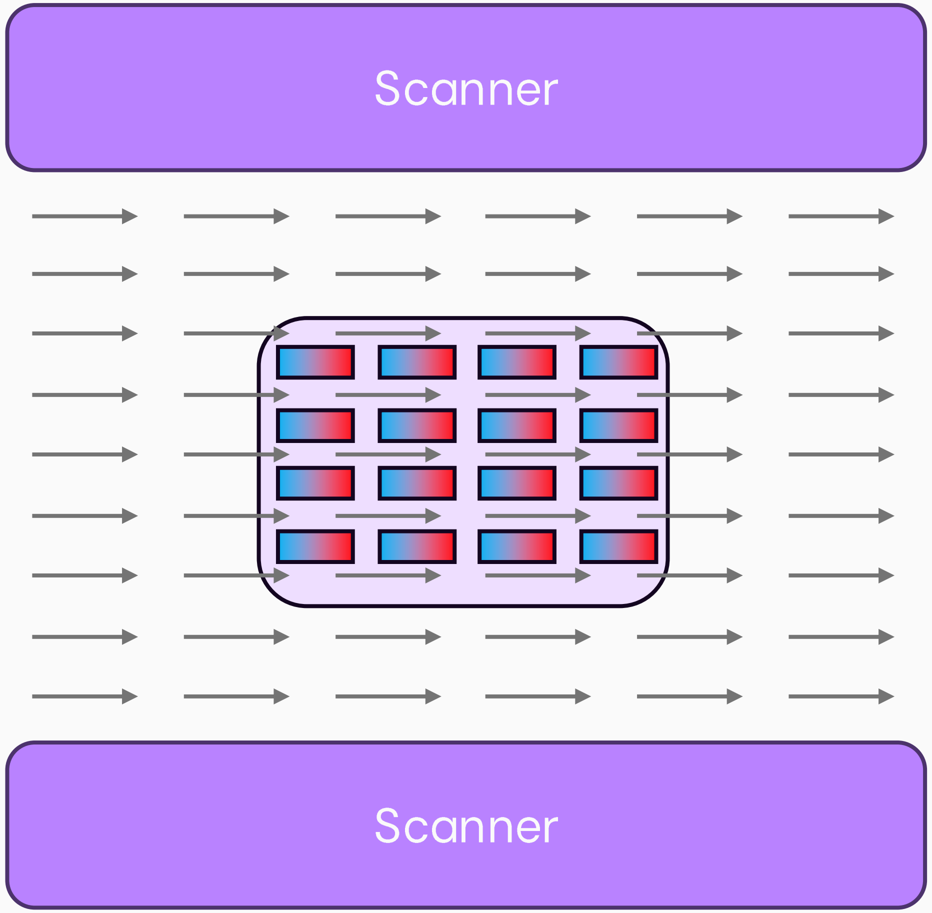
https://mriquestions.com/most-dangerous-place.html
https://mriquestions.com/passive-shimming.html

Adding an object



❑ Let’s start with a perfectly shimmed magnetic field

Adding an object



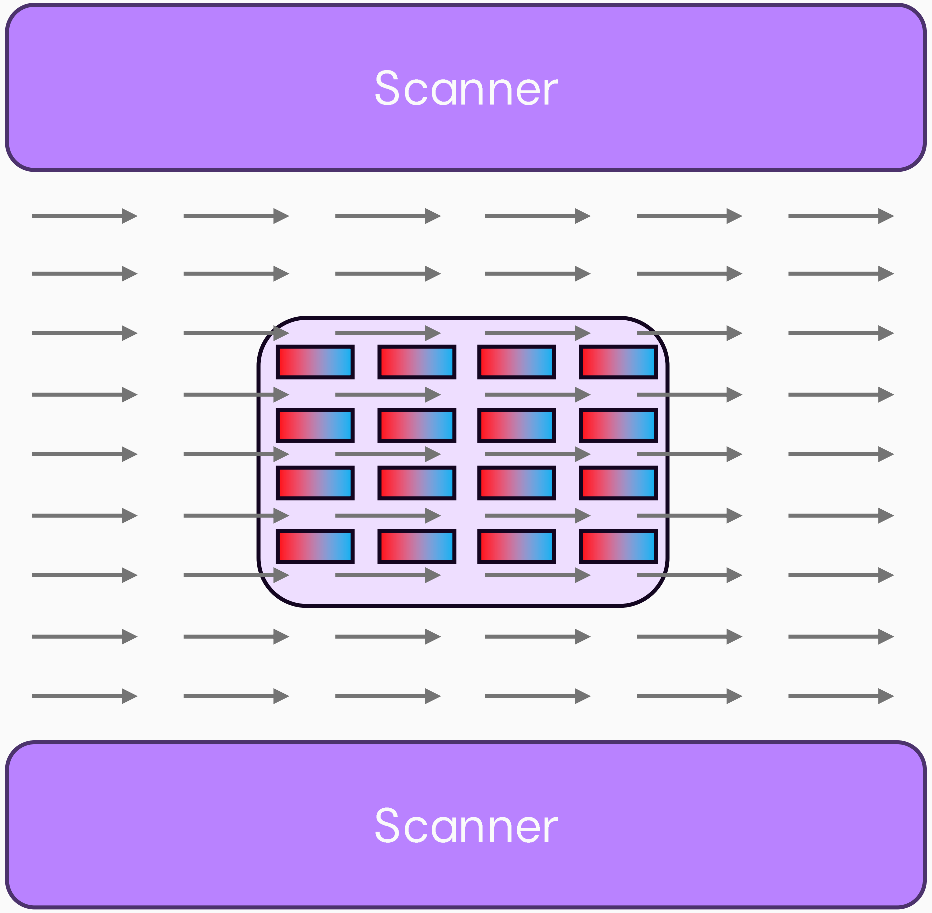
- ❑ Let's start with a perfectly shimmed magnetic field

- ❑ As soon as we **insert an object**, it gets polarised.

  - ➢ Its content acts like **little magnets**, aligned with the magnetic field.
  - ➢ Their strength depends on a quantity known as **magnetic susceptibility** χ.

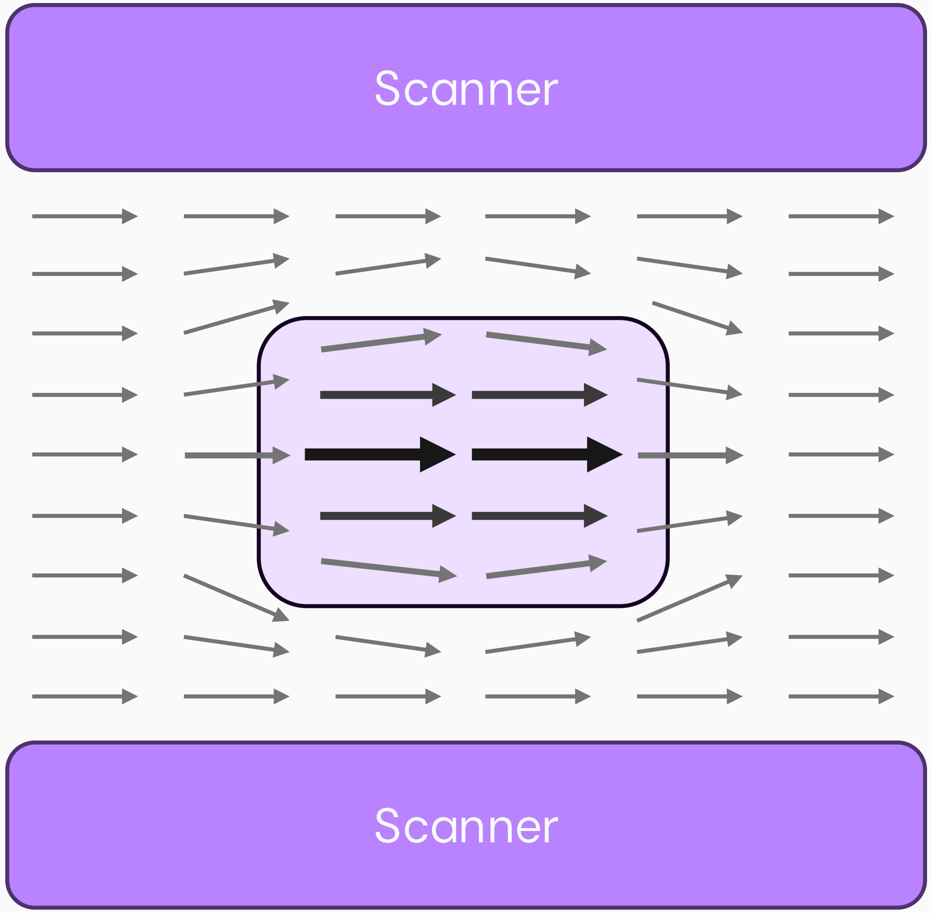
  - ➢ When $\chi > 0$, the material is **paramagnetic**, and the magnets align in the same direction as the field (North to South). Air -> $\chi = 0.4$ ppm.

Adding an object



- ❑ Let's start with a perfectly shimmed magnetic field
- ❑ As soon as we **insert an object**, it gets polarised.
  - Its content acts like **little magnets**, aligned with the magnetic field.
  - Their strength depends on a quantity known as **magnetic susceptibility** χ.
  - When $\chi > 0$, the material is **paramagnetic**, and the magnets align in the same direction as the field (North to South). Air -> $\chi = 0.4$ ppm.
  - When $\chi < 0$, the material is **diamagnetic**, and the magnets align in the opposite direction to the field (South to North) . Brain -> $\chi = -9.1$ ppm

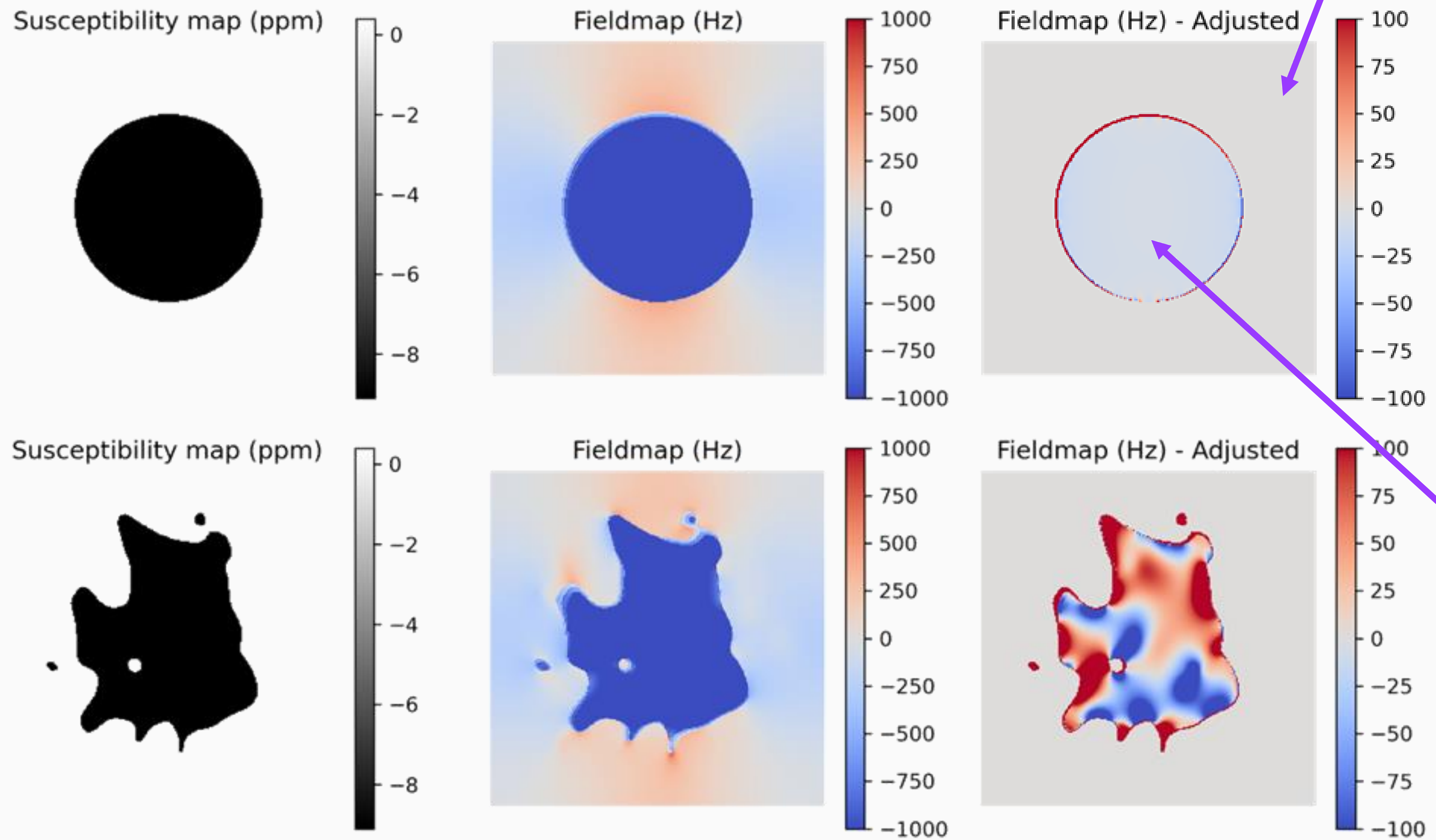
Adding an object



- ❑ Let’s start with a perfectly shimmed magnetic field
- ❑ As soon as we **insert an object**, it gets polarised.
- ❑ The main magnetic field and the magnetic dipoles both contributes to the effective field, leading to a new **equilibrium**.
- ❑ If the **shape** of the object and its **magnetic susceptibility are known**, we can compute the induced magnetic field.

Magnetic susceptibility (of a blob)

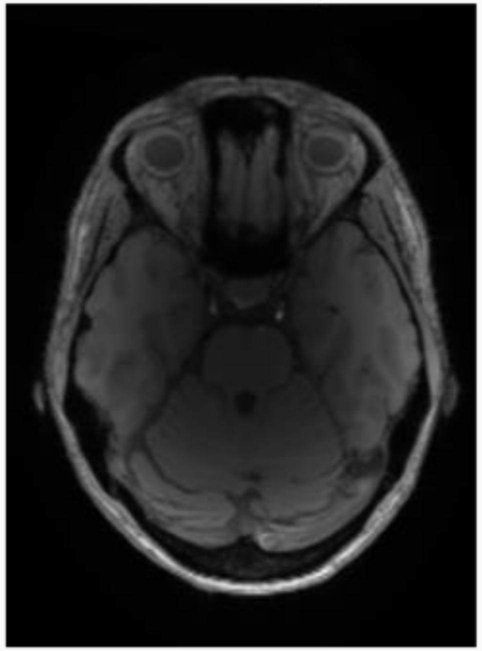
I masked the background
(It cannot be measured and has no impact on MR imaging)



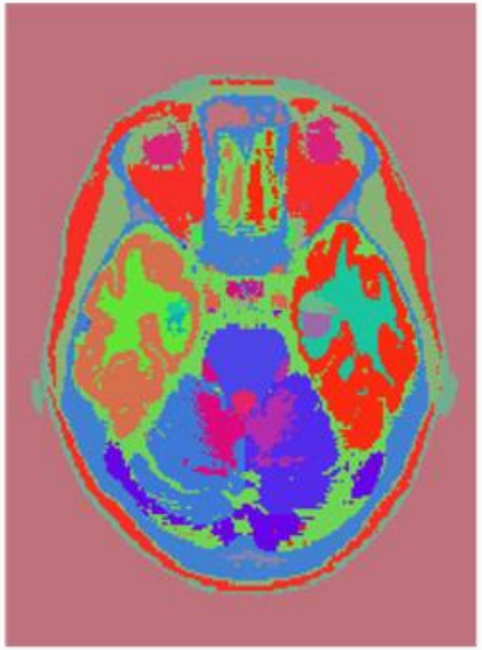
I subtracted the mean field in the object
(Global field offsets are corrected for by the “frequency adjust” step in an MRI scanner)

Magnetic susceptibility (of a head)

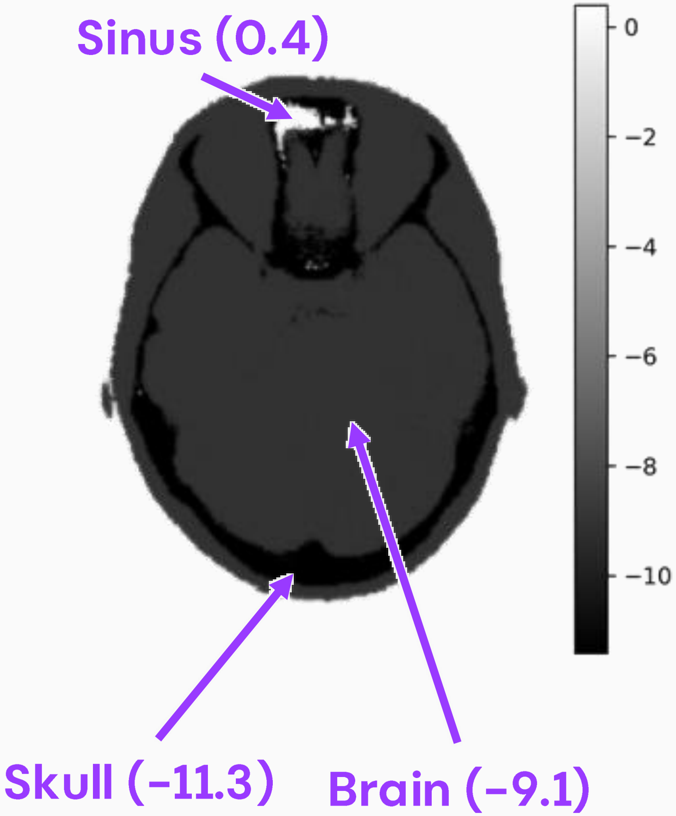
Anatomical image



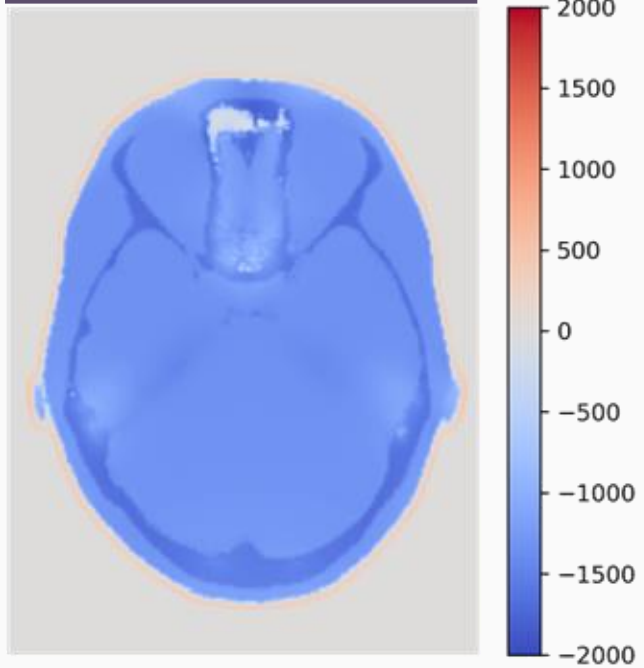
Anatomical labels



Susceptibility map
χ (ppm)



Field map
φ (Hz)



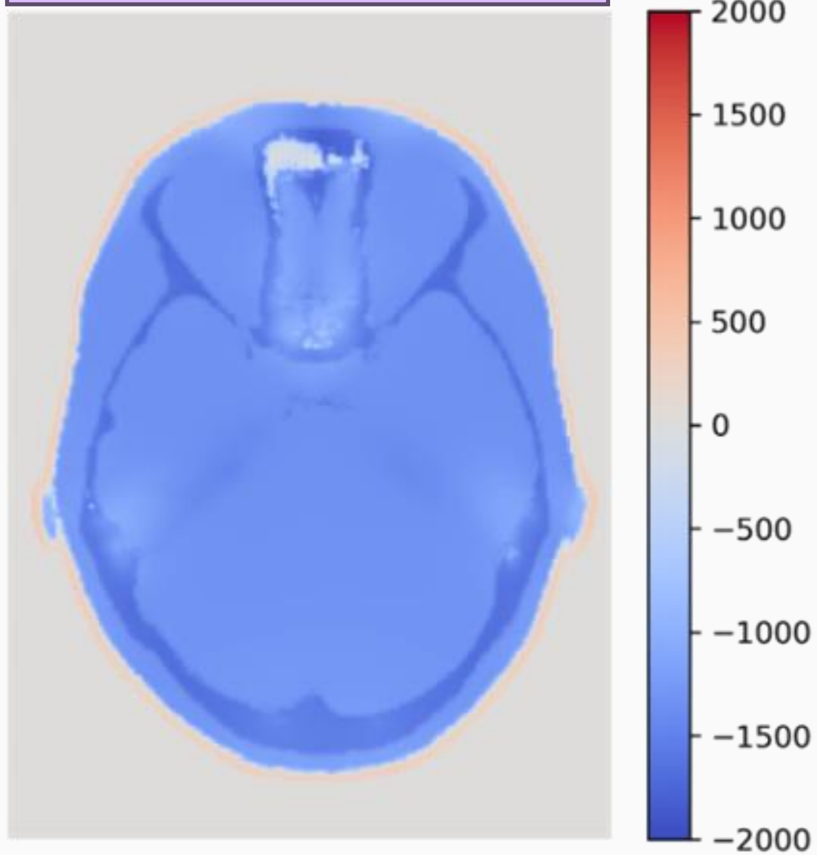
Note:

$\gamma = 43\ \mathrm{MHz/T}$

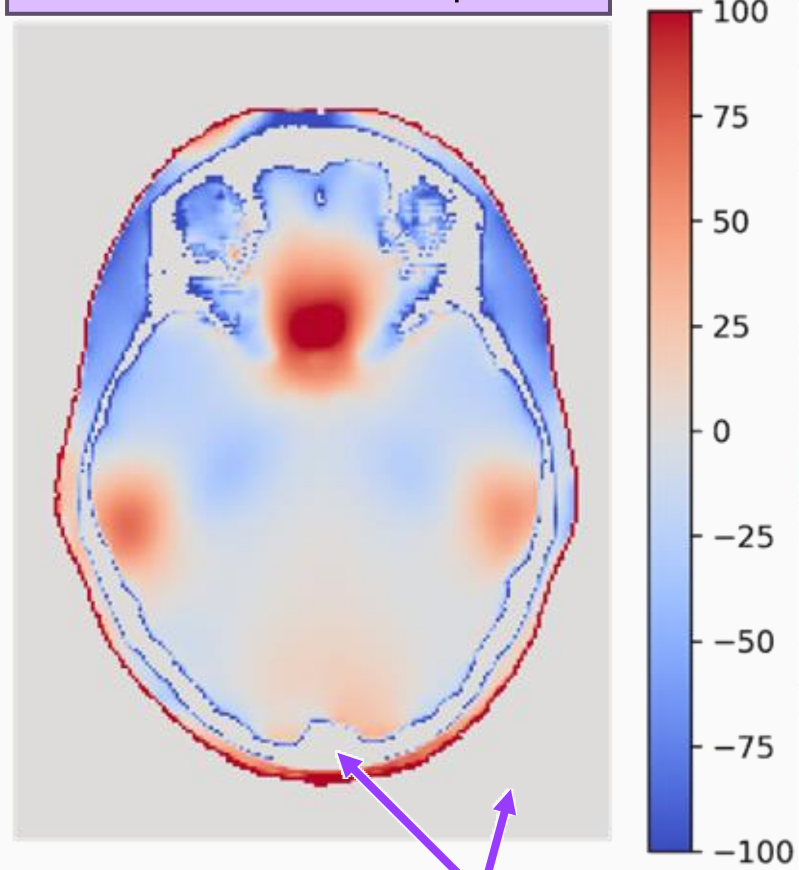
$1000\ \mathrm{Hz} \Leftrightarrow 0.2\ \mathrm{mT}$

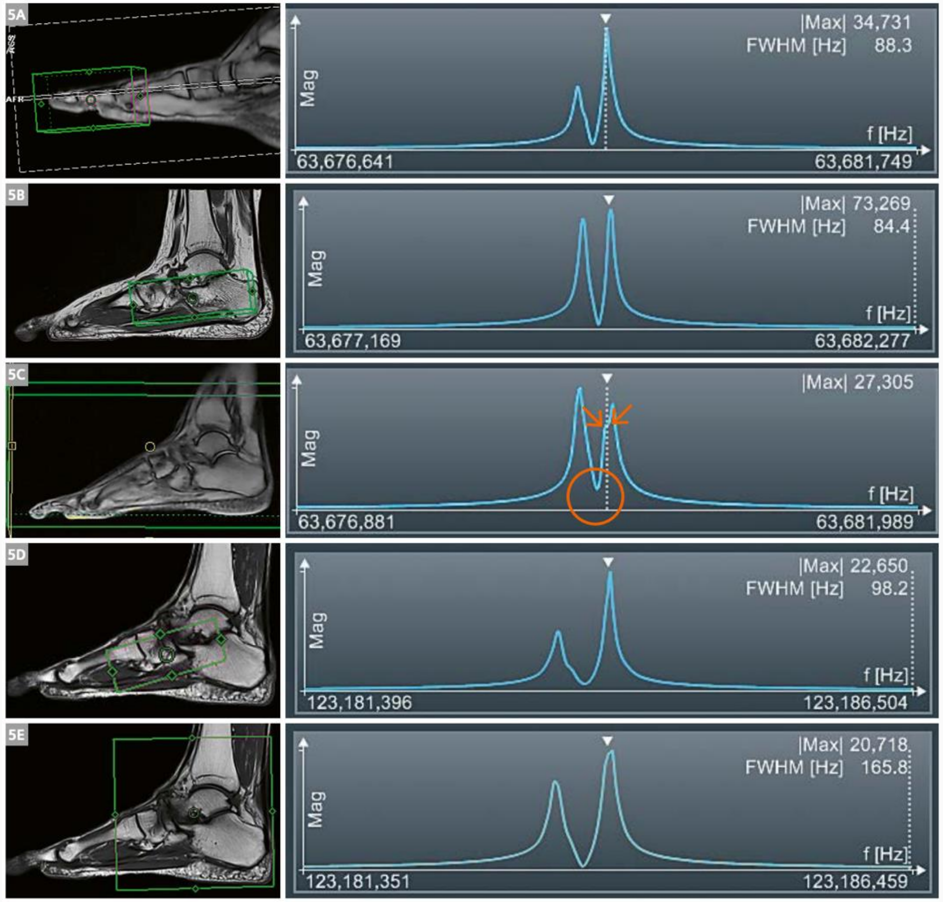
Center frequency adjust

Original field map (Hz)



Centered field map (Hz)

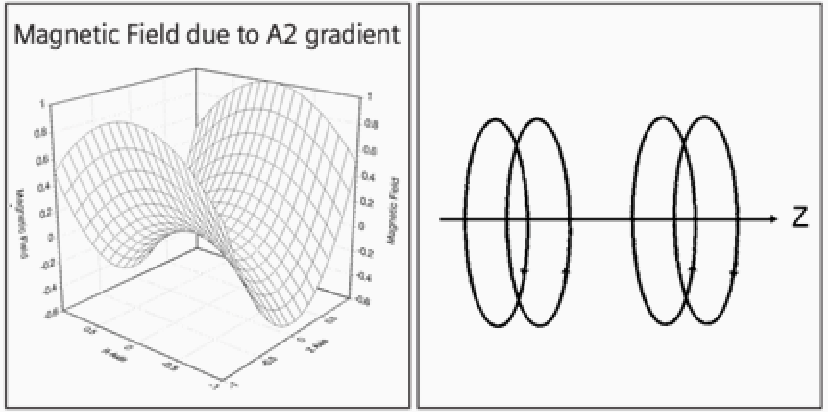




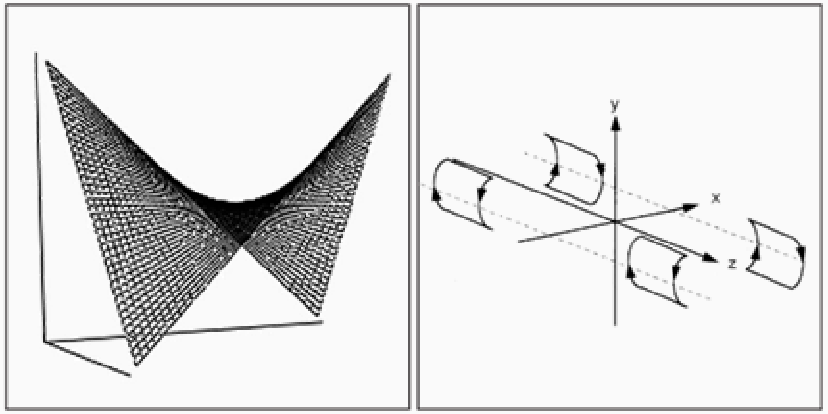
I masked the background (air + bone)
(It cannot be measured and has no impact on MR imaging)

Active shimming

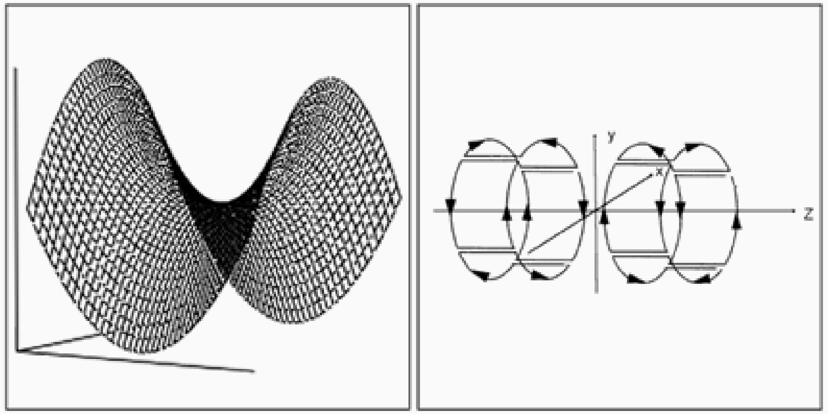
- ❑ Field offset -> Frequency adjust (zero-th order shim)
- ❑ Field slope -> Gradient adjust (first order shim)
- ❑ Other components -> Active shimming (second order shim)



z^2



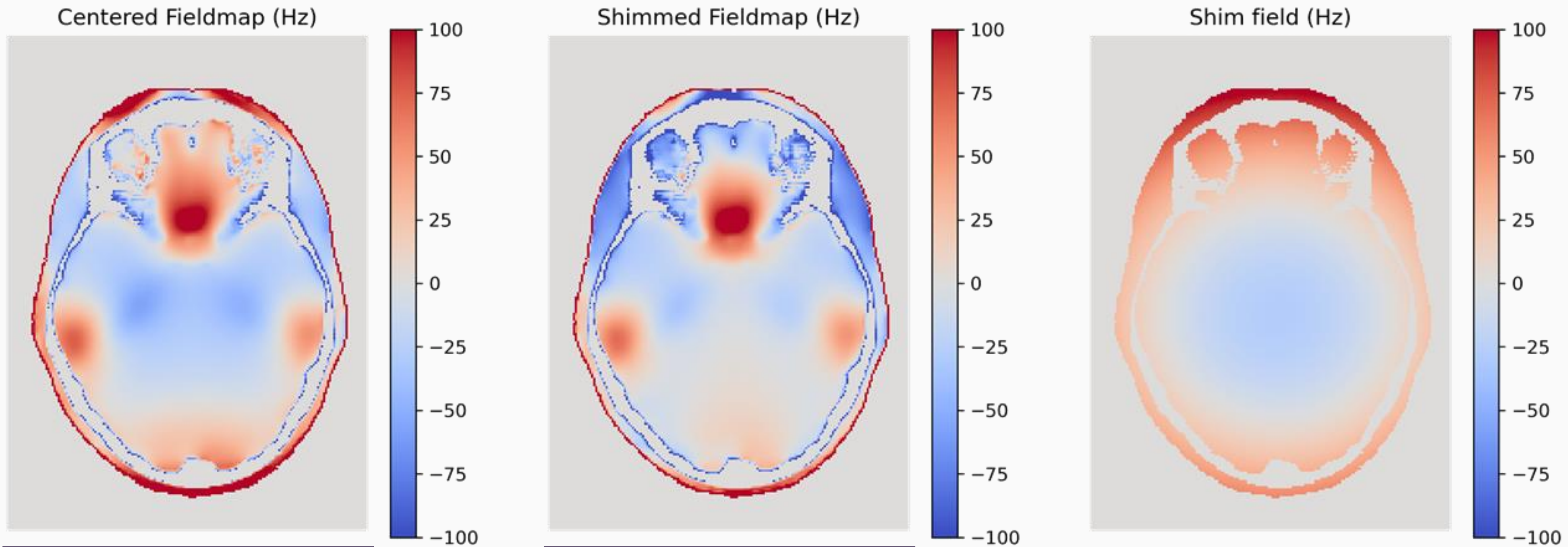
zx | zy



xy | x^2-y^2

Second Order Shimming of High Field Magnets, Siemens

Active shimming



RMS = 33 Hz

RMS = 28 Hz

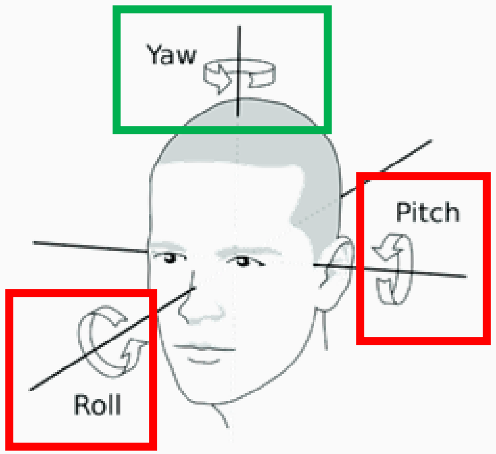
Interaction with head motion

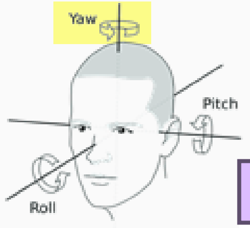
- The field map φ depends **only** on the derivative of the susceptibility map χ with respect to the direction of the main magnetic field: $\frac{\partial \chi}{\partial z}$

- Thus, the field map is **covariant** under rotations about z.
  This means that:
  the field map of the "*susceptibility map rotated by θ_z*"
  = the "*field map of the susceptibility map*" rotated by θ_z

- However, the field map is **not covariant** under rotations about x or y.

  - **The field map is head-position dependant**





Interaction with head motion (yaw [z])

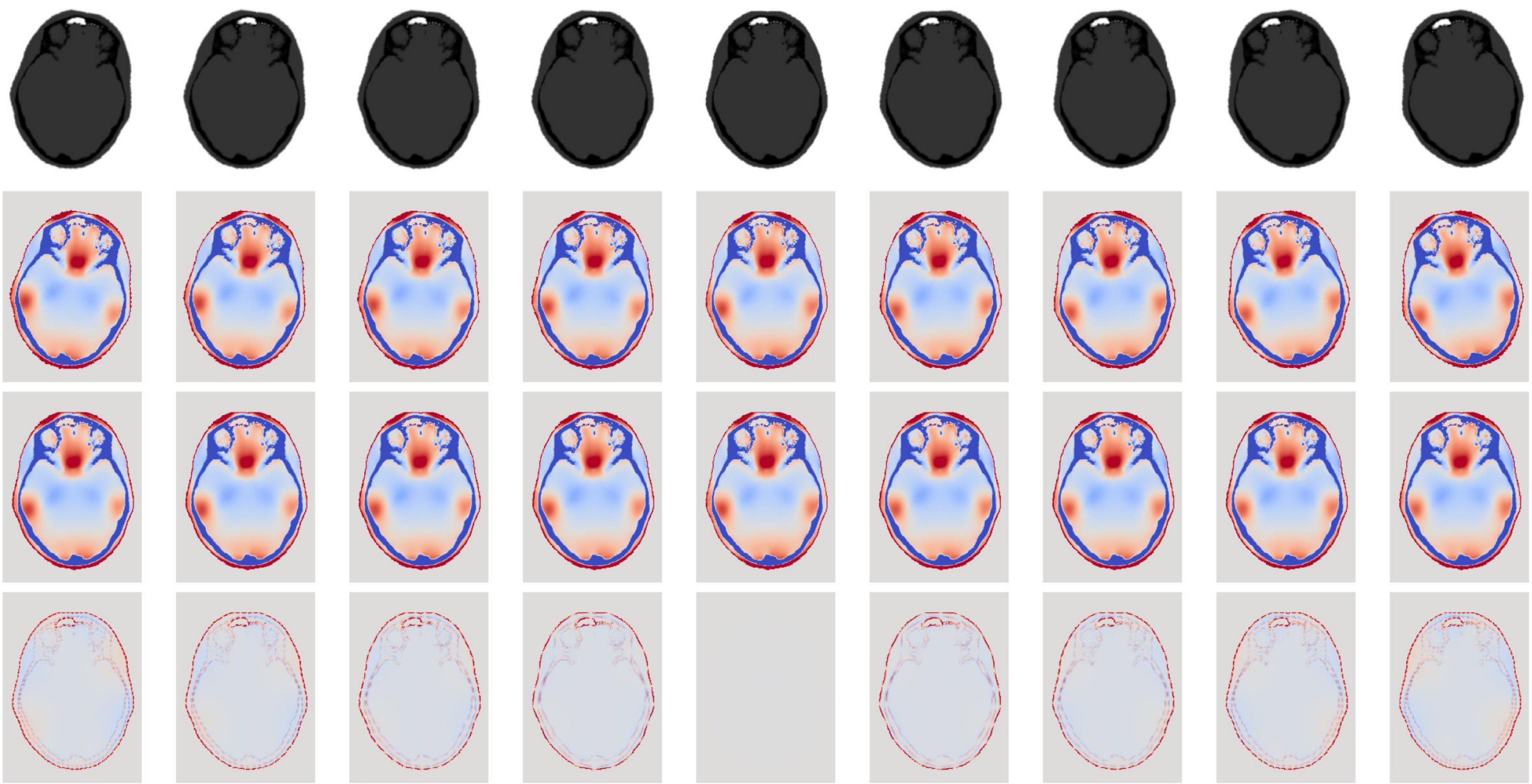
-10 deg	Rotation	+10 deg

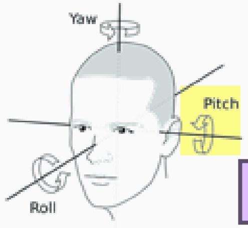
Rotated χ_θ

Field φ_θ

Motion-corrected $\tilde{\varphi}_\theta$

Difference $\tilde{\varphi}_\theta - \varphi_0$





Interaction with head motion (pitch [x])

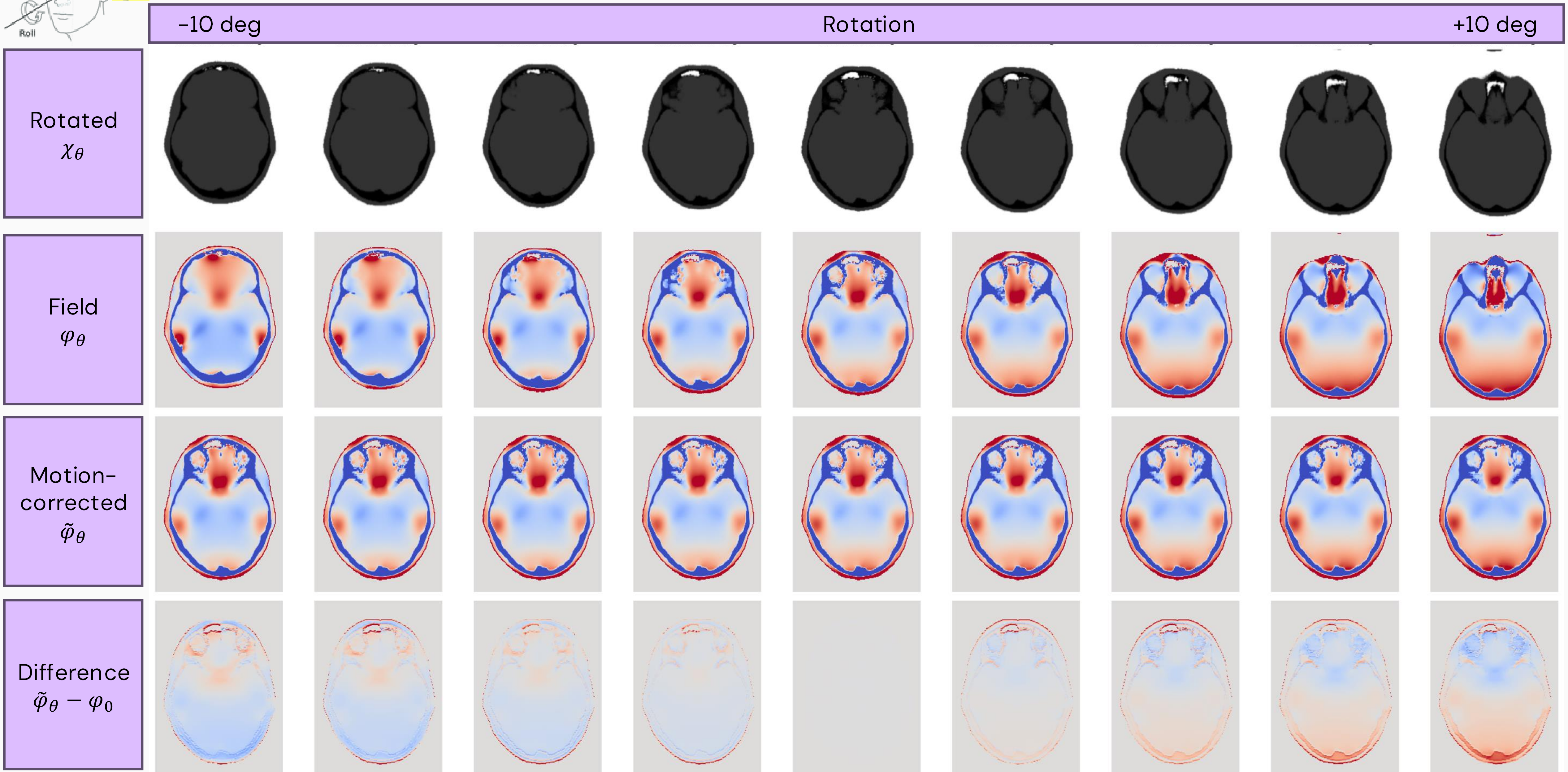
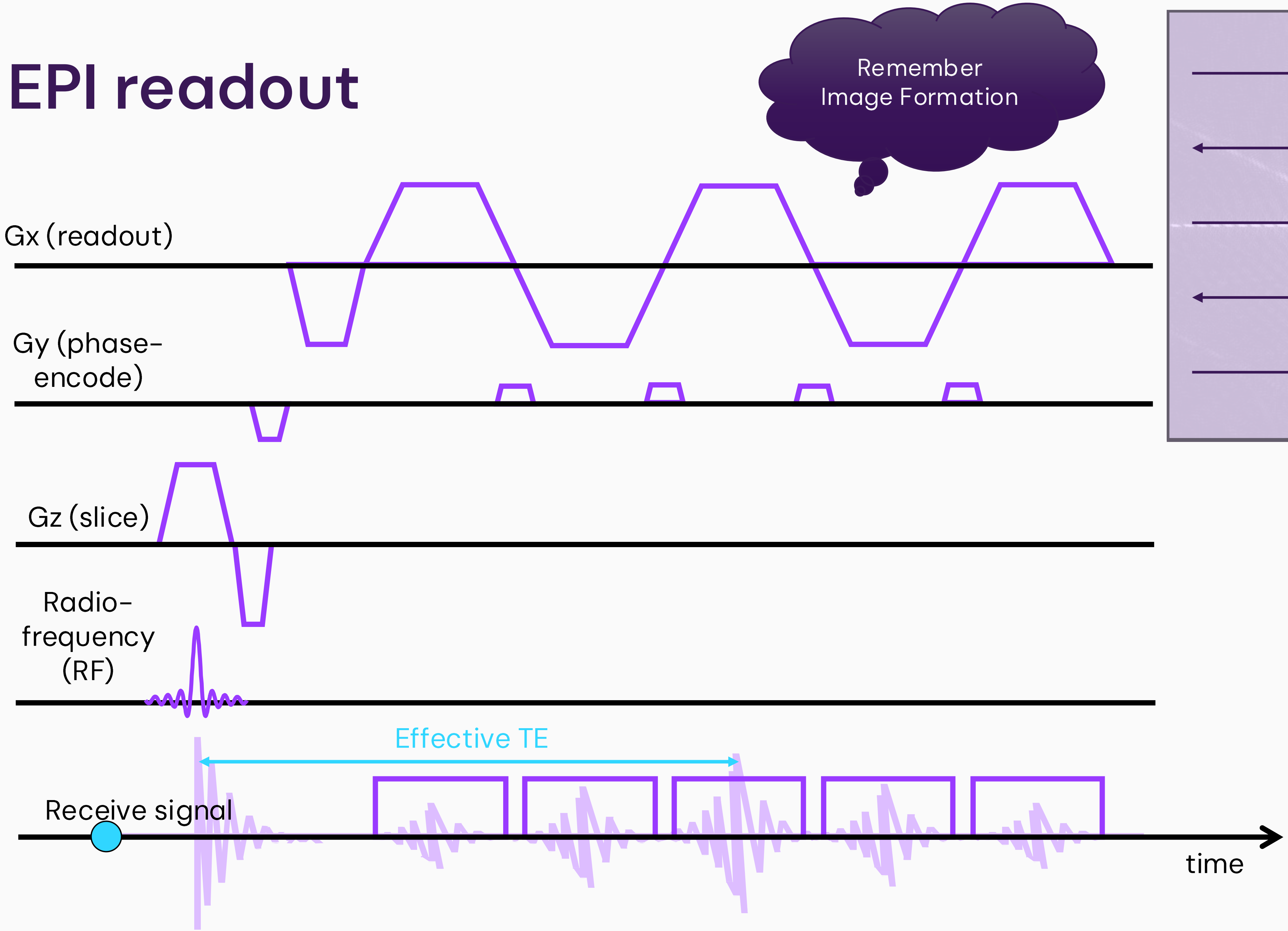
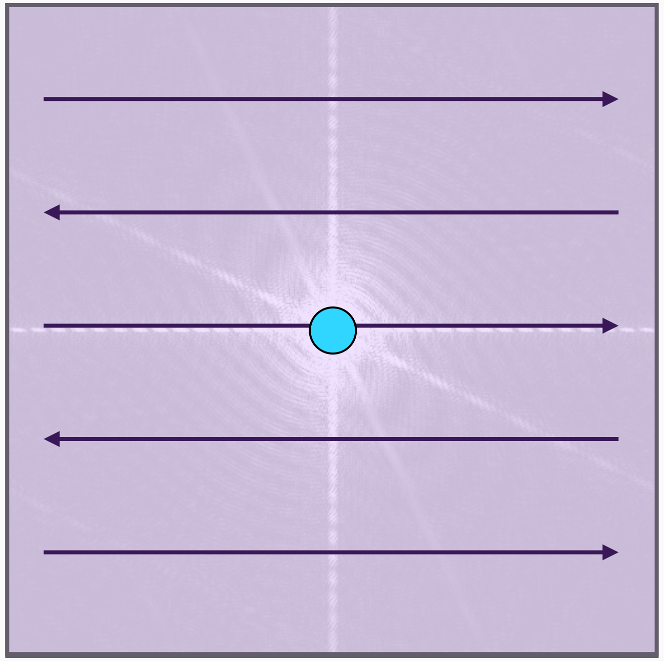


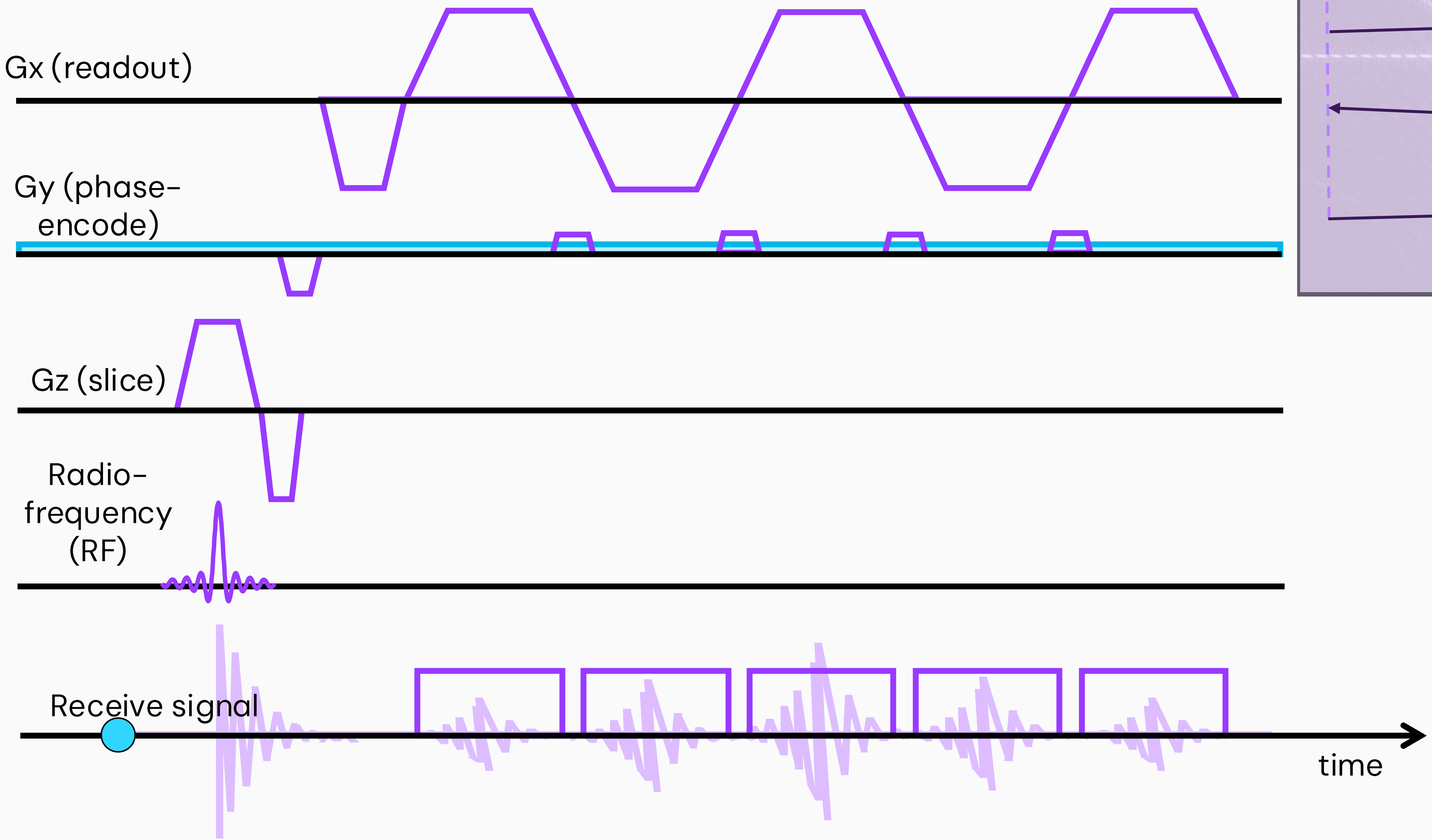
Image distortions in EPI

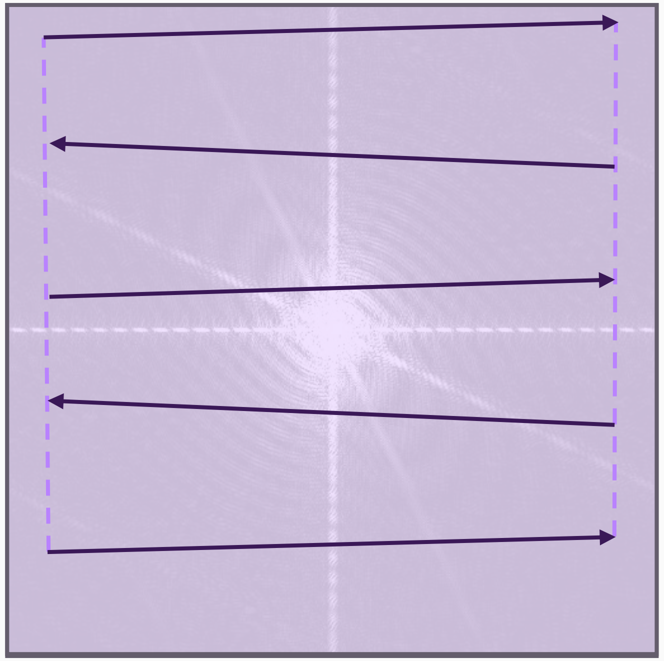
EPI readout


Remember
Image Formation
Gx (readout)
Gy (phase-
encode)
Gz (slice)
Radio-
frequency
(RF)
Effective TE
Receive signal
time

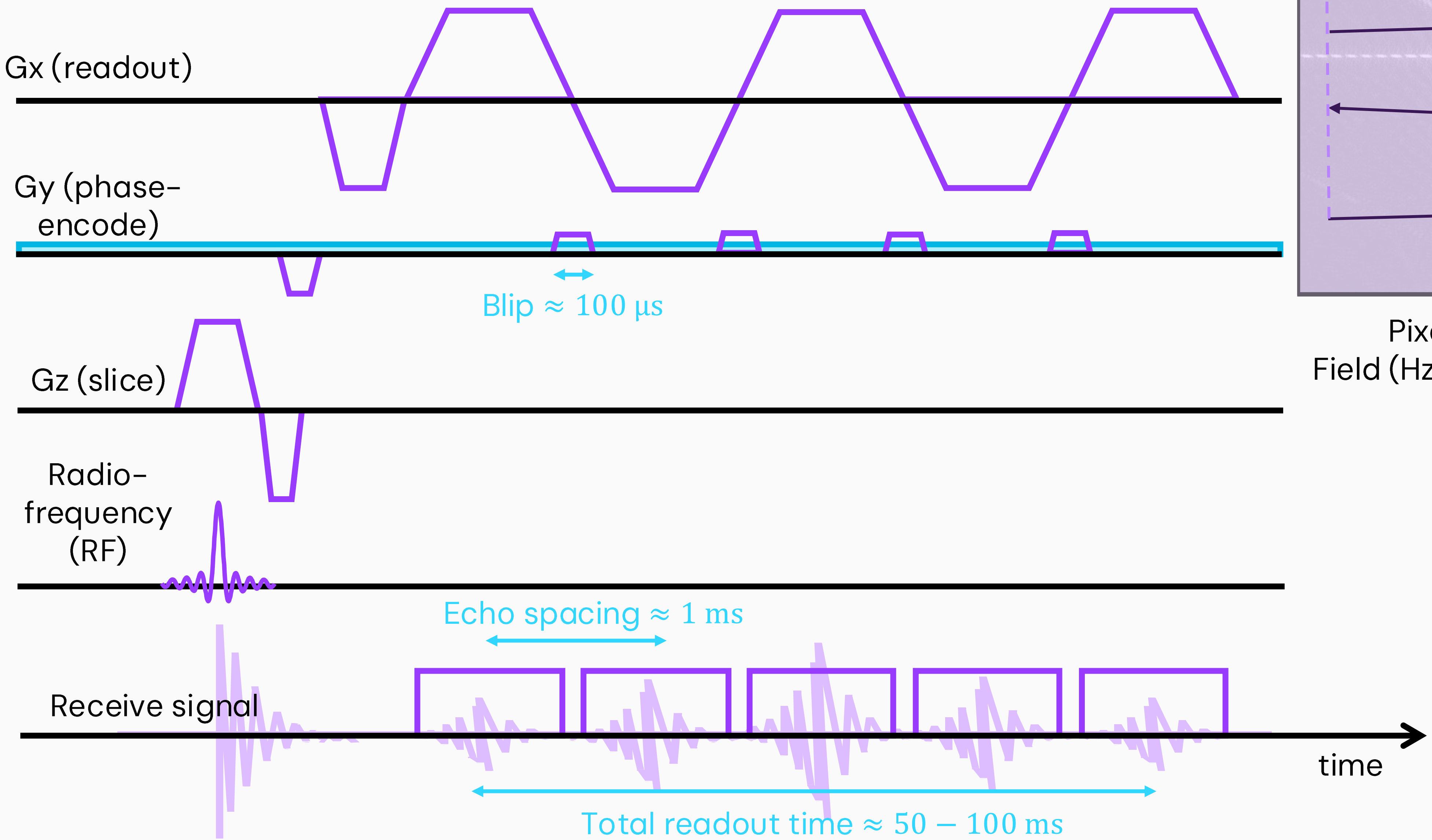


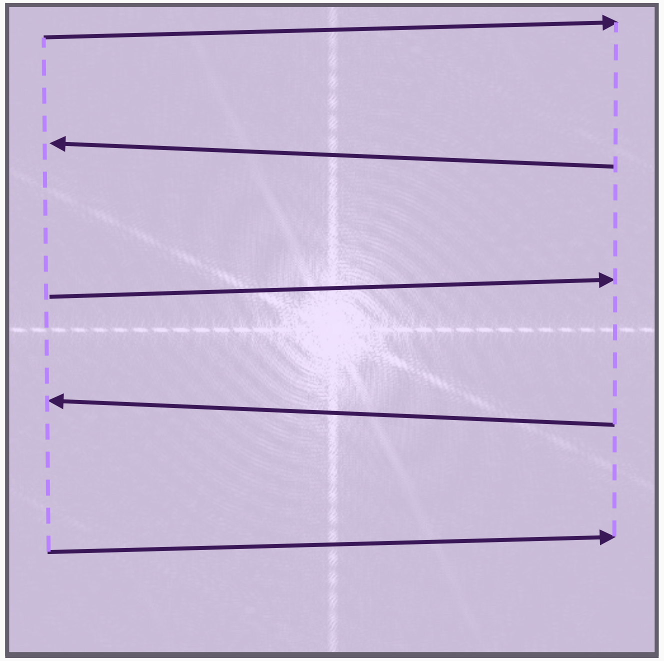
Local gradients





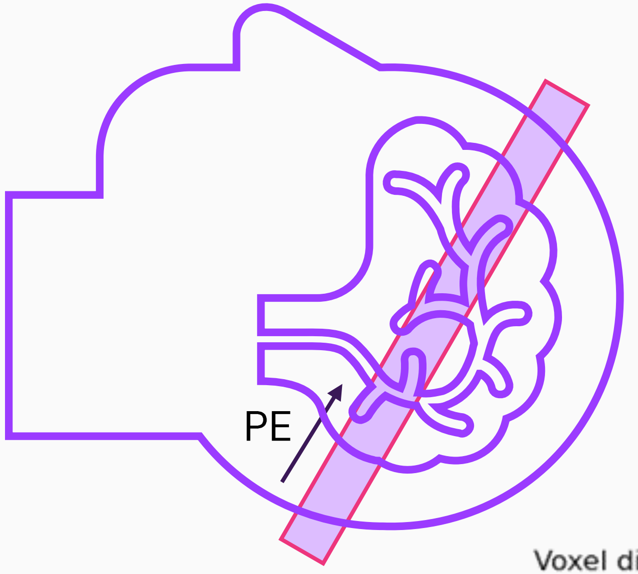
Local gradients



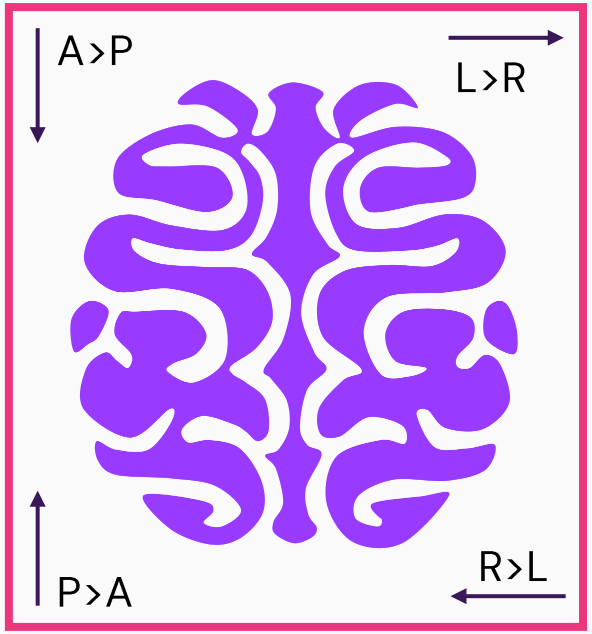


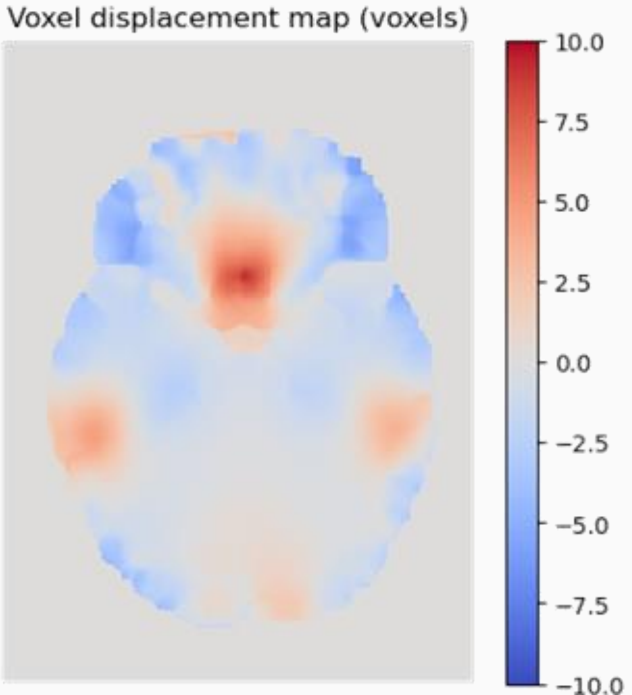
Pixel Displacement =
Field (Hz) x Total Readout Time (s)

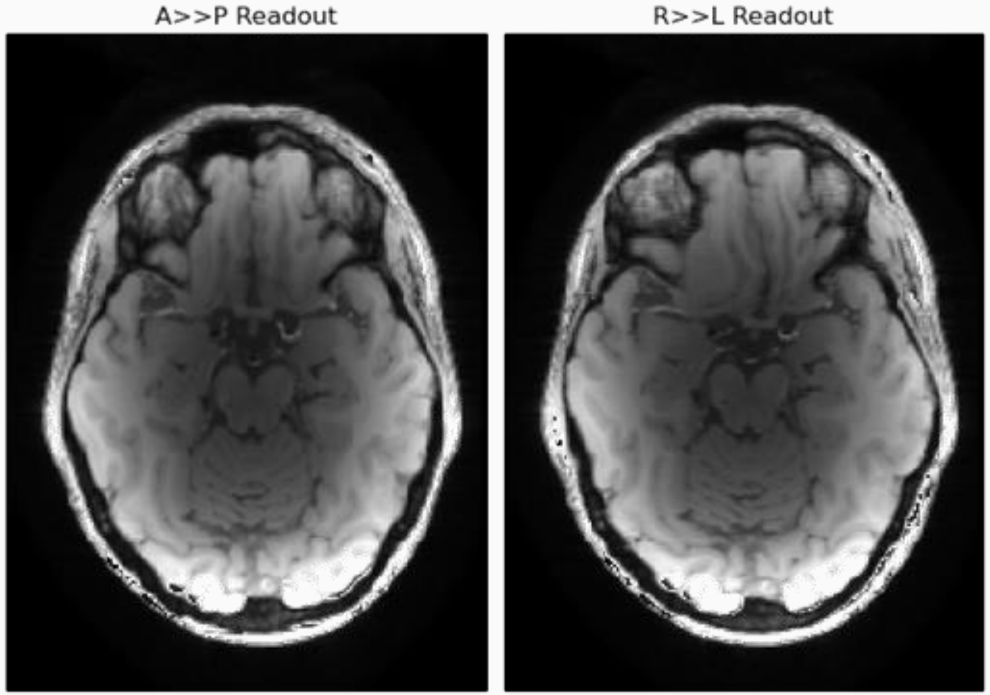
Spatial distortions



- Spatial distortions are along the **phase-encode direction.**
- They depend on the slice **orientation**.
- They also depend on the **direction** of the phase-encode direction (i.e., its polarity)

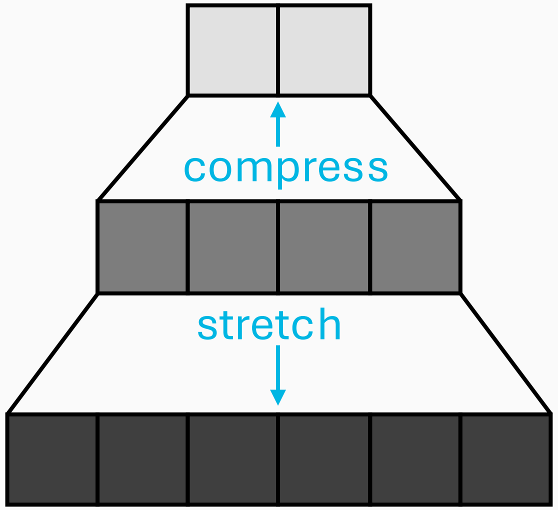




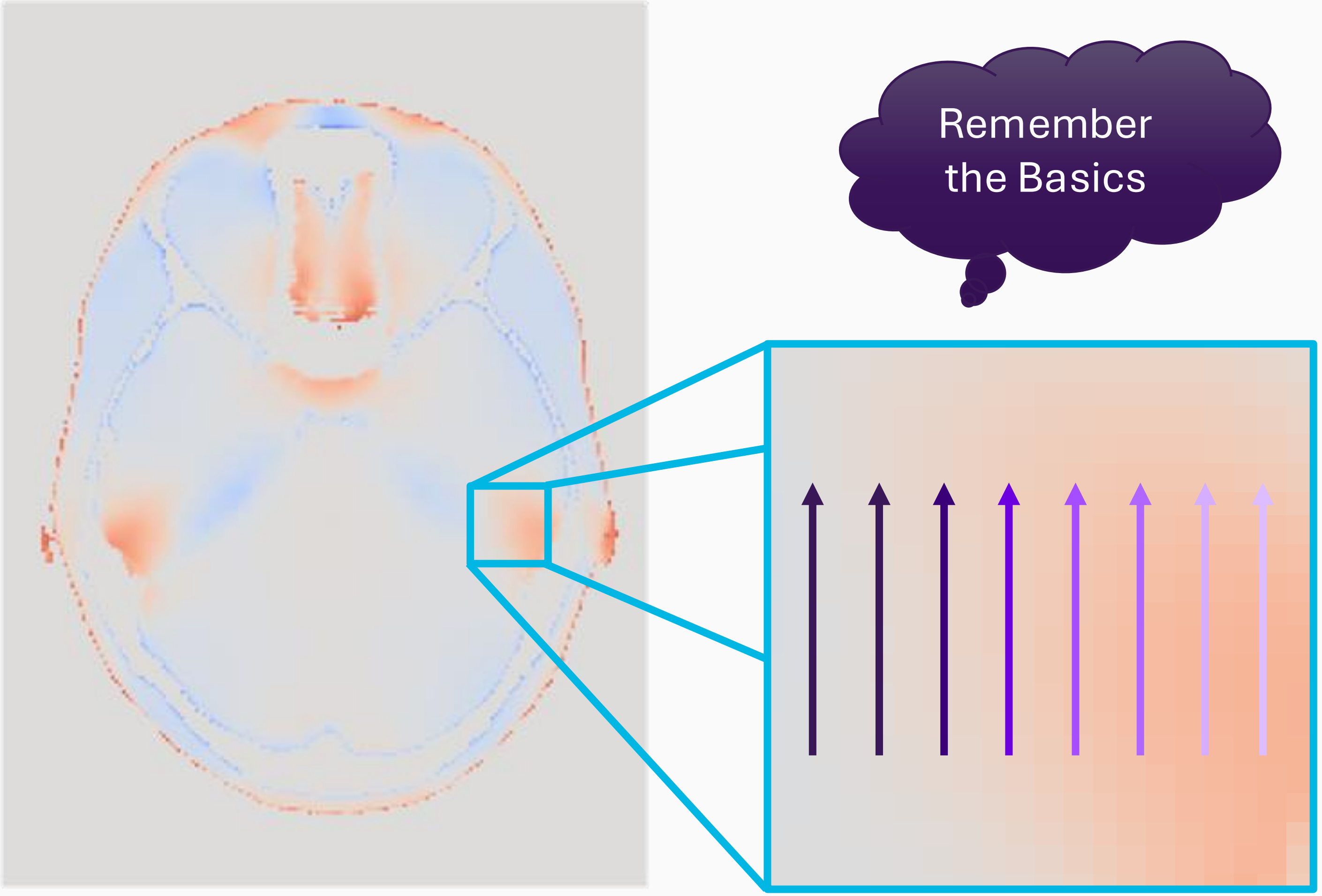


Related artifacts – signal modulation

- The number of protons that generate the signal is constant
  - If the image is **stretched**, they are distributed over more voxels, which caused a **lower intensity signal**.
  - If the image is **compressed**, they are distributed over fewer voxels, which caused a **higher intensity signal**.
  - In general, the intensity is modulated by the **Jacobian determinant** of the distortion field.



Related artifacts – Decreased T2*

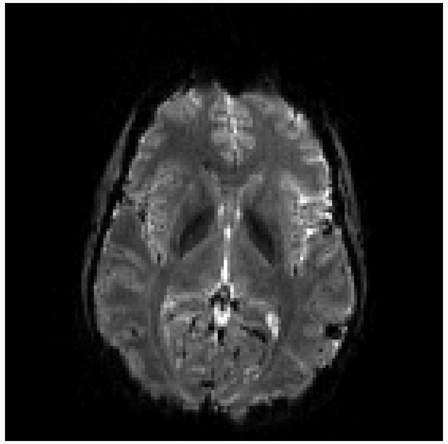


- ❑ Local gradients are **never refocused**
  - ➢ **Decreased T2***
  - ➢ **Faster decay**
  - ➢ **Lower signal**

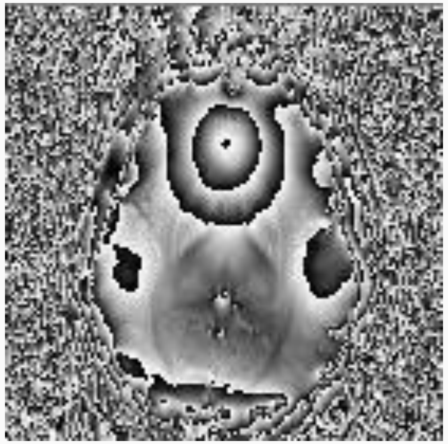
Field mapping

MRI phase

Magnitude



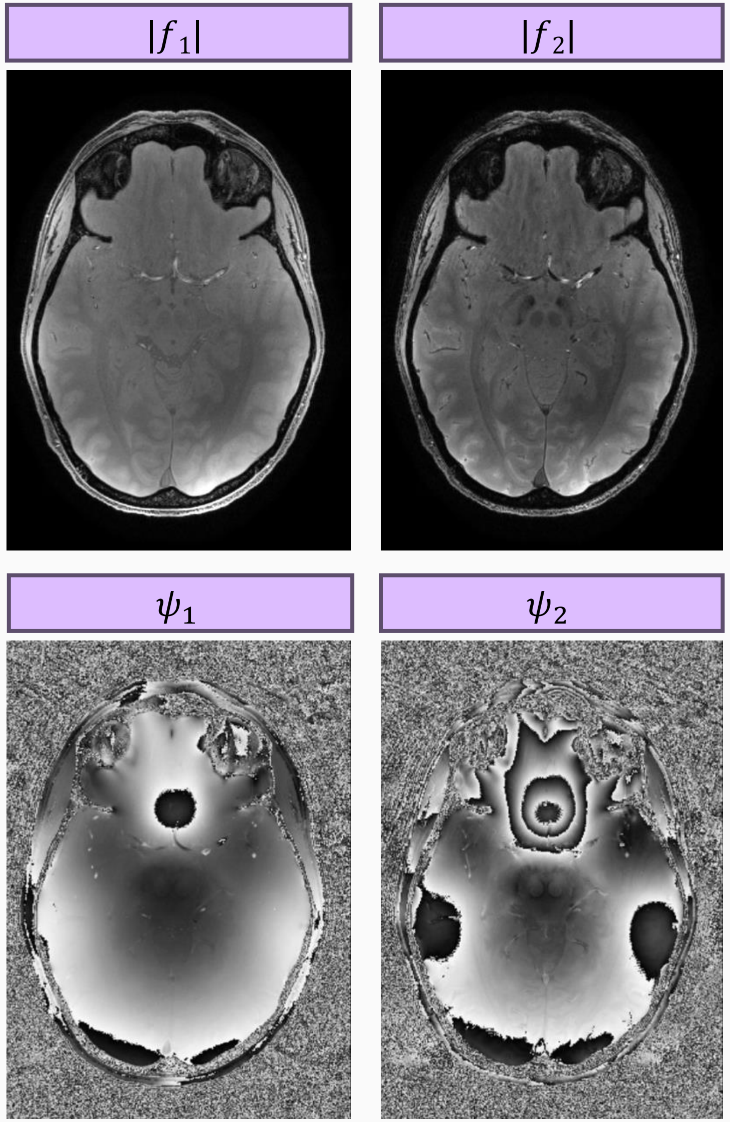
Phase (-π, +π)



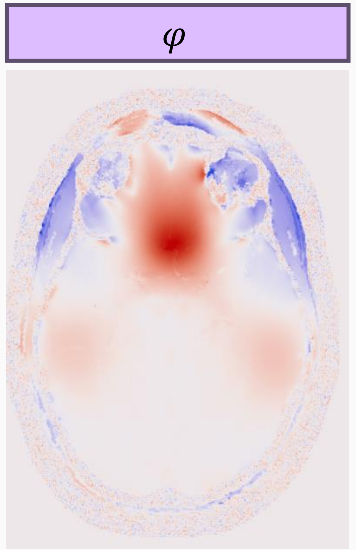
- The MRI signal is actually **complex**: $f = |f| \cdot \exp(i \cdot \psi)$
- The **phase relates directly to the field map**: $\psi = 2\pi \cdot \mathrm{TE} \cdot \varphi$
  - In practice, there is also a TE-independent component: $\psi = \psi_0 + 2\pi \cdot \mathrm{TE} \cdot \varphi$
  - This is due to the intrinsic phase of the receive coil(s). **See next chapter**.
- The receiver cannot differentiate phases that are 2π apart: **the phase wraps**
- There are many phase unwrapping algorithms:
  - Laplacian unwrapping (Schofield & Zhu, Optics Letters 2003)
  - Region growing (PRELUDE: Jenkinson, MRM 2003; ROMEO: Dymerska, MRM 2020)

Double (or multi) echo mapping

- ❑ Acquire Gradient Echo images at 2 different echo times
  - ➢ Some methods use more than two echoes
- ❑ Take the difference of the phases
  - ➢ The difference image may still have phase wraps.
  - ➢ If using more than two echoes, multi-echo phase unwrapping must be performed first (see: ROMEO)
- ❑ Convert Radians to Hertz



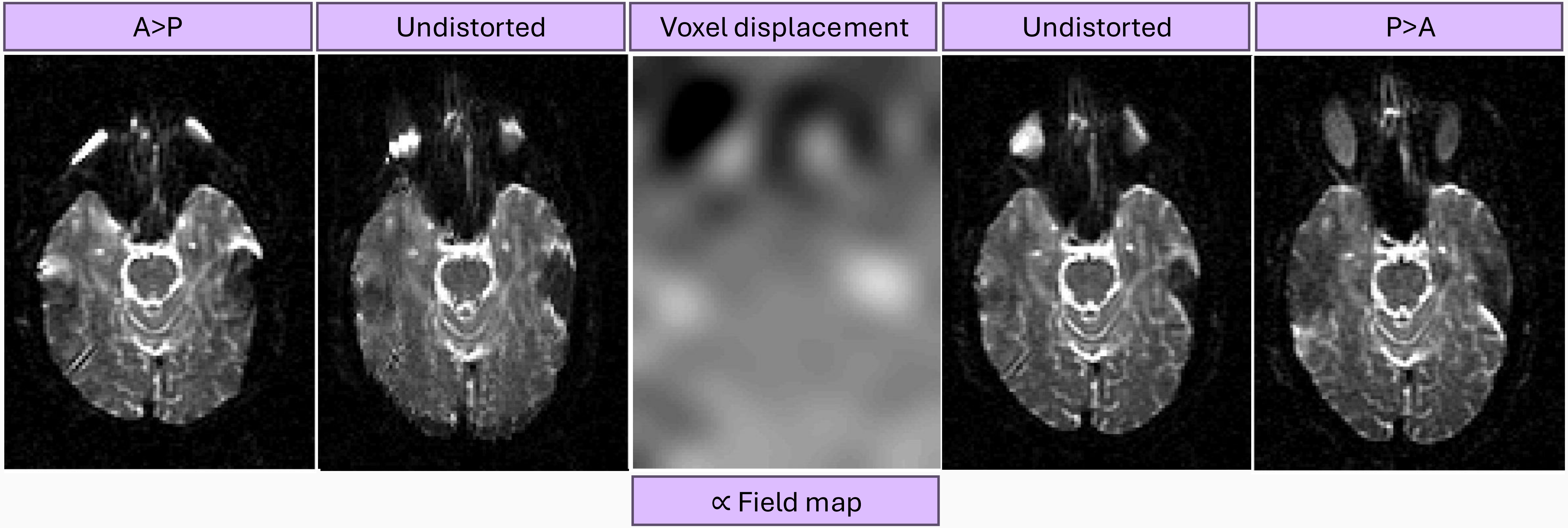
$$\frac{\psi_2 - \psi_1}{2\pi(\mathrm{TE}_2 - \mathrm{TE}_1)}$$



Reversed polarity mapping

Voxel displacement = Field (Hz) x Total Readout Time (s) x Phase Encoding direction

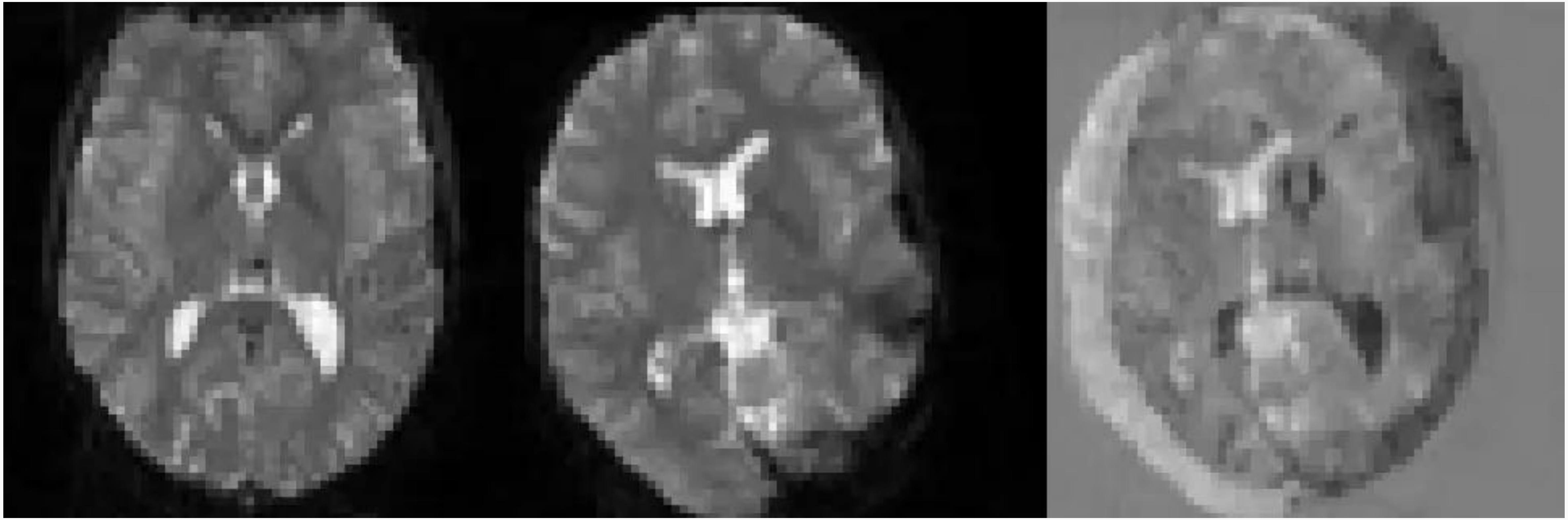
=> Voxel displacement (A>P) = – Voxel displacement (P>A)



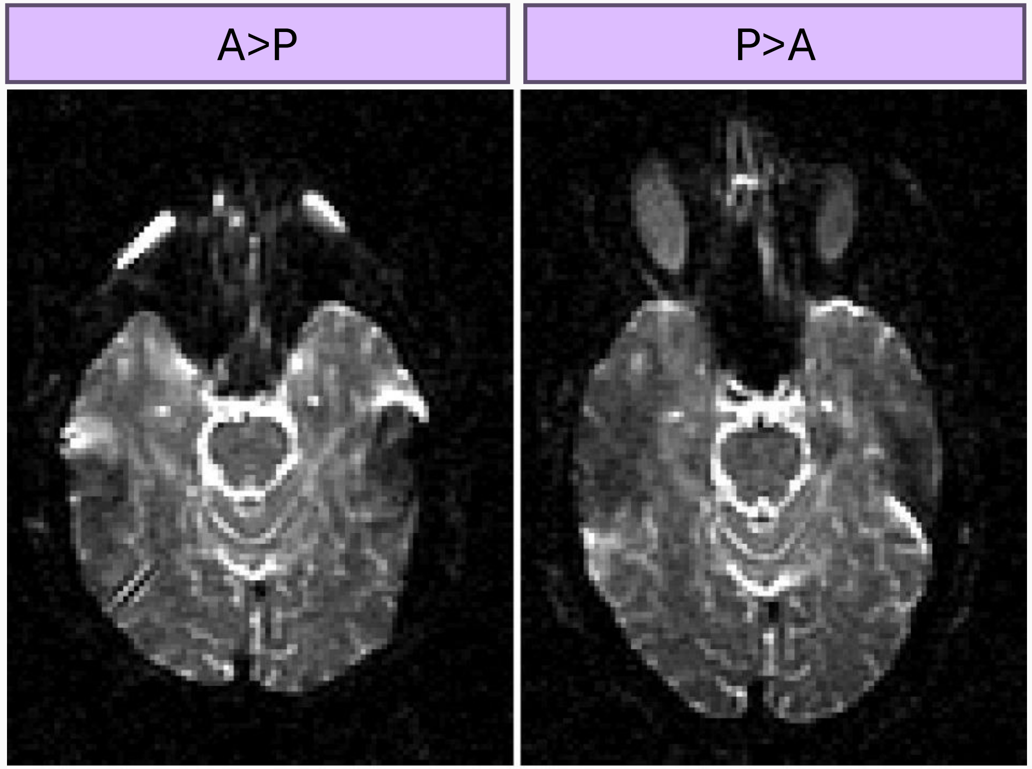
Andersson, Skare & Ashburner. NeuroImage (2003)

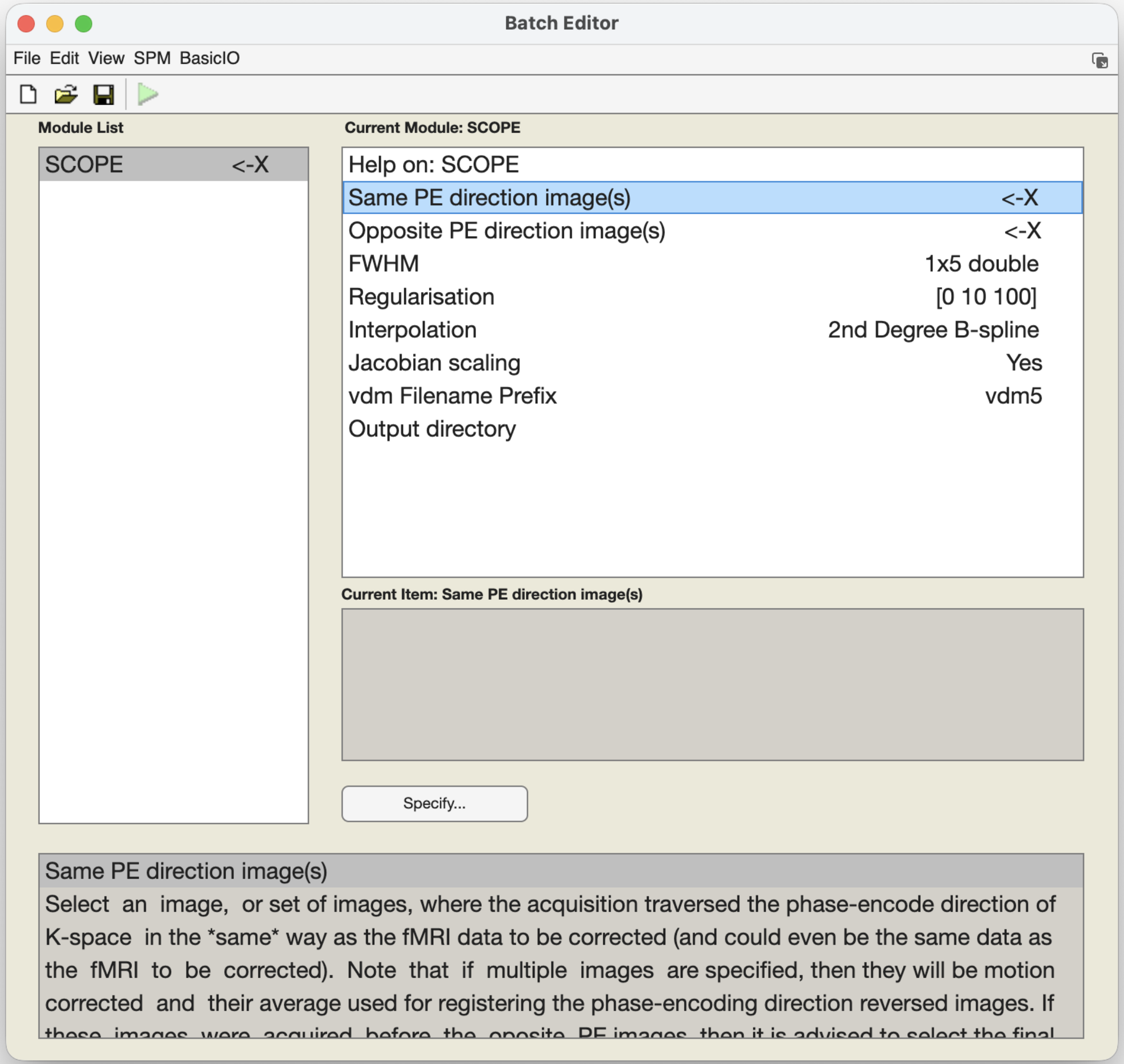
Distortion correction in SPM

Realign



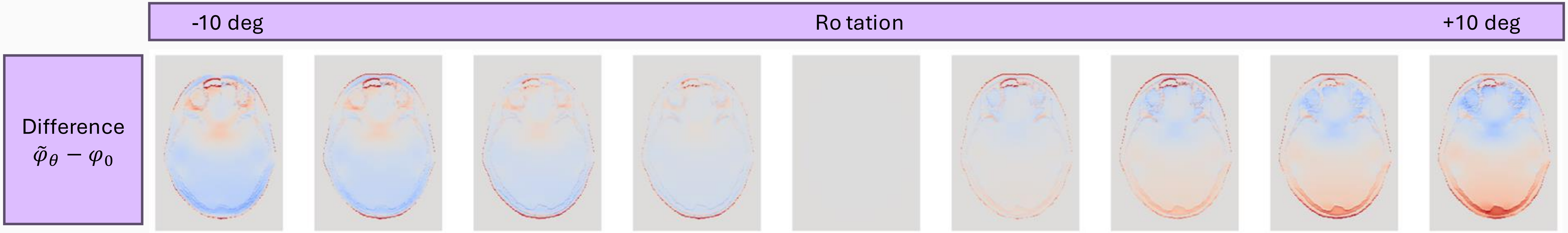
SCOPE (SPM) = TOPUP (FSL)





Andersson, Skare & Ashburner. NeuroImage (2003)

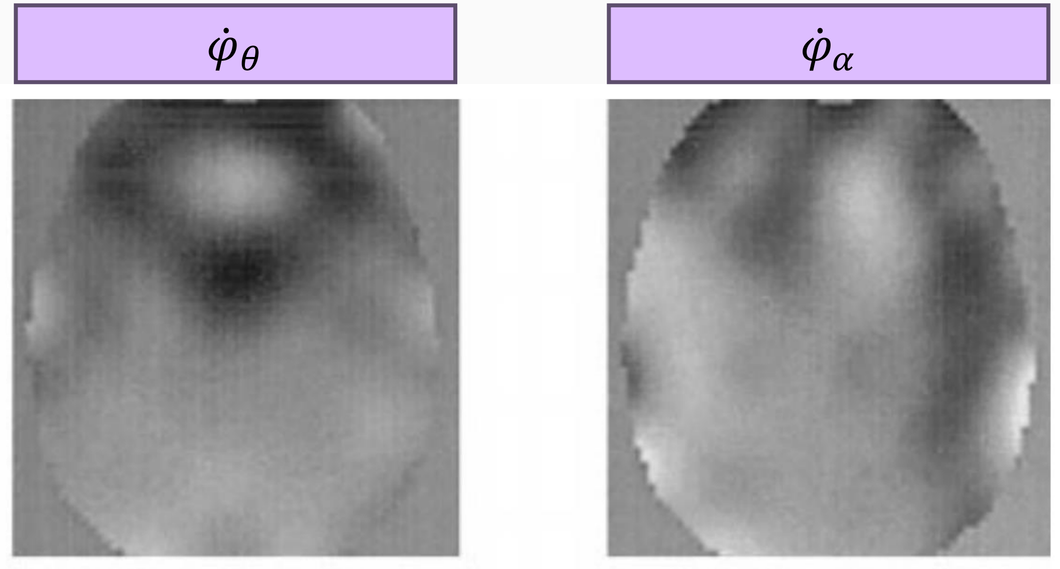
Realign & Unwarp

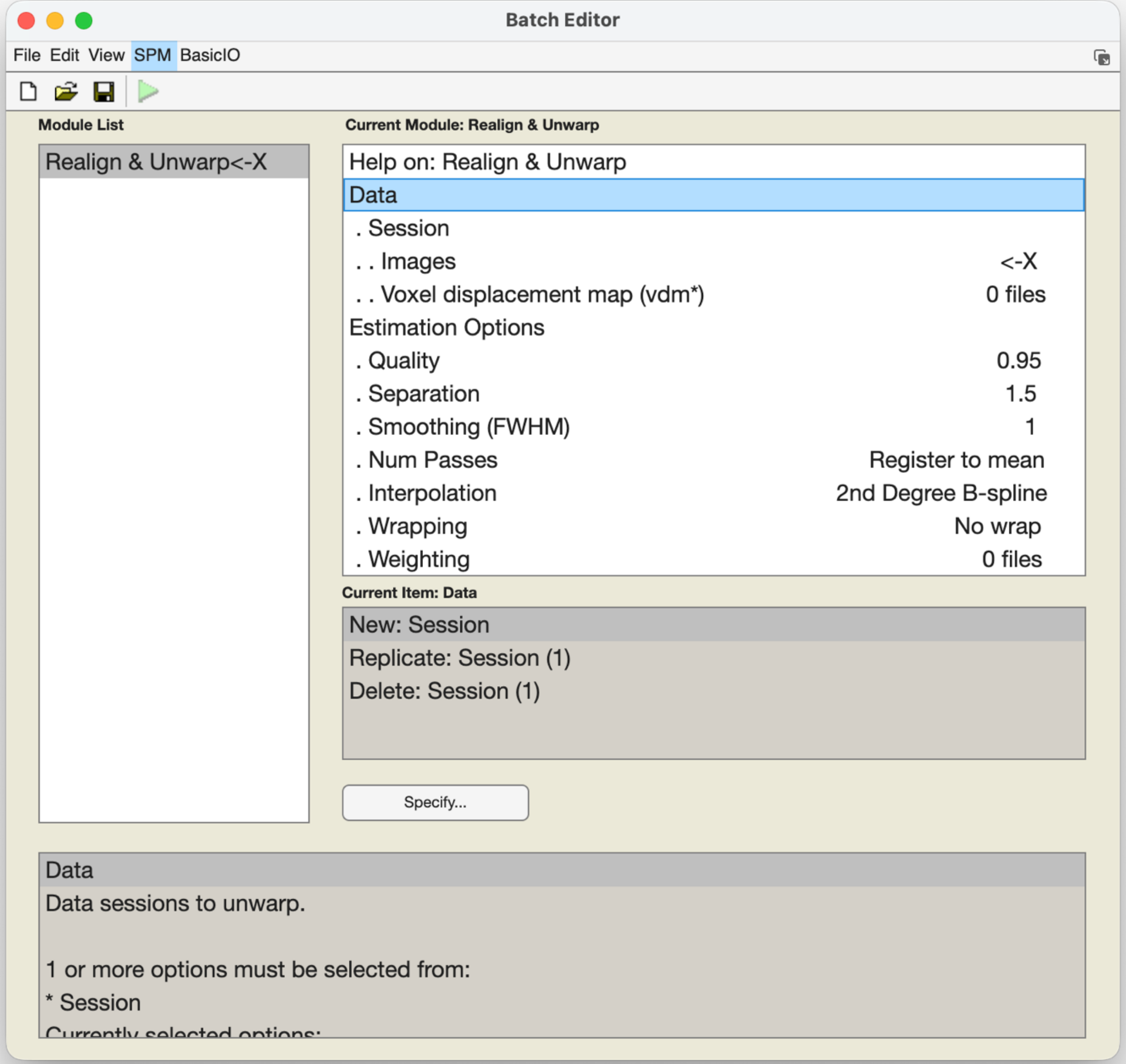


- First, realign the time series -> One set of rotation parameters per frame: $\{\theta_t, \alpha_t\}$
- First-order Taylor expansion: $\varphi_{\theta,\alpha}(\mathbf{x}) = \varphi_0(\mathbf{x}) + \theta \cdot \dot{\varphi}_\theta(\mathbf{x}) + \alpha \cdot \dot{\varphi}_\alpha(\mathbf{x})$
- Corresponds to a General Linear Model with design matrix $[\theta, \alpha]$ and coefficients $[\dot{\varphi}_\theta, \dot{\varphi}_\alpha]$
- Plug it into the deformation model: $f_t(\mathbf{x}) = f(\varphi_{\theta_t,\alpha_t}(\mathbf{x}) \cdot \mathbf{n}_{\theta_t,\alpha_t})$
- Optimise for the undistorted mean image f and the coefficients $[\dot{\varphi}_\theta, \dot{\varphi}_\alpha]$

Andersson & al. NeuroImage (2001)

Realign & Unwarp

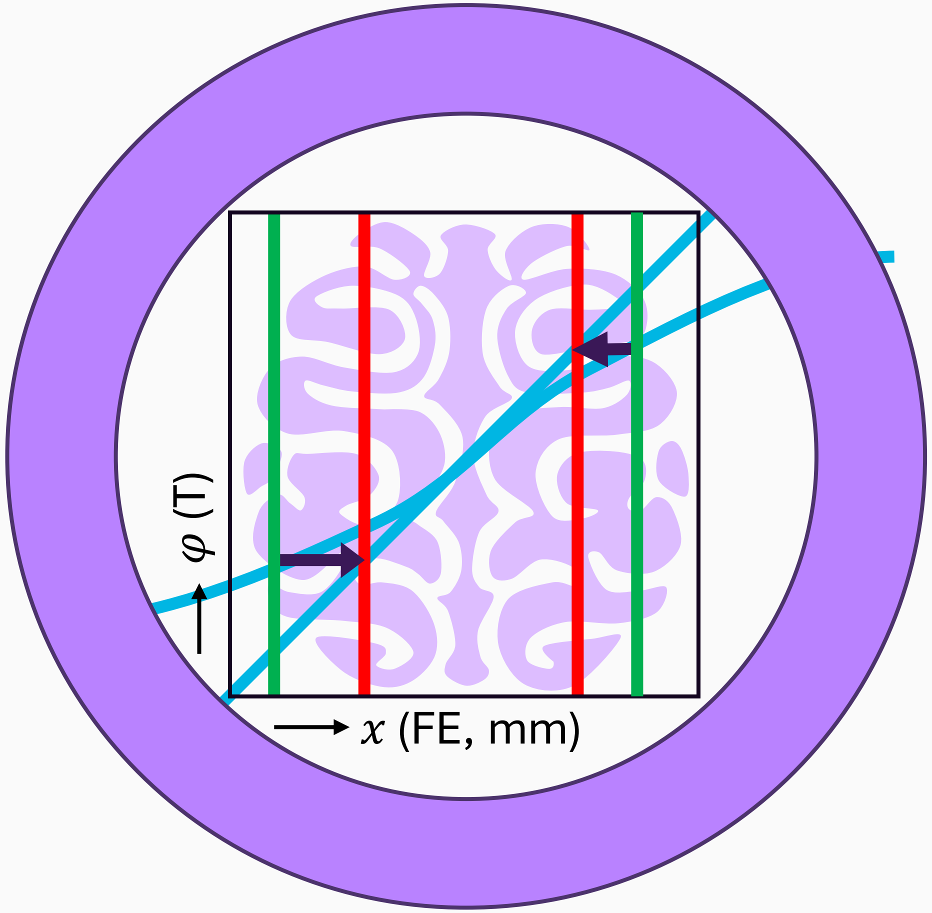




Andersson & al. NeuroImage (2001)

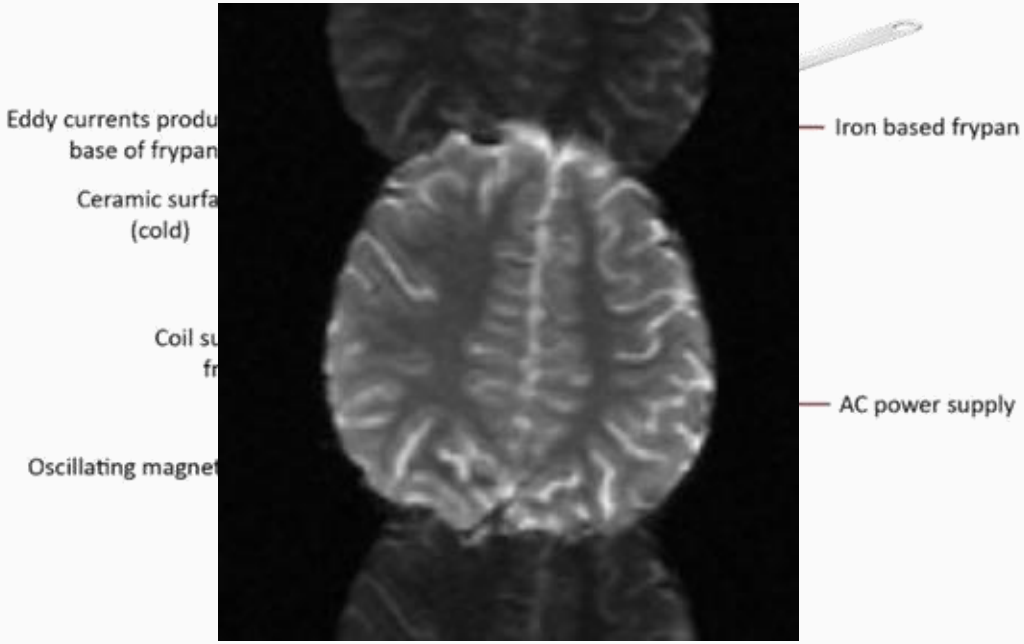
Other sources of distortions

Gradient nonlinearity



- Gradients are not **perfectly linear**, especially the further we move from the isocenter.
- This leads to **signal mislocalisation** and therefore geometric distortions.
- Some vendors include **precomputed gradient linearity maps** (private), which can be used to correct for these distortions.

Eddy currents



- ❑ **Rapidly switching gradients** create an <u>oscillating</u> magnetic field
- ❑ Common in EPI (gradient blips).

- ➢ The oscillating field induces **eddy currents** in conductive material. Most of the scanner is made of conductive material!
- ➢ **In EPI**, eddy currents cause phase shifts between the odd and even echos acquired in EPI, resulting in **N/2 ghosts**.
- ➢ They can also induce spurious gradient fields, resulting in scaling or shearing.

https://mriquestions.com/nyquist-n2-ghosts.html
https://fsl.fmrib.ox.ac.uk/fsl/docs/diffusion/eddy/index.html