Advanced Cognitive Neuroscience

Week 49: What was it all about?

PhD

Information meeting on Ph.d. applications and Ph.d. life
For everybody and in particular students interested in *language, linguistics, communication, and cognition*.

Time: Thursday 11 December 14.15-15.45
On-site Location: Building 1481, room 366
Online participation Zoom link: https://aarhusuniversity.zoom.us/j/62978903090

Do you dream of applying for at Ph.d. on a topic related to language, linguistics, communication, and cognition, but don't know how to get started? Or do you already have a Ph.d. application in the making but want some tips and tricks on how to improve it? Do you want to know more about Ph.d. life to figure out if this is something for you at all? Or do you just want free cookies? Then come to the Ph.d. information meeting!

There will be short presentations (followed by ample opportunity to ask questions) by:

Anna-Merete Thinggaard, recently started Ph.d.-student
Marianne Hoffmeister, Ph.d administrator
Mikkel Wallentin, Ph.d.-program director (Language, Linguistics, Communication and Cognition)

The next deadline for Faculty Ph.d.-stipends is 15 March 2026 (call will be published approx. 1 month ahead), but now is the time to start thinking about it.

You can apply for a Ph.d. as a Master's student or with a 1 year Master's degree (4+4 scheme), if you have 60-90 ECTS credits after your Bachelor's degree (at the start of the PhD – not the application).
You can also apply if you have a 2-year Master's degree (5+3 scheme).

Find more information about applying here:
https://phd.arts.au.dk/applicants/general-information

See you there,

EXAM

Submission deadline:

<u>December 16</u>

Your video

- Don’t necessarily change parts on which you didn’t receive “bad” feedback
- Your final video can thus contain old parts and new parts

Your report

- You will receive feedback end of this week
- Please upload both a track changes version (if changes were made) and a clean version of the report

Evaluation results

Svarprocent

	Studerende
Besvaret	21
Inviteret	36
Svarprocent	58,33%

“Response rate: Students – Answered 21, Invited 36, Response rate 58.33%.”

Translated by Lumo

Evaluation results

Translated questionnaire items (Danish → English)

Danish statement	English translation	Mean (Likert 1-5)
Jeg vurderer det samlede udbytte af undervisningsforløbet som	I assess the overall benefit of the teaching program as	**4.24**
Jeg kan se, hvordan mit kursus er relevant for min samlede uddannelse.	I can see how my course is relevant to my overall education.	**4.62**
Kursusforløbet har bidraget til at opbygge min faglige viden og mine kompetencer.	The course has contributed to building my professional knowledge and skills.	**4.62**
Kursusforløbet motiverer mig til at engagere mig i undervisningen og arbejde aktivt med indholdet.	The course motivates me to engage in teaching and work actively with the material.	**4.43**
Jeg oplever, at dialogen mellem underviseren og holdet har været konstruktiv.	I experience that the dialogue between the instructor and the group has been constructive.	**4.71**
Jeg har oplevet undervisningsrummet som trygt.	I have experienced the learning environment as safe.	**4.86**

Evaluation results

I ASSESS THE OVERALL BENEFIT OF THE TEACHING PROGRAM AS

Translation (Danish → English)

Rating description	Rating value	Number of respondents	Percentage
Very high benefit	**5**	7	**33.33 %**
High benefit	**4**	12	**57.14 %**
Some benefit	**3**	2	**9.52 %**
Little benefit	**2**	0	**0 %**
No benefit	**1**	0	**0 %**
Total	—	**21**	**100 %**

Evaluation results

I ASSESS THE OVERALL BENEFIT OF THE TEACHING PROGRAM AS

Kommentar
- Although it is one of the most demanding courses I took part in, I still think there is very good outcome in terms of how much I have learned and how many skills I acquired.
- there could have been more knowledge on the brain in general during lectures and less on the math and formulas of meg. Not saying cut the maths out completely but it could have been more evenly divided, or at least with a bigger focus on how to utilize the formulas and why they matter. It's as if almost all the lectures were focused on formulas, except our own exam presentations
- Fantastic course. En meget perfekt balance mellem følelse af fri og fastlagt læring.

Evaluation results

I CAN SEE HOW MY COURSE IS RELEVANT TO MY OVERALL EDUCATION

Response distribution

Likert rating	Meaning (English)	Number of respondents	Percentage
5	Strongly agree	14	**66.67 %**
4	Mostly agree	6	**28.57 %**
3	Neither agree nor disagree	1	**4.76 %**
2	Mostly disagree	0	**0 %**
1	Disagree	0	**0 %**
Total	—	**21**	**100 %**

Evaluation results

I CAN SEE HOW MY COURSE IS RELEVANT TO MY OVERALL EDUCATION

Kommentar
- It is very objectively relevant to cognitive science
- Personligt vil jeg ikke arbejde med neuroscience relateret, så det er ikke super relevant for mig, men det var stadig spændende og er sikkert mega relevant til folk som gerne vil arbejde med det.
- I can see why it is important but I think it is mostly useful for people wanting to go the Neuro PhD route.
- Yes, however, I feel like the amount of "spotlight" MEG mechanics got in favor of methods could benefit from being shifted. More specifically, after the first few weeks I found it hard to follow the connectivity between the different methods introduced and their place in the MEG data analysis pipeline. I would find slightly differently structured or more intentional notebooks helpful – sometimes it felt unclear what exactly the following notebook built on the previous one.
- Kurset står lidt i kontrast til de andre kurser og det er op til en selv at danne forbindelsen.

Evaluation results

THE COURSE HAS CONTRIBUTED TO BUILDING MY PROFESSIONAL KNOWLEDGE AND MY COMPETENCIES

Likert rating	English meaning	Number of respondents	Percentage
5	Strongly agree	14	**66.67 %**
4	Mostly agree	6	**28.57 %**
3	Neither agree nor disagree	1	**4.76 %**
2	Mostly disagree	0	**0 %**
1	Disagree	0	**0 %**
Total	—	**21**	**100 %**

Evaluation results

THE COURSE HAS CONTRIBUTED TO BUILDING MY PROFESSIONAL KNOWLEDGE AND MY COMPETENCIES

Kommentar
- The books we had to read were very informative and thorough, which the lectures reinforced
- Det har været fedt at bruge noget af den viden vi har fået tidligere fra neuro og også methods2 og methods3

Evaluation results

THE COURSE MOTIVATES ME TO ENGAGE IN THE TEACHING AND WORK ACTIVELY WITH THE MATERIAL

Response distribution

Likert rating	English meaning	Number of respondents	Percentage
5	Strongly agree	12	**57.14 %**
4	Mostly agree	6	**28.57 %**
3	Neither agree nor disagree	3	**14.29 %**
2	Mostly disagree	0	**0 %**
1	Disagree	0	**0 %**
Total	—	**21**	**100 %**

Evaluation results

THE COURSE MOTIVATES ME TO ENGAGE IN THE TEACHING AND WORK ACTIVELY WITH THE MATERIAL

Kommentar
- I would however point out that the report did take so much energy, that I for the first time in my schooling felt no excitement to learn
- I didn't have much other "choice" as the portfolio assignments required a lot of focus and constant preparation for the lectures and classes.
- I spent way more time on neuro that on nlp and decmak combined. That's despite mainly focusing on the parts of the portfolio and skipping lots of the readings due to time.
- You had to in order to meet expectations and delivery of assignments.
- Det fungerede rigtig godt at underviser stillede krav til aktiv deltagelse. GitHub som "hub" for kursets materialer og mail–baseret kommunikation ramte ved siden af skiven; der havde selv Brightspace været bedre. Notebooks med kildekode var præget af megen redundans og generel "messiness".

Evaluation results

I FIND THAT THE DIALOGUE BETWEEN THE INSTRUCTOR AND THE GROUP HAS BEEN CONSTRUCTIVE

Response distribution

Likert rating	English meaning	Number of respondents	Percentage
5	Strongly agree	16	**76.19 %**
4	Mostly agree	4	**19.05 %**
3	Neither agree nor disagree	1	**4.76 %**
2	Mostly disagree	0	**0 %**
1	Disagree	0	**0 %**
N/A	Not applicable / Not relevant	0	**0 %**
Total	—	**21**	**100 %**

Evaluation results

I FIND THAT THE DIALOGUE BETWEEN THE INSTRUCTOR AND THE GROUP HAS BEEN CONSTRUCTIVE

Kommentar
- I agree completely. Feedback is well received.
- Having all information in one place would be less confusing than recieving a lot of mails with updates
- You are easy to talk to, and have been easy to contact with questions.
- Specifikatoner for videoexplainer og rapport var alt for vage fra start, hvad der gav stor uvished og frustration, fordi det var svært at gå i gang med at lave arbejdet. Underviser var meget villig til at svare på spørgsmål, men var desværre tit optaget fordi der var så mange af slagsen.

Evaluation results

I HAVE EXPERIENCED THE LEARNING ENVIRONMENT AS SAFE

Response distribution

Likert rating	English meaning	Number of respondents	Percentage
5	Strongly agree	18	**85.71 %**
4	Mostly agree	3	**14.29 %**
3	Neither agree nor disagree	0	**0 %**
2	Mostly disagree	0	**0 %**
1	Disagree	0	**0 %**
Total	—	**21**	**100 %**

Evaluation results

I HAVE EXPERIENCED THE LEARNING ENVIRONMENT AS SAFE

Kommentar
- I felt safe asking questions and not understanding things.
- Det bidrog meget positivt at underviser havde stor faglig stolthed og tilsvarende engagement. Krav om aktiv deltagelse var bakket op af tålmodighed og ydmyghed fra underviser der tillod at man kunne udstille sin (fejlslagne) opfattelse uden være bange for at blive nedgjort/dømt for det.

Evaluation results

HOW HAVE THE ELEMENTS OF THE COURSE CONTRIBUTED MOST TO YOUR LEARNING?

Kommentarer
Lau er meget skarp og fremstår meget engageret. Jeg har en god gruppe. Det har også bidraget til min læring, at vi skulle lave både video, aflevering og oplæg, men det har også krævet rigtigt meget tid som har presset mig lidt ift de andre kurser.
Teaching, but the exam tasks thoughout the semester have also been very motivating.
Lectures
work in group on projects, practical excerices, preparing for presentation as well as individual assignment
Jeg har virkelig en følelse af at vi har taget et kæmpe fagligt spring siden kurset i neuro på bacheloren. Det er en mega fed oplevelse
I loved the math and the exercises and the different types of exam, I do however thing the report could be restructured so it might not be a full research paper – but maybe focus more on methods and analysis which seemed to be the teaching goal of that part

Evaluation results

HOW HAVE THE ELEMENTS OF THE COURSE CONTRIBUTED MOST TO YOUR LEARNING?

The books we had to read and the lectures in the first half of the course. Some constructive points I would like to mention is first that there is no space to write any constructive criticism, which I think should be important, and specifically about the course, that the workload is way over the expected amount. I think this should either be communicated in the beginning or reduced in the future. The second assignment especially is very difficult to divide, so one person generally ended up working on all the analysis while the others did the rest. It felt like we had an exam season before the exam season which extended very stressful periods and hindered my availability to all other courses for weeks. I did learn a lot but would prefer less workload so it is manageable especially considering all the other courses as well. But otherwise the course content is great, it is very interesting and relevant, the teacher is great at explaining things and helping us and the material provided is very useful. Overall it is my favourite course in the semester regardless of workload.
Eksamensformatet
Working with neural decoding and the MEG primer
Eksamensmetoden! Fedt med video, fremlæggelser og rapport. Dog kunne det have været fedt hvis alle havde afleveret rapporten senest ugen inden de første fremlæggelser blev afholdt, så man ikke skulle skifte mellem opgaverne op mod deadline.
The parts of the portfolio, generally a good exam format, it was nice that not everything in the exam was about code but actually understanding neurons, research etc and being able to communicate this
I really enjoyed the exam format with the video and oral presentation, through out the semester.
Going through the MEG data collection ourselves. The presentation, the preparation for which helped contextualize MEG methods and place them in a research environment.

Evaluation results

HOW HAVE THE ELEMENTS OF THE COURSE CONTRIBUTED MOST TO YOUR LEARNING?

Eksamensformen. Jeg kan godt lide at der både var mundtligt og skriftligt, og at det er en portfolio eksamen. At være på Skejby var også meget spændende.
Hands–on arbejdet og adgang til ekspertise. Tvunget gruppearbejde og en "åben" opgaveformulering ifm. rapport gav store udfordringer med ensretning og gav derfor meget spildarbejde.
Virkelig god og dedikeret undervisning, med en stærk forbindelse mellem teori og praksis. Og meget tjekket med workshoppen på Skejby også. Det har været meget inspirerende.
hands–on tasks (the MEG workshop, writing the report and the presentations). also the few times we were solving equations in class, although i wish we had these earlier in the semester
Gode forelæsninger, engageret underviser & gode portfolioopgaver
Præsentationer og mundtlig faglighed
Working in a study–group on most of the assignments, helped with understanding the course material better.
Arbejdet med source reconstruction på matematisk plan og machine learning ift det specifikke eksperiment var virkeligt godt

Summary by lumo

4. Key Recommendations

1. **Reduce & Communicate Workload** – Publish a realistic time-budget at the start; consider spreading large portfolio tasks over the term.
2. **Rebalance Content** – Increase neuro-biology background, keep math but frame it as a tool; integrate methods more clearly into the MEG analysis pipeline.
3. **Centralize Course Materials** – Use a single LMS (Brightspace, Teams, etc.) for announcements, files, and links; limit email traffic.
4. **Clarify Assignment Specs** – Provide detailed rubrics and timelines for video, report, and presentation tasks; set the report deadline a week before presentations.
5. **Structure Group Projects** – Define explicit roles or sub-tasks so work is evenly distributed and duplication is avoided.
6. **Clean Up Notebooks** – Supply clean, step-by-step notebooks; remove redundant cells; include a "road-map" comment block showing dependencies.
7. **Introduce Early Math Boot-Camp** – Brief refresher on required calculus/linear algebra at the semester start to ease later technical sections.

Summary by lumo

5. Bottom Line

The course receives **very high satisfaction scores** (averages 4.4–4.9) and is praised for its **engaged instructor, safe learning climate, and hands-on portfolio assessments**. The primary challenges are **excessive workload, uneven balance between neuro-biology and heavy mathematics, and logistical clarity**. Addressing these issues—especially workload management and clearer, centralized communication—should preserve the strong learning outcomes while reducing student stress.

The course plan

Week 36:
Lesson 0: What is it all about?
Class 0: Setting up UCloud and installing MNE-Python

Week 37:
No Teaching

Week 38:
Lesson 1: Workshop paradigm: Measuring visual subjective experience + MR Recordings
Class 1: Running an MEG analysis of visual responses

Week 39:
MEG workshop: Measuring and predicting visual subjective experience

Week 40:
Lesson 2: Basic physiology and Evoked responses
Class 2: Evoked responses to different levels of subjective experience

Week 41:
Lesson 3: Multivariate statistics
Class 3: Predicting subjective experience in sensor space
<u>Deadline for feedback: Video Explainer</u>

Week 42:
Autumn Break

Week 43:
Lesson 4: Forward modelling and dipole estimation
Class 4: Creating a forward model and fitting dipoles

Week 44:
Lesson 5: Inverse modelling: Minimum-norm estimate
Class 5: Predicting subjective experience in source space

Week 45:
Lesson 6: Inverse modelling: Beamforming
Class 6: Predicting subjective experience in source space, continued

Week 46:
Lesson 7: What about that other cortex? - the cerebellar one
Class 7: Oral presentations (part 1)
<u>Deadline for feedback: Lab report</u>

Week 47:
Lesson 8: Guest lecture: Laura Bock Paulsen: Respiratory analyses
Class 8: Oral presentations (part 2)

Week 48:
Lesson 9: Guest lecture: Barbara Pomiechowska: Using OPM-MEG to study brain and cognitive development in infancy
Class 9: Oral presentations (part 3)

Week 49:
Lesson 0 again: What was it all about?
Class 10: Oral presentations (part 4)

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Lesson 0 again: What was it all about?
Class 10: Oral presentations (part 4)

Academic regulations - objectives

KNOWLEDGE

- describe the anatomy and physiology of the human brain, and explain the brain basis of cognitive function
- contrast different cognitive neuroscience methods in terms of their strengths and weaknesses, and use this knowledge to develop appropriate experimental research for investigating different cognitive functions of the brain.

Academic regulations - objectives

SKILLS

- run experiments using neuroimaging and/or neurophysiological measurement equipment
- use advanced statistical methods to make inferences about cognitive brain functions from neuroimaging and/or neurophysiological data.

Academic regulations - objectives

COMPETENCES

- independently identify the appropriate measurement technology and experimental designs for investigating different cognitive functions
- identify cases in which statistical methods taught in the course can be applied to domains outside of cognitive neuroscience.

Overall idea of the course

- We will focus on magnetoencephalography (MEG)
  - but leverage magnetic resonance imaging to do source reconstruction of the MEG signals
- We will investigate how subjective experience is build in the brain
- We will learn how to apply multivariate statistics to reduce these very rich data sets (MEG: 306,000 data points per second)
- We will learn how to facilitate the rich spatio-temporal data that MEG provides
- We will learn about the brain while doing so

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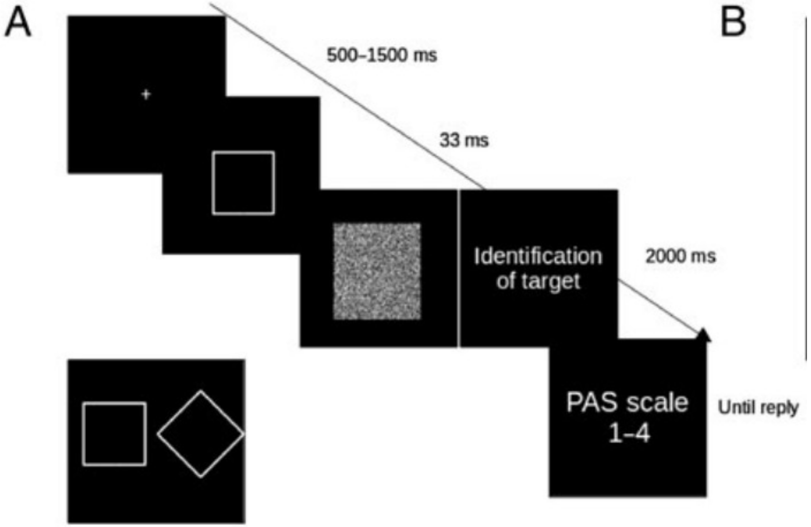
Workshop

SUBJECTIVE EXPERIENCE

from Center of Functionally Integrative Neuroscience



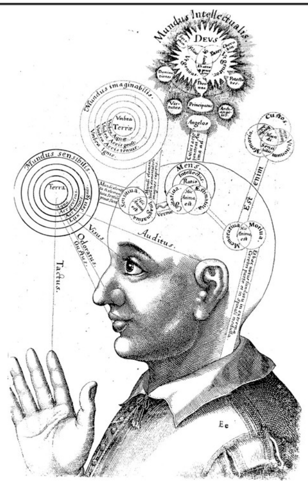
Andersen LM, Pedersen MN, Sandberg K, Overgaard M (2016) Occipital MEG Activity in the Early Time Range (<300 ms) Predicts Graded Changes in Perceptual Consciousness. Cerebral Cortex 26:2677–2688.
https://doi.org/10.1093/cercor/bhv108

Workshop

SUBJECTIVE EXPERIENCE

Table 1 The Perceptual Awareness Scale (PAS)

Label	Description [from Ramsøy and Overgaard (2004)]
(1) No Experience (NE)	No impression of the stimulus. All answers are seen as mere guesses.
(2) Weak Glimpse (WG)	A feeling that something has been shown. Not characterized by any content, and this cannot be specified any further.
(3) Almost Clear Experience (ACE)	Ambiguous experience of the stimulus. Some stimulus aspects are experienced more vividly than others. A feeling of almost being certain about one's answer.
(4) Clear Experience (CE)	Non-ambiguous experience of the stimulus. No doubt in one's answer.



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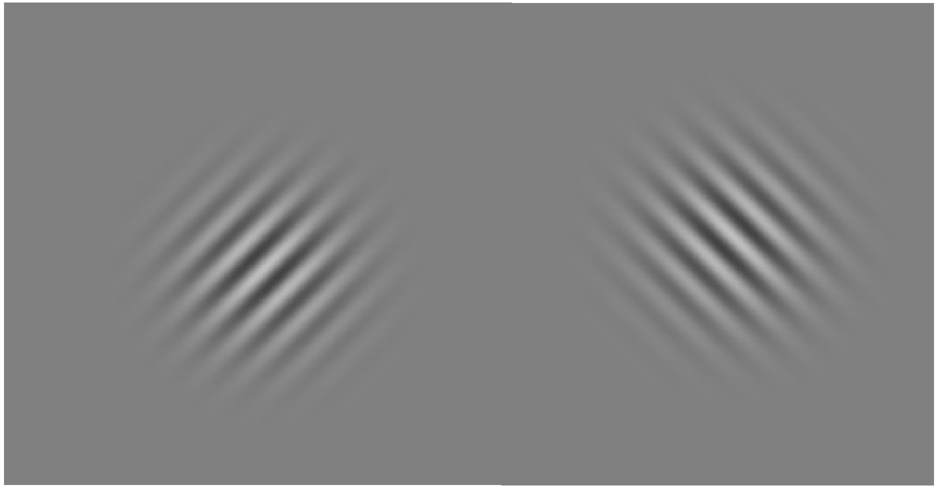
Ramsøy TZ, Overgaard M (2004) Introspection and subliminal perception. Phenomenology and the Cognitive Sciences 3:1–23.
https://doi.org/10.1023/B:PHEN.0000041900.30172.e8

By Robert Fludd - Utriusque cosmi maioris scilicet et minoris […] historia, tomus II (1619), tractatus I, sectio I, liber X,
De triplici animae in corpore visione, Public Domain, https://commons.wikimedia.org/w/index.php?curid=699073

```python
#%% RUN EXPERIMENT

## initalise
experiment = Experiment()

## setting up experiment
experiment.open_GUI()
experiment.set_experiment_parameters()
experiment.check_user()
experiment.write_to_terminal('refresh_rate')
experiment.define_io_files()
experiment.write_to_terminal('setting_path')
experiment.define_texts()
experiment.create_experiment_window()
experiment.define_visual_stimuli()
experiment.present_instructions('welcome')

## practice
experiment.present_instructions('practice')
experiment.run_practice()

## experiment
experiment.set_experiment_parameters()
experiment.present_instructions('experiment')
experiment.run_experiment()

## thank you

experiment.present_instructions('thank_you')
```

Try out the experiment on your own computer

https://github.com/ualsbombe/2025_advanced_cognitive_neuroscience/blob/main/experiment/subjective_experience_v0.py



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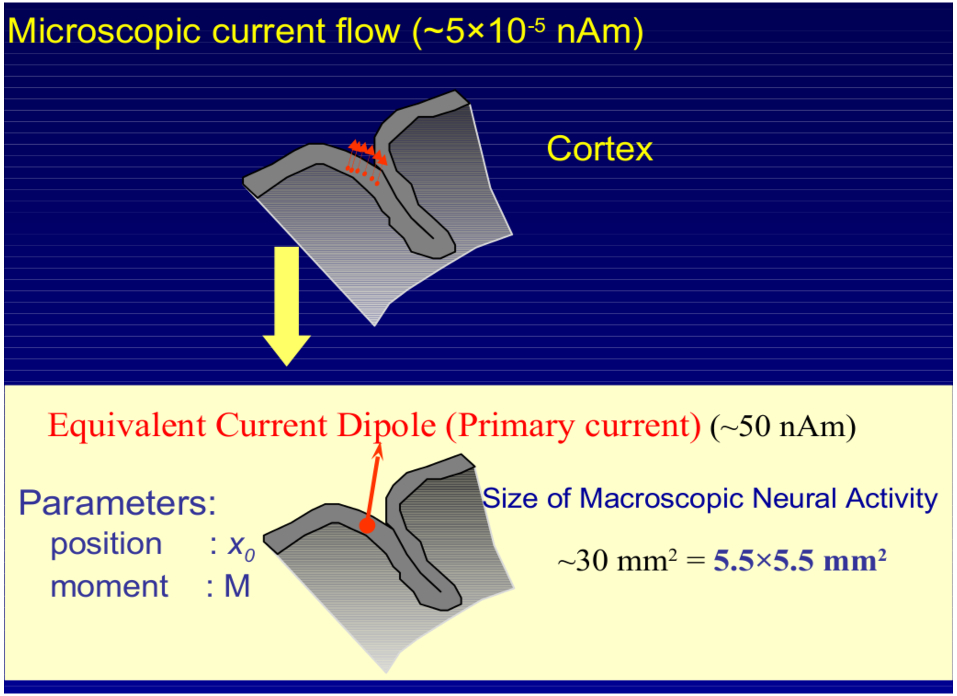
Class 10: Oral presentations (part 4)

Learning goals

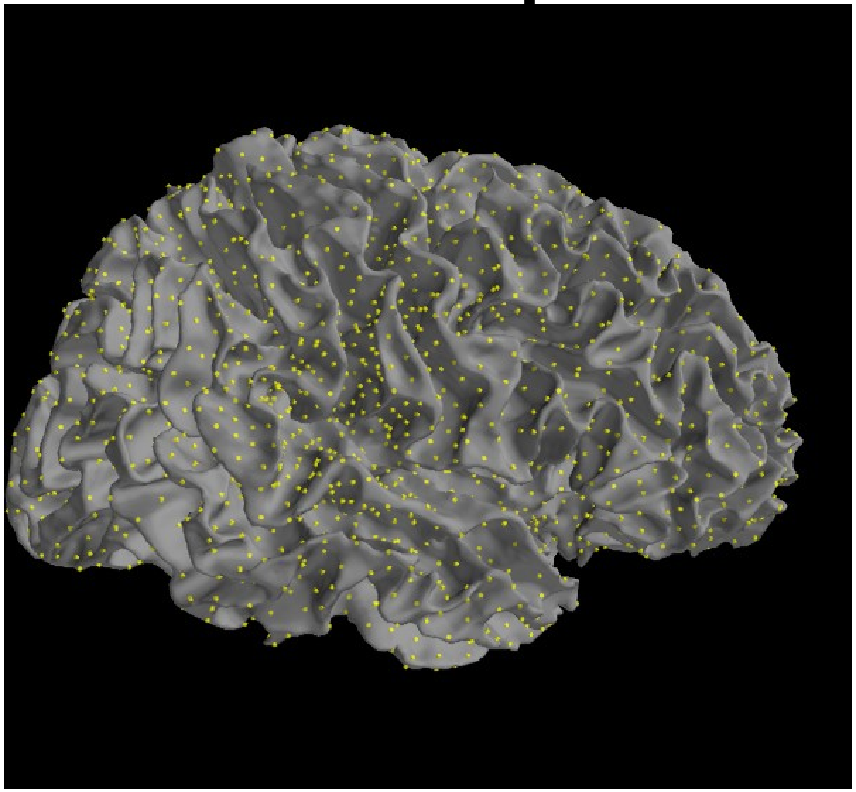
- Learning
  - where the electrophysiological signals mainly originate from
  - where and how are the electrophysiological signals measured
  - how the signals measurable from radial and tangential dipoles differ

Equivalent Current Dipole

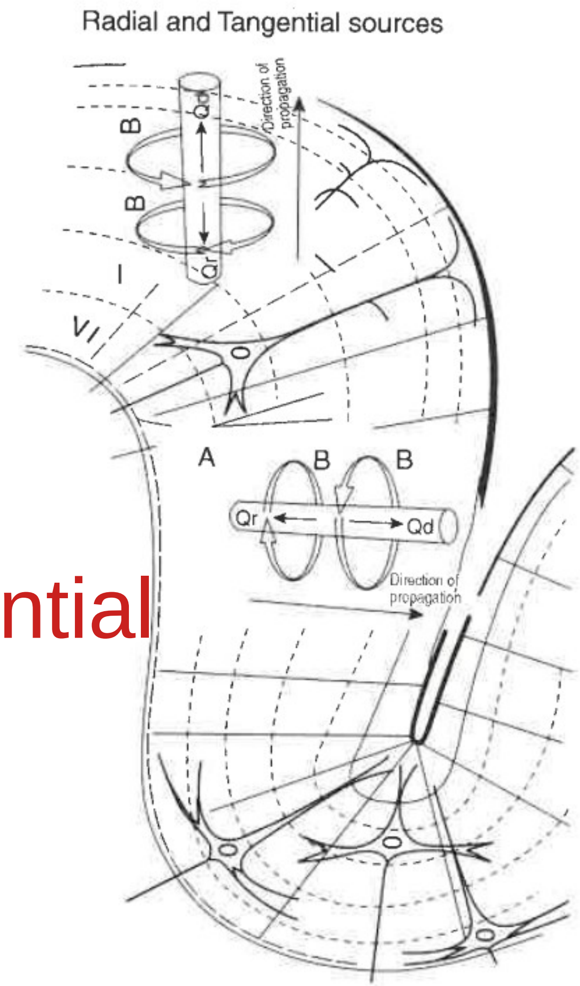


From Stephanie Sillekens

Source space with equivalent current dipoles



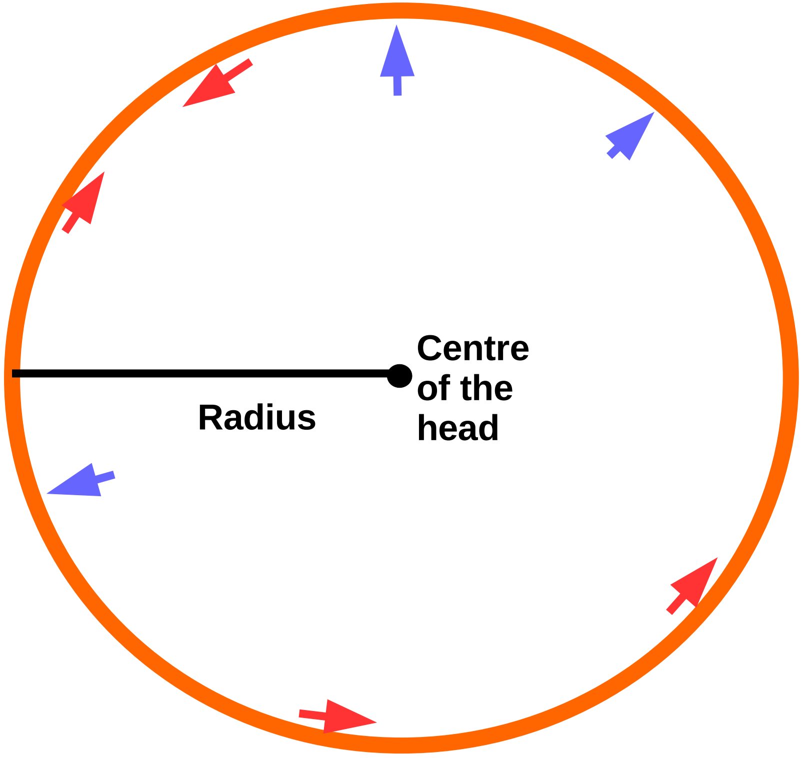
Radial



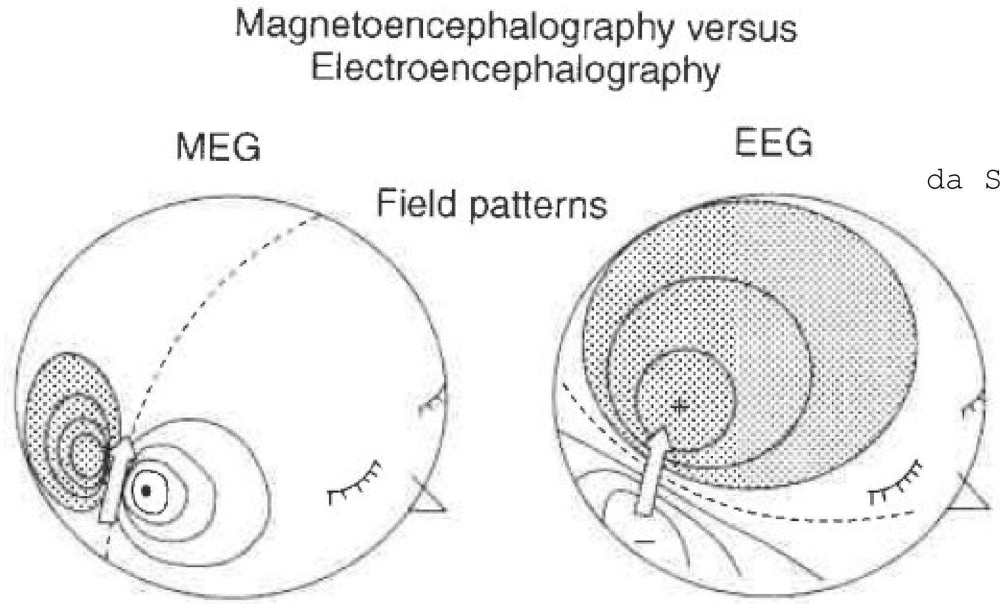
Tangential

da Silva, 2010

Radial and tangential dipoles (primary current)

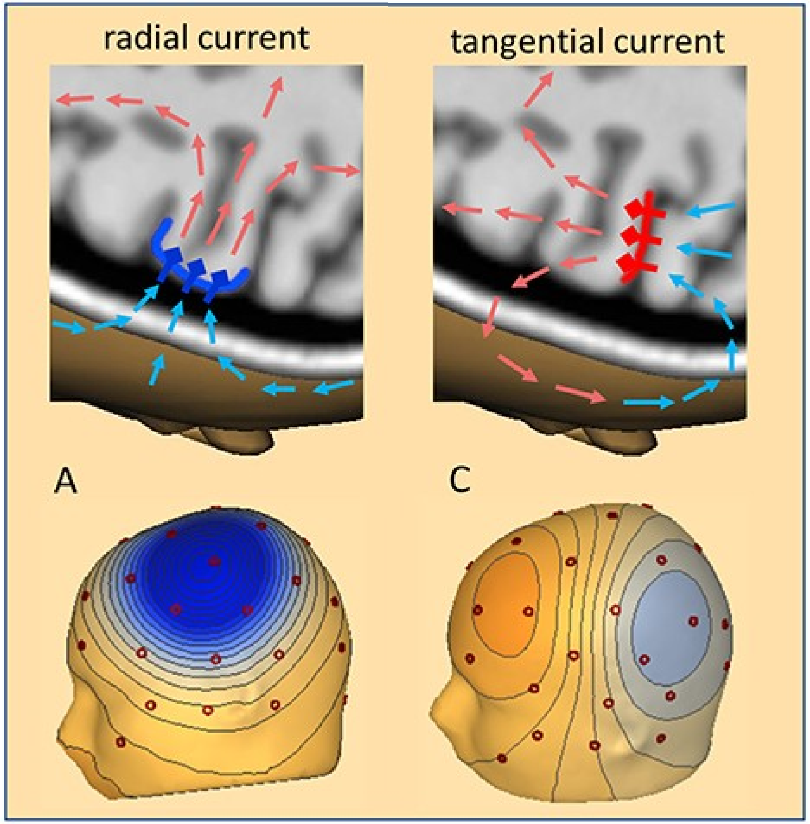


Tangential dipoles



da Silva, 2010

EEG – radial vs. tangential

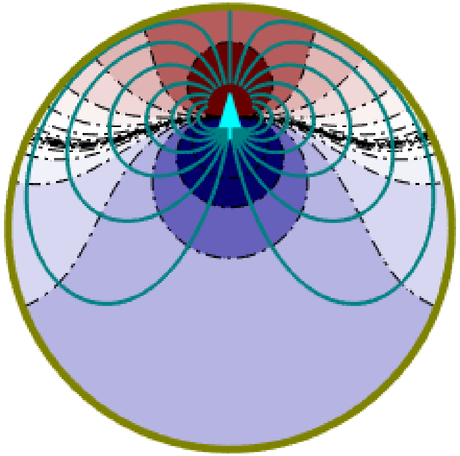


Scherg et al., 2019

MEG – what about radial sources?

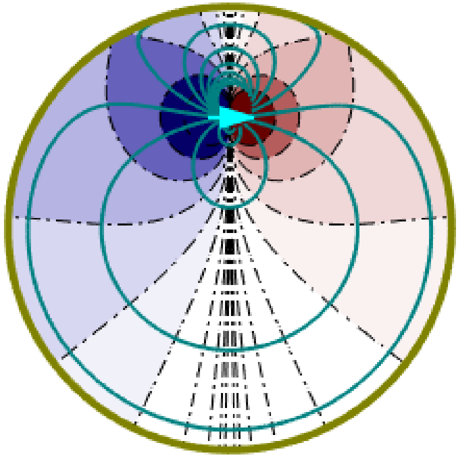
The magnetic field (*B*) is proportional to the vector sum of all electric current (Q_T). For a radial dipole, the primary current (Q_P) and the volume currents (Q_V) *cancel* one another ($Q_P + Q_V = Q_T = 0 \Rightarrow B = 0$) due to the perfect *symmetry* of the volume current in a sphere-shaped volume conductor

Radial



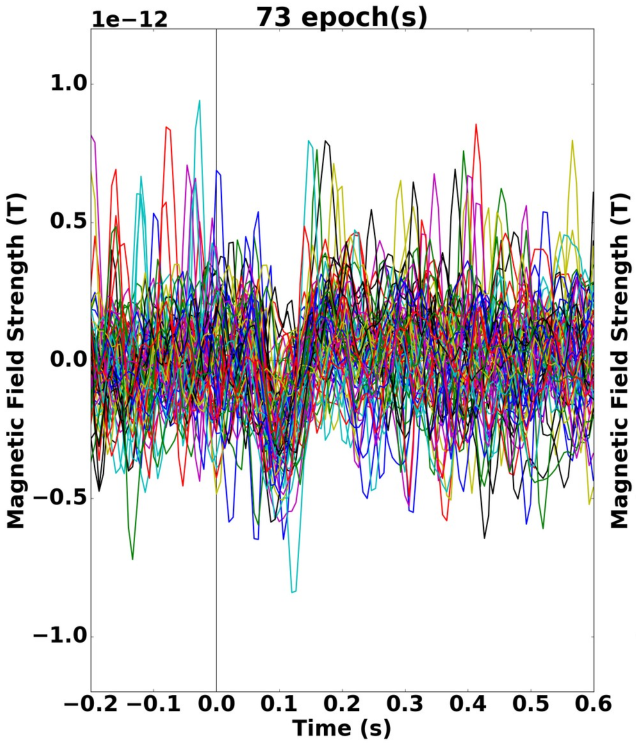
Courtesy of Christopher Bailey
https://github.com/cjayb/meeg_training

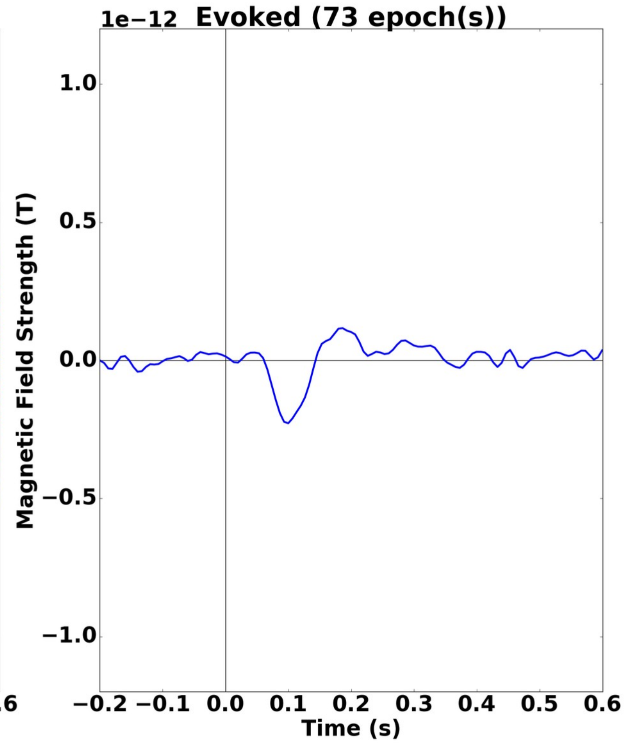
Tangential

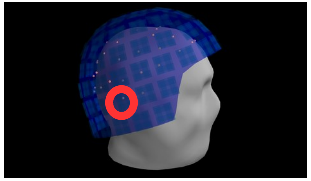


For a tangential dipole, the volume currents are *asymmetric*, thus $Q_T \neq 0$ $\Rightarrow B \neq 0$

Epochs and Evoked







Learning goals

- Learning
  - where the electrophysiological signals mainly originate from
  - where and how are the electrophysiological signals measured
  - how the signals measurable from radial and tangential dipoles differ

The course plan

Week 36:
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Class 0: Setting up UCloud and installing MNE-Python

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No Teaching

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Class 10: Oral presentations (part 4)

Learning goals

- You should (re)learn:
  - the basics of logistic regression
  - what targets could be aimed at in our experiment
  - what the pros and cons of multivariate statistics are for MEG data
    - what are the differences between sensor space decoding and source space decoding
- How to set up a pipeline
  - Standardisation
  - Feature selection (e.g. PCA)
  - Finding optimal hyperparameters (e.g. Grid Search)

At least four ingredients needed

GENERALISED LINEAR MODEL

1) A data vector: $y = (y_1, \ldots, y_n)$

2) Predictors: X and coefficients β, forming a linear predictor $X\beta$

3) A *link function* g: yielding a vector of transformed data $\hat{y} = g^{-1}(X\hat{\beta})$ that are used to model the data

4) A data distribution: $p(y \mid \hat{y})$

$$(X\beta = \beta_0 + X_1\beta_1 + \ldots + X_k\beta_k)$$

Gelman A, Hill J (2006) Data Analysis Using Regression and Multilevel/Hierarchical Models. Cambridge University Press: Chapter 6

2) Predictors: X and coefficients β, forming a linear predictor $X\beta$

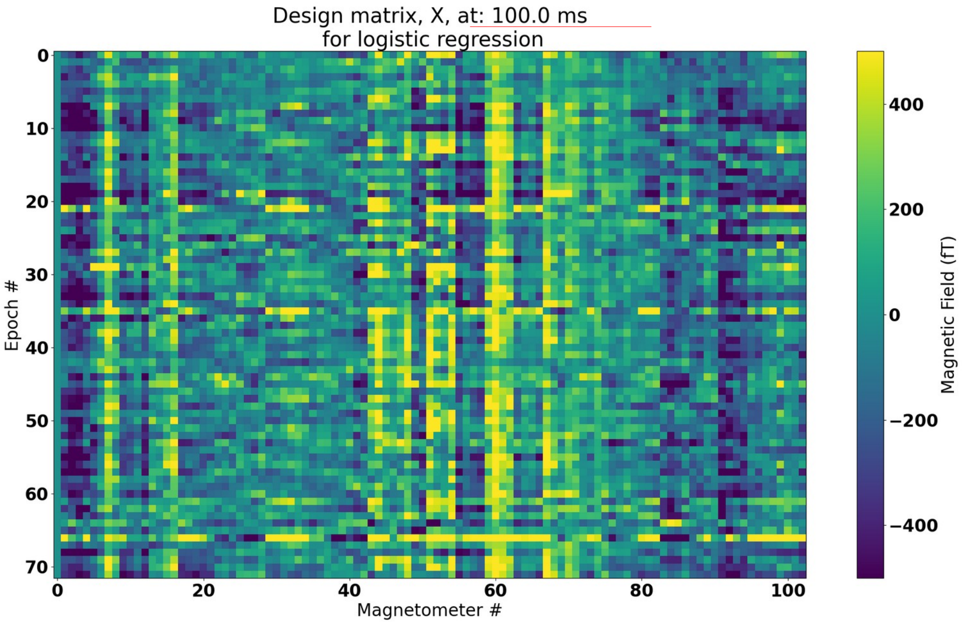
```python
def plot_design_matrix_at_time_index(time_index):

    X = 1e15 * epochs_sample['LA'].get_data()[:, :, time_index]
    X = np.insert(X, 0, 1, axis=1) # adding intercept term

    plt.figure()
    plt.imshow(X, vmin=-500, vmax=500)
    plt.colorbar(label='Magnetic Field (fT)')
    plt.ylabel('Epoch #')
    plt.xlabel('Magnetometer #')
    plt.title(f'Design matrix, X, at: '
              f'{1e3*np.round(epochs_sample.times[time_index], 3)}'
              ' ms\n for logistic regression' )
    plt.show()

plot_design_matrix_at_time_index(180)
plot_design_matrix_at_time_index(30)
```

$X =$



$\beta =$ to be estimated

Note that we (generally) want to fit a model per time point

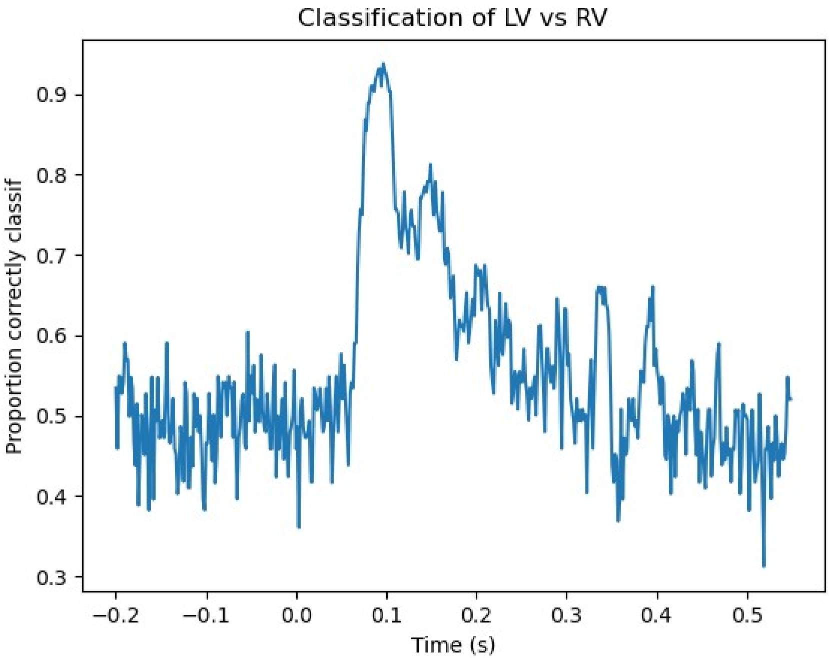
```python
#%% do logistic regression per time sample

from sklearn.linear_model import LogisticRegression
from sklearn.model_selection import cross_val_score, StratifiedKFold
from sklearn.preprocessing import StandardScaler

scores_list_samples = [None] * n_samples

sc = StandardScaler()

for sample_index in range(n_samples):
    print(sample_index)
    this_X = X[:, :, sample_index]
    this_X_std = sc.fit_transform(this_X) ## standardise the data
    logr = LogisticRegression(C=1e-3)
    scores_list_samples[sample_index] = np.mean(cross_val_score(logr,
                                                 this_X_std,
                                                 y,
                                                 cv=StratifiedKFold()))
```

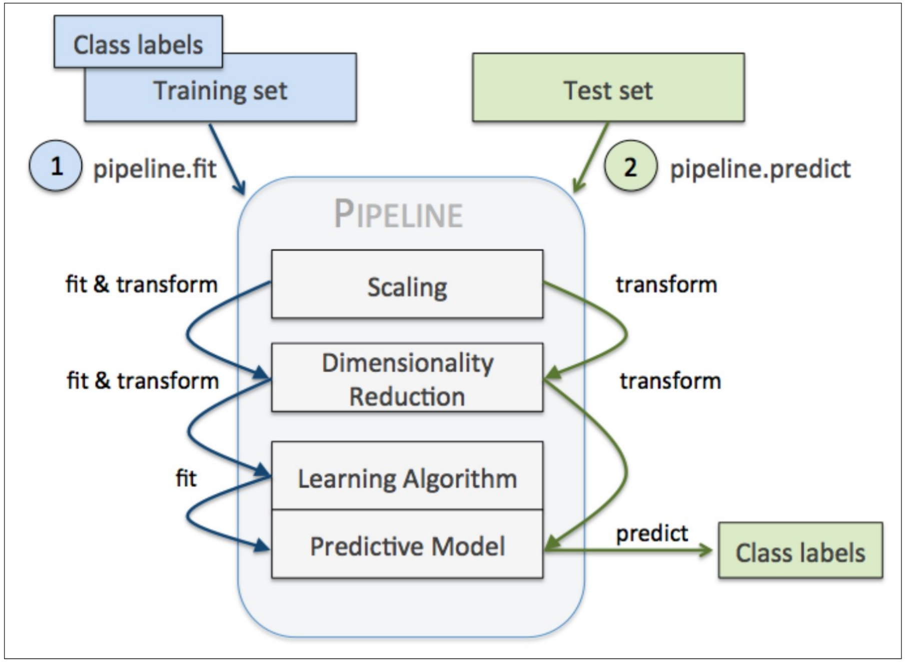



```
this_X.shape
(144, 87)
```

```
y.shape
(144,)
```

How many features/independent variables and how many repetitions?

Pipelines (scikit-learn)




```python
#%% PIPELINE WAY

from sklearn.preprocessing import StandardScaler
from sklearn.decomposition import PCA
from sklearn.linear_model  import LogisticRegression
from sklearn.pipeline      import Pipeline

pipe_lr = Pipeline(
    [
         ('scl', StandardScaler()),
         ('pca', PCA(n_components=2)),
         ('clf', LogisticRegression(random_state=1,
                                    penalty='l2',
                                    tol=1e-4,
                                    C=1.0))
    ]
                  )

pipe_lr.fit(X_train, y_train)
print('Training accuracy: %.3f' %  pipe_lr.score(X_train, y_train))
print('Test accuracy: %.3f'     %  pipe_lr.score(X_test, y_test))
```

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- Learning
  - what the ingredients of a forward model are
  - how the forward model links sources of the brain to sensors
  - what co-registration of MRI and MEG amounts to
  - how to fit dipoles

The problem in a nutshell

$$\boldsymbol{Y}_{m\times t}=\boldsymbol{W}_{m\times n}\boldsymbol{X}_{m\times t}$$

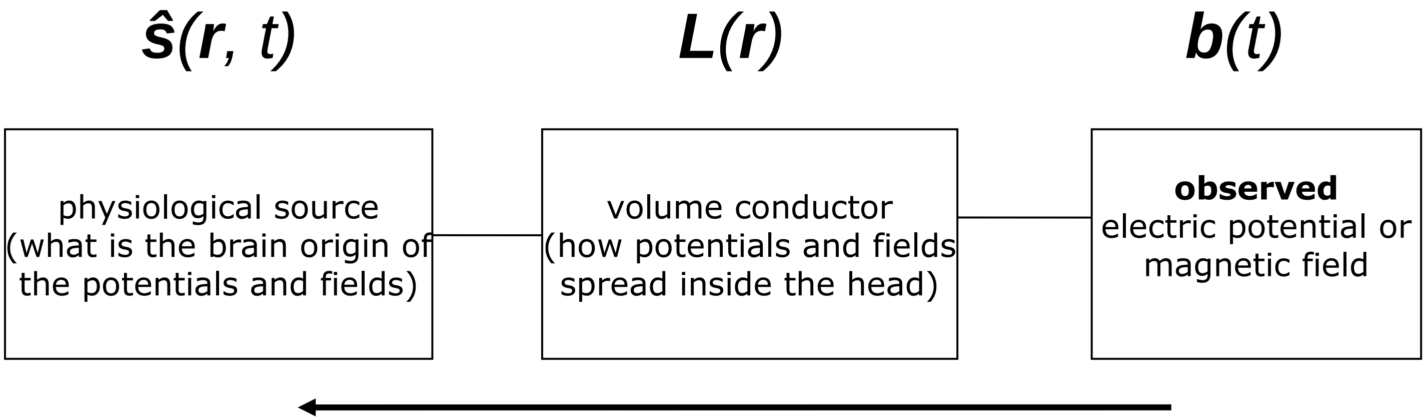
Y: the true signal (magnetic field)
X: the neural generators
W: a weighting matrix (the leadfield)
n >> m

The problem in a nutshell

$$\boldsymbol{b}(t)=\boldsymbol{L}(r)\boldsymbol{s}(\boldsymbol{r},t)+\boldsymbol{n}(t)$$

b*(t)*: the measured magnetic field at time *t*
s(r*, t)*: the sources at position ***r*** at time *t*
L*(r):* leadfield of sources a position ***r*** (a weighting matrix)
n(*t*): normally distributed noise at each time *t*

Inverse modelling



inverse model
(source reconstruction)

Forward modelling

forward model

$$\mathbf{s}(\mathbf{r}, t) \xrightarrow{\mathbf{L}(\mathbf{r})} \hat{\mathbf{b}}(t)$$

physiological source (what is the brain origin of the potentials and fields)	volume conductor (how potentials and fields spread inside the head)	***expected*** electric potential or magnetic field

IMPORTANT

Without a plausible forward model restricting the solution space, an infinite number of inverse models could explain the data

since n (number of sources) >> m (number of sensors)

Ingredients for a forward model, ***L***(***r***)

- A source model _src_
  - Telling us *the origin* of brain activity
- A volume conductor _bem_
  - Telling us how electric currents *spread* within the head _bem solution_
- Sensor positions _info_
  - Telling us *where* the sensors are relative to the sources
  - These need to be transformed into MR space

Info structure

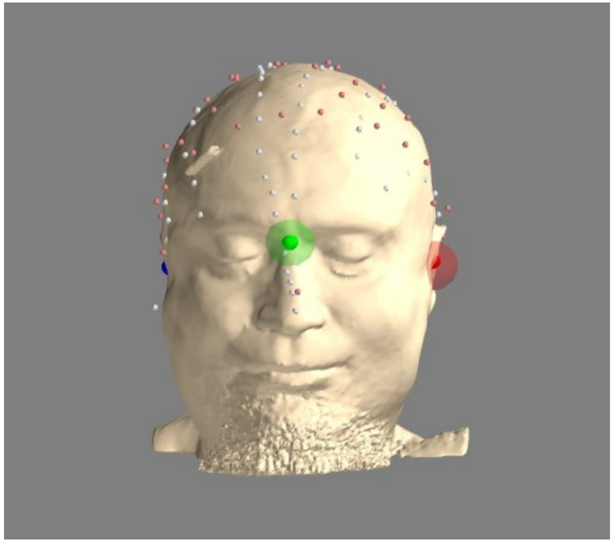
```
In [29]: info = mne.io.read_info('workshop_2025_raw.fif')
```

```
In [30]: info['dev_head_t']
Out[30]:
<Transform | MEG device->head>
[[ 0.99853134  0.04444526  0.03098306 -0.00409153]
 [-0.04400658  0.99892318 -0.01469979  0.00523906]
 [-0.03160303  0.01331474  0.99941182  0.05708658]
 [ 0.          0.          0.          1.        ]]
```

```
In [32]: info['chs'][3]
Out[32]:
{'scanno': 4,
 'logno': 111,
 'kind': 1 (FIFFV_MEG_CH),
 'range': 1.9073486328125e-05,
 'cal': 1.329999999022391e-10,
 'coil_type': 3022 (FIFFV_COIL_VV_MAG_T1),
 'loc': array([-0.1066    ,  0.0464    , -0.0604    , -0.0127    ,  0.0057    ,
        -0.99990302, -0.186801  , -0.98240298, -0.0033    , -0.98232698,
         0.18674099,  0.013541  ]),
 'unit': 112 (FIFF_UNIT_T),
 'unit_mul': 0 (FIFF_UNITM_NONE),
 'ch_name': 'MEG0111',
 'coord_frame': 1 (FIFFV_COORD_DEVICE)}
```

Co-registration

1. Nasion
2. Left pre-auricular point
3. Right pre-auricular point



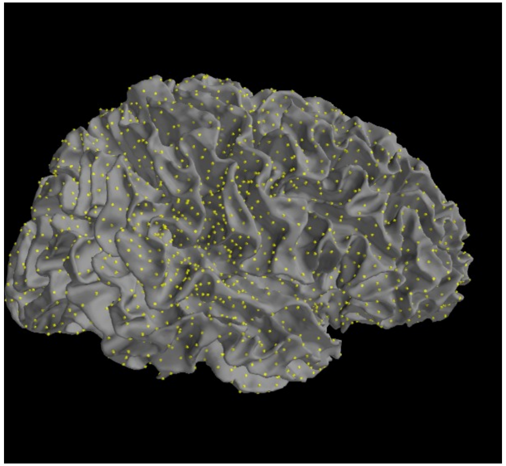
```
In [7]: trans = mne.read_trans('workshop_2025-trans.fif')

In [8]: trans
Out[8]:
<Transform | head->MRI (surface RAS)>
[[ 0.99968028 -0.02514233 -0.00269039  0.00789862]
 [ 0.02285611  0.94399983 -0.3291533  -0.00342108]
 [ 0.01081541  0.32898656  0.9442727  -0.03508078]
 [ 0.          0.          0.          1.        ]]
```

```
In [32]: info['chs'][3]
Out[32]:
{'scanno': 4,
 'logno': 111,
 'kind': 1 (FIFFV_MEG_CH),
 'range': 1.9073486328125e-05,
 'cal': 1.329999999022391e-10,
 'coil_type': 3022 (FIFFV_COIL_VV_MAG_T1),
 'loc': array([-0.1066    ,  0.0464    , -0.0604    , -0.0127    ,  0.0057    ,
       -0.99990302, -0.186801  , -0.98240298, -0.0033    , -0.98232698,
        0.18674099,  0.013541  ]),
 'unit': 112 (FIFF_UNIT_T),
 'unit_mul': 0 (FIFF_UNITM_NONE),
 'ch_name': 'MEG0111',
 'coord_frame': 1 (FIFFV_COORD_DEVICE)}
```

Use an algorithm to minimize the distance between points and head shape. The MR and the MEG are now co-registered

Source model example



```
#%% CORTICAL SURFACE SOURCE SPACE

for subject in subjects:
    cort_src = mne.source_space.setup_source_space(subject,
                                                    subjects_dir=subjects_dir,
                                                    n_jobs=-1)
    bem_path = join(subjects_dir, subject, 'bem')
    write_filename = subject + '-oct-6-src.fif'
    mne.source_space.write_source_spaces(join(bem_path, write_filename),
                                         cort_src)
```

Contents of the *fwd*

STORY I TOLD LAST TIME

```
In [44]: fwd['sol']['data'].shape
Out[44]: (366, 22494)
```

```
In [50]: fwd['src']
Out[50]: <SourceSpaces: [<surface (lh), n_vertices=155407, n_used=3732>,
<surface (rh), n_vertices=156866, n_used=3766>] head coords, subject
'sample', ~31.0 MiB>
```

```
In [49]: len(evoked_sample.ch_names)
Out[49]: 366
```

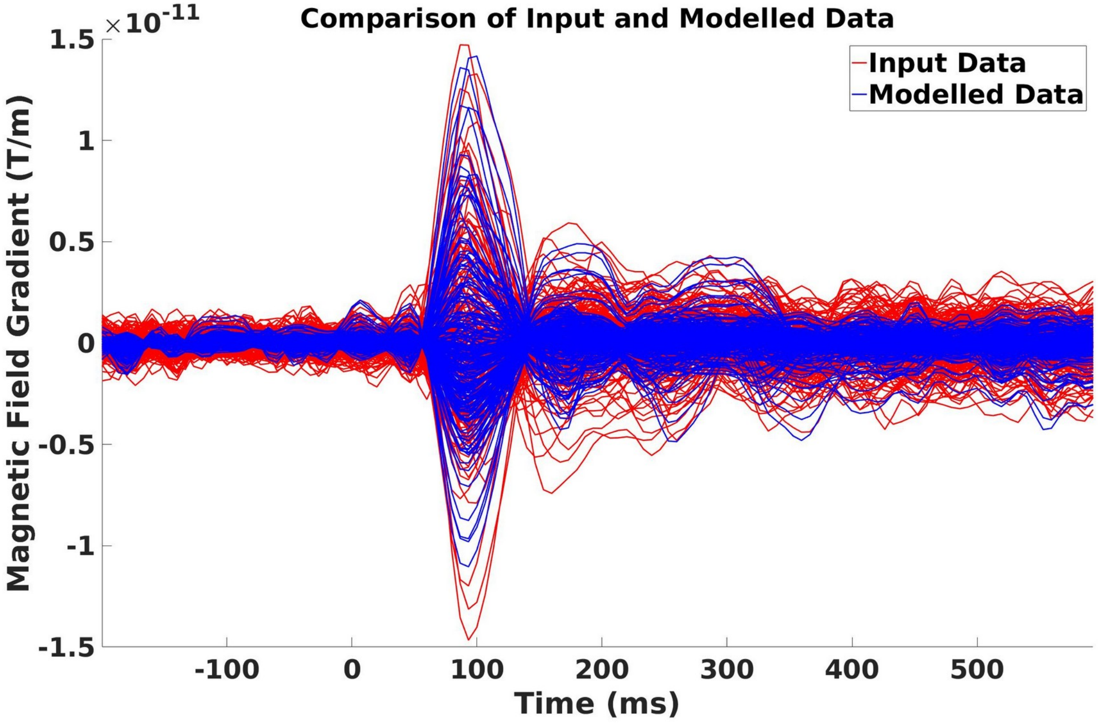
```
In [51]: len(fwd['src'])
Out[51]: 2
```

```
In [56]: fwd['sol']['data'].shape[1] // 3
Out[56]: 7498
```

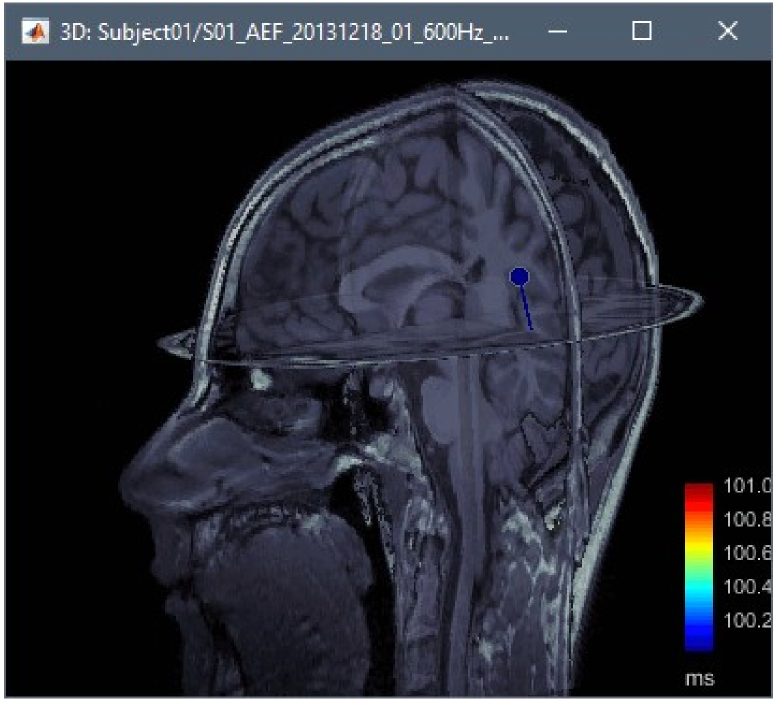
```
In [52]: fwd['src'][0]['nuse'] + fwd['src'][1]['nuse']
Out[52]: 7498
```

```
In [58]: evoked_sample.ch_names[2]
Out[58]: 'MEG 0111'
```

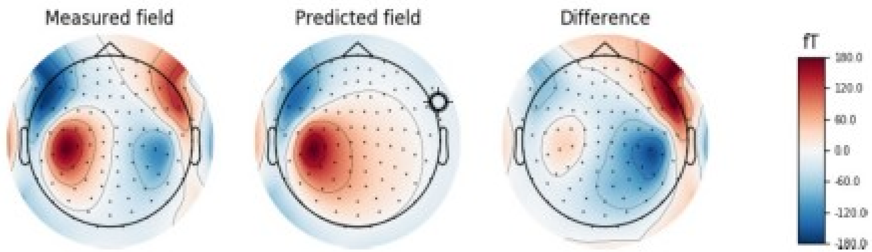
```
In [57]: fwd['sol']['data'][2, :]
Out[57]:
array([-7.1391241e-07,  9.5892676e-07,  7.8583281e-07, ...,
        9.4759559e-07, -2.4599572e-07, -6.7779990e-07],
      shape=(22494,), dtype=float32)
```



Comparison of Input and Modelled Data
$\times 10^{-11}$
Input Data
Modelled Data
Magnetic Field Gradient (T/m)
Time (ms)
1.5
1
0.5
0
-0.5
-1
-1.5
-100
0
100
200
300
400
500



3D: Subject01/S01_AEF_20131218_01_600Hz_...
101.0
100.8
100.6
100.4
100.2
ms



Measured field
Predicted field
Difference
fT

Dipole fitting

1. Scan all the sources within your source space to find the optimal starting position

Minimize the following expression, i.e. the discrepancy between model and observed data (“+” is the pseudoinverse)

$$\left[\boldsymbol{b}(t) - \boldsymbol{L}(\boldsymbol{r})\boldsymbol{L}(\boldsymbol{r})^{+}\boldsymbol{b}(t)\right]^2$$

L(r) = the lead field for any given source *(r)*
b*(t)* = the observed magnetic field or the electric potential at a given time point *(t)*
L(r)$^{+}$ = the pseudoinverse of ***L(r)***

Derivation

$\boldsymbol{b}(t)$: measured data

$\hat{\boldsymbol{s}}(\boldsymbol{r}, t)$: fitted dipole

$\boldsymbol{L}(\boldsymbol{r})$: forward solution

$\hat{\boldsymbol{b}}(t) = \boldsymbol{L}(r)\boldsymbol{s}(\boldsymbol{r}, t)$: according to forward model

$[\boldsymbol{b}(t) - \hat{\boldsymbol{b}}(t)]^2$: to be minimised

$$\hat{\boldsymbol{s}}(\boldsymbol{r}, t) = \boldsymbol{L}(\boldsymbol{r})^+\boldsymbol{b}(t)$$

$\hat{\boldsymbol{b}}(t) = \boldsymbol{L}(\boldsymbol{r})\boldsymbol{L}(\boldsymbol{r})^+\boldsymbol{b}(t)$: using $\hat{\boldsymbol{s}}(\boldsymbol{r}, t)$ for $\boldsymbol{s}(\boldsymbol{r}, t)$

$[\boldsymbol{b}(t) - \boldsymbol{L}(\boldsymbol{r})\boldsymbol{L}(\boldsymbol{r})^+\boldsymbol{b}(t)]^2$: cost function

Learning goals

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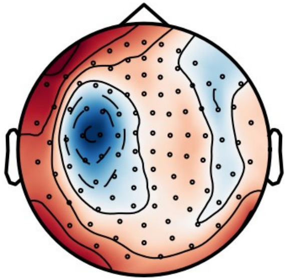
Learning goals

- Learning
  - how to derive the minimum-norm estimate
  - how the minimum-norm estimate forces all activity in ***b***(*t*) to go into $\hat{\boldsymbol{\nu}}_{vox}(t)$
  - Why dSPM is the default choice?

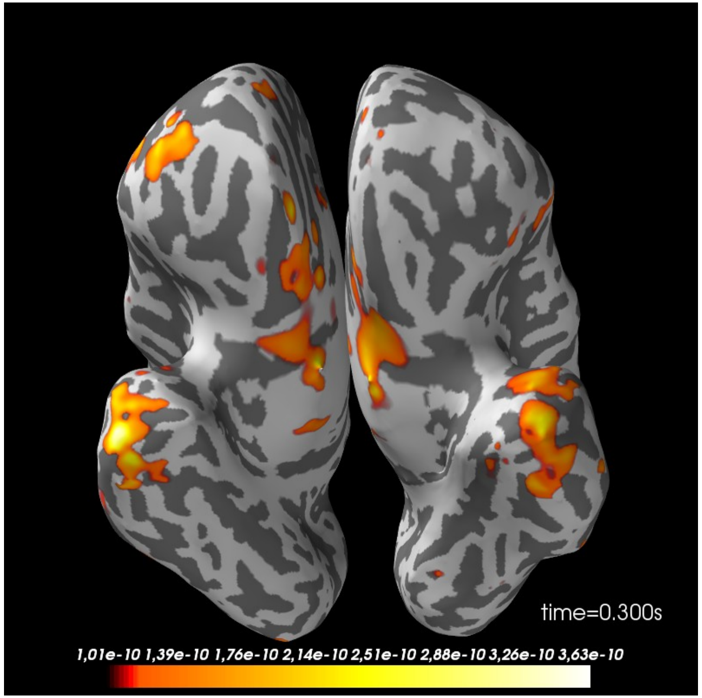
Comparisons between dipole fits and MNE

- MNE
  - Can model more complex responses than dipole fits

300 ms



SEEMS to be a more temporal (lobe) response



Minimum Norm Estimate

$$\hat{\boldsymbol{\nu}}_{vox}(t) = \boldsymbol{L}_V^T(\boldsymbol{G} + \epsilon\boldsymbol{I})^{-1}\boldsymbol{b}(t).$$

$\hat{v}_{vox}(t)$ = all the sources in the brain at a given time point
$\mathbf{L}_V^T$ = the leadfield (the estimated forward model)
G = *the Gram matrix* ($\mathbf{G} \approx \mathbf{L}_V\mathbf{L}_V^T$)
ε = a constant
I = the identity matrix
b*(t)* = the observed magnetic field or the electric potential at a given time point

We thus only need the leadfield and the observed data to estimate source activity ($\hat{v}_{vox}(t)$)

Solution for deriving the MNE

Equations

$$\boldsymbol{b}(t) = \boldsymbol{L_V}\,\boldsymbol{v_{vox}}(t)$$

if these were scalar variables,
how would you isolate $\boldsymbol{v}_{vox}(t)$
(ignoring $\boldsymbol{n}(t)$) ?

We cannot divide with matrices, but multiplying by the inverse is possible, e.g.

$$\boldsymbol{b}(t) = \boldsymbol{L_V} \boldsymbol{v_{vox}}(t)$$

$$\boldsymbol{L_V^{-1}} \boldsymbol{b}(t) = \boldsymbol{L_V^{-1}} \boldsymbol{L_V} \boldsymbol{v_{vox}}(t)$$

$$\boldsymbol{L_V^{-1}} \boldsymbol{b}(t) = \boldsymbol{I} \boldsymbol{v_{vox}}(t)$$

$$\boldsymbol{L_V^{-1}} \boldsymbol{b}(t) = \boldsymbol{v_{vox}}(t)$$

$$\boldsymbol{v_{vox}}(t) = \boldsymbol{L_V^{-1}} \boldsymbol{b}(t)$$

but $\boldsymbol{L}_v$ is an $M \times 3N$ matrix and $M < 3N$

$(M = \text{number of sensors}, N = \text{number of sources})$

Is the inverse matrix of $\boldsymbol{L}_v$ then defined?

No, but the generalised inverse is $\boldsymbol{L_V^+}$

$$\boldsymbol{L_V^+} = \boldsymbol{L_V^T}[\boldsymbol{L_V}\boldsymbol{L_V^T}]^{(-1)}$$

thus we can isolate $\boldsymbol{v}_{vox}(t)$ by multiplying both sides with the generalised inverse

$$\boldsymbol{b}(t) = \boldsymbol{L_V}\boldsymbol{v_{vox}}(t)$$

and our estimate for $\boldsymbol{v}_{vox}(t)$ becomes:

$$\hat{\boldsymbol{v}}_{vox}(t) = \boldsymbol{L_V^T}[\boldsymbol{L_V}\boldsymbol{L_V^T}]^{(-1)}\boldsymbol{b}(t)$$

$$\hat{\boldsymbol{v}}_{vox}(t)=\boldsymbol{L}_{\boldsymbol{v}}^{\boldsymbol{T}}[\boldsymbol{L}_{\boldsymbol{v}}\boldsymbol{L}_{\boldsymbol{v}}^{\boldsymbol{T}}]^{(-1)}\boldsymbol{b}(t)$$

$$\boldsymbol{G}=\boldsymbol{L}_{\boldsymbol{v}}\boldsymbol{L}_{\boldsymbol{v}}^{\boldsymbol{T}}$$

$$\hat{\boldsymbol{v}}_{vox}(t)=\boldsymbol{L}_{\boldsymbol{v}}^{\boldsymbol{T}}\boldsymbol{G}^{(-1)}\boldsymbol{b}(t)$$

G is square (306 x 306) so in principle invertible, but it is rank-deficient, because sensors see the same things

How can we make it invertible?

Regularisation

$$\hat{\boldsymbol{v}}_{vox}(t) = \boldsymbol{L}_{\boldsymbol{v}}^{\boldsymbol{T}}(\boldsymbol{G} + \epsilon \boldsymbol{I})^{(-1)} \boldsymbol{b}(t)$$

ϵ : a scalar, (higher values indicate more regularisation)

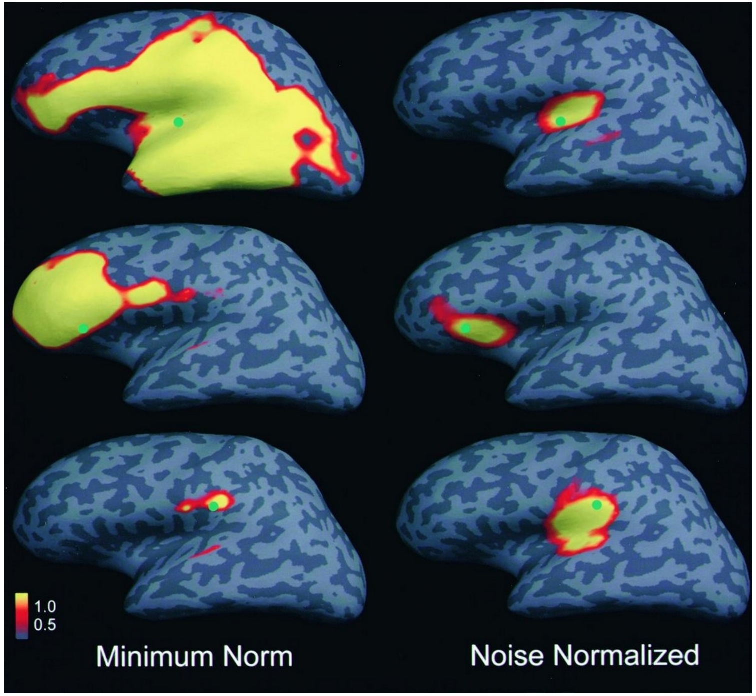
$\boldsymbol{I}$: the identity matrix

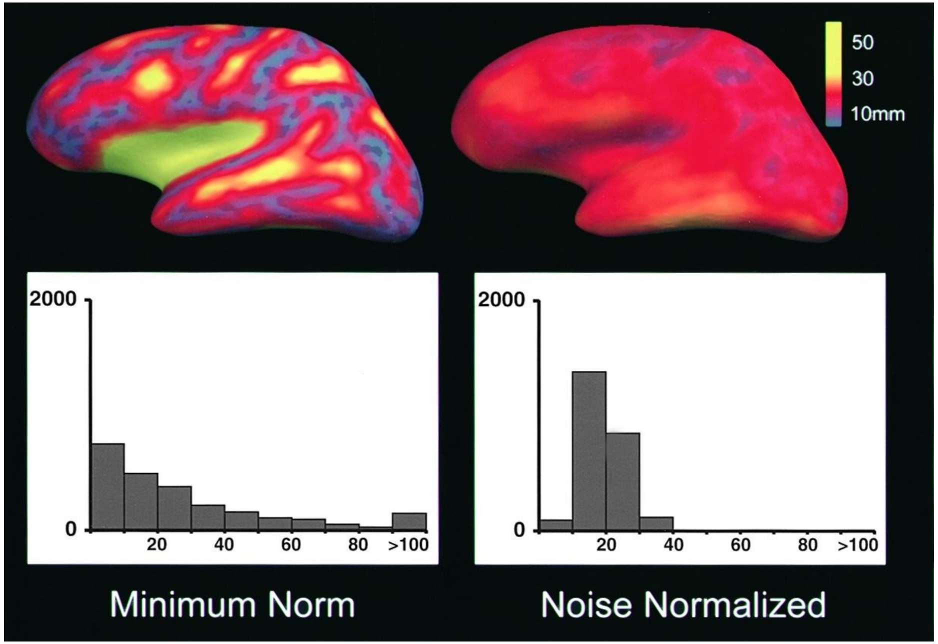
this solution minimises the cost function *F*:

$$F = \|\boldsymbol{b}(t) - \boldsymbol{L}_{\boldsymbol{v}} \hat{\boldsymbol{v}}_{vox}(t)\|^2 \quad + \quad \epsilon \|\hat{\boldsymbol{v}}_{vox}(t)\|^2$$

Surface bias

Mitigated by choosing the dSPM method





Dale AM, Liu AK, Fischl BR, et al (2000) Dynamic Statistical Parametric Mapping: Combining fMRI and MEG for High-Resolution Imaging of Cortical Activity. Neuron 26:55–67. https://doi.org/10.1016/S0896-6273(00)81138-1

Learning goals

- Learning
  - how to derive the minimum-norm estimate
  - how the minimum-norm estimate forces all activity in ***b***(*t*) to go into $\hat{\boldsymbol{\nu}}_{vox}(t)$
  - Why dSPM is the default choice?

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Learning goals

- Getting an understanding of the beamformer;
  - how it reconstructs sources
  - how it dampens non-brain sources
  - how it can be applied across the whole brain
  - understanding the code for applying it
- Getting the dots connected so far

Inverse model types

- Dipole fitting
  - Only a single or a few dipolar sources are active at given time sample
  - The solution is *overdetermined:* there are more data channels (hundreds) than sources (a few)

$$[\boldsymbol{b}(t)-\underline{\boldsymbol{L}(\boldsymbol{r})\boldsymbol{L}(\boldsymbol{r})^{+}}\boldsymbol{b}(t)]^2$$

- Minimum Norm Estimate
  - All (cortical) sources are active all the time
  - The solution is *underdetermined*: there are more sources (thousands) than channels (hundreds)

$$\hat{\boldsymbol{v}}_{vox}(t)=\underline{\boldsymbol{L}_V^T}(\boldsymbol{G}+\epsilon\boldsymbol{I})^{(-1)}\boldsymbol{b}(t)$$

- Beamformer
  - All sources are estimated independently from one another

$$\boldsymbol{w}(\boldsymbol{r})=\frac{\boldsymbol{R}^{-1}\underline{\boldsymbol{L}}(\boldsymbol{r})}{\underline{\boldsymbol{L}}^T(\boldsymbol{r})\boldsymbol{R}^{-1}\underline{\boldsymbol{L}}(\boldsymbol{r})}$$

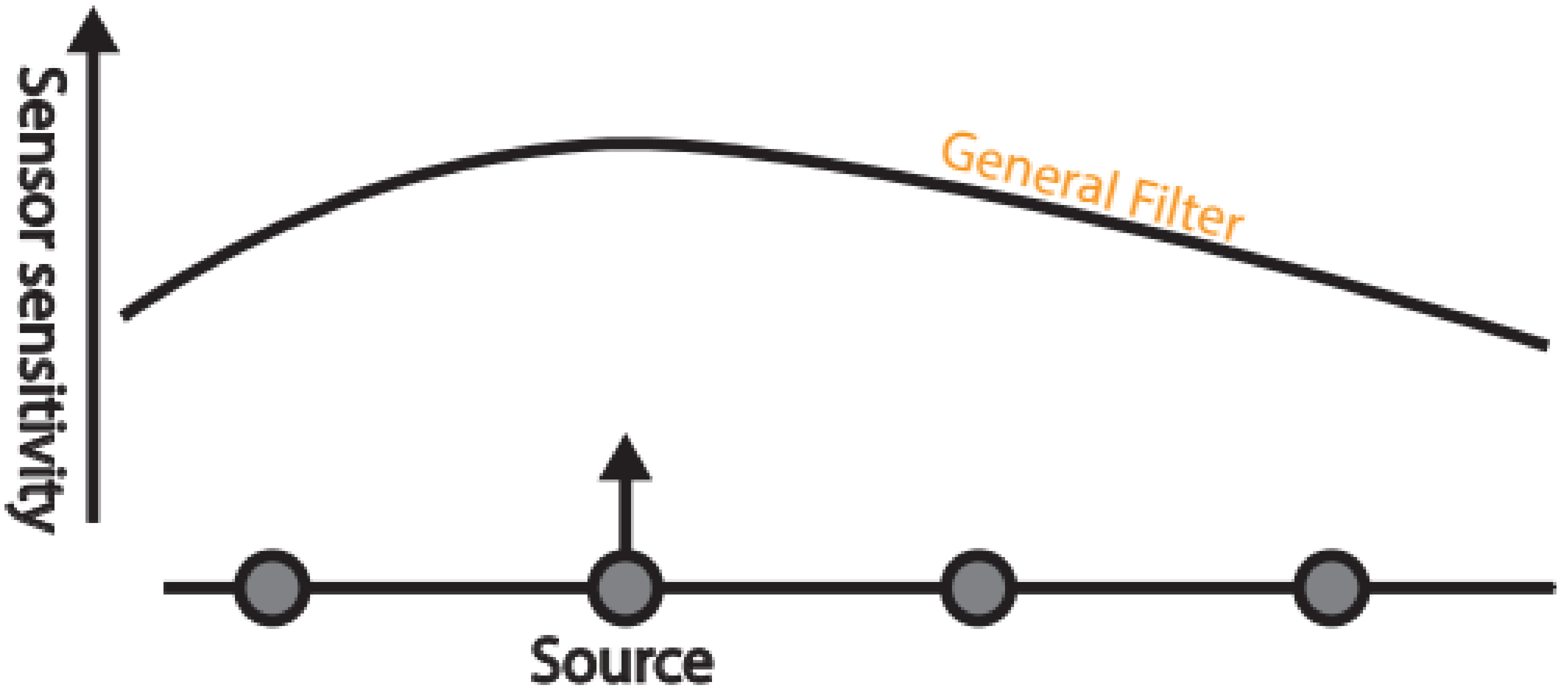
Beamformer

$$\hat{\boldsymbol{s}}(\boldsymbol{r},\, t) = \boldsymbol{w}^T(\boldsymbol{r})\,\boldsymbol{b}(t)$$

- For each source, $\boldsymbol{r}$, find a spatial filter, $\boldsymbol{w}^T$, that when multiplied onto the observed magnetic field or electric potential, $\boldsymbol{b}(t)$, returns a good estimate of the underlying source activation, $\hat{s}(\boldsymbol{r}, t)$, for each time point, t

Spatial sensitivity and leakage of a filter

Unity passband

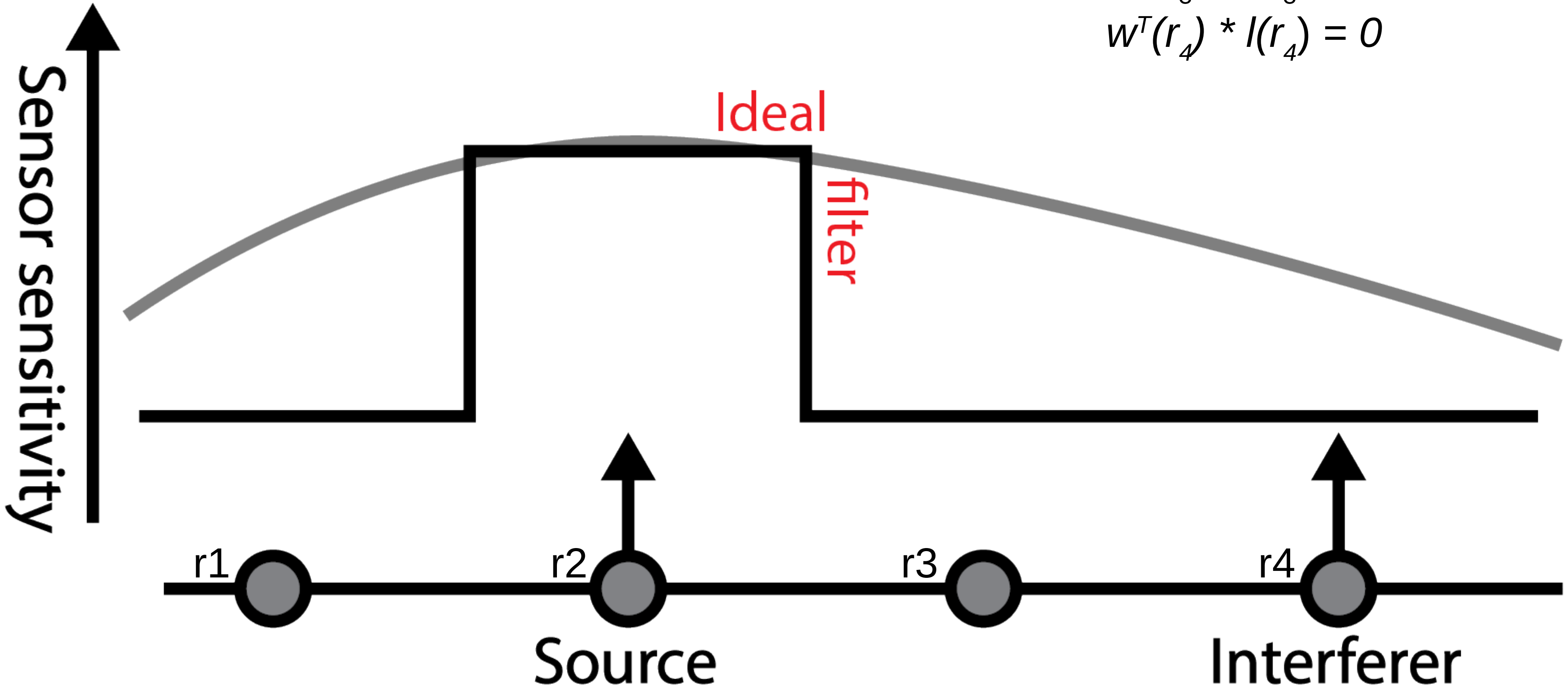


Spatial sensitivity and leakage of a filter

Unity passband

Minimum beamformer output

$w^T(r_1) * l(r_1) = 0$
$w^T(r_2) * l(r_2) = 1$
$w^T(r_3) * l(r_3) = 0$
$w^T(r_4) * l(r_4) = 0$

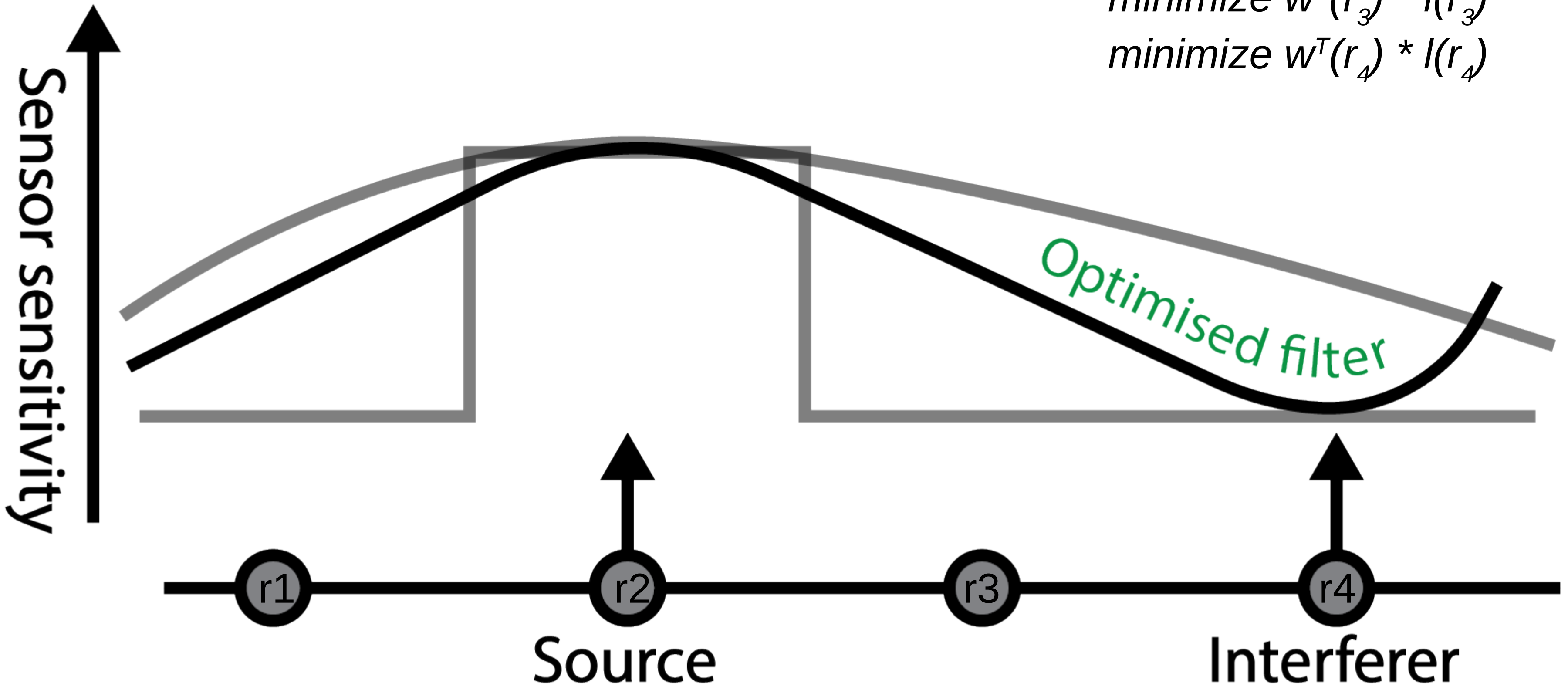


Spatial sensitivity and leakage of a filter

Unity passband

Minimum beamformer output

minimize $w^T(r_1) * l(r_1)$
$w^T(r_2) * l(r_2) = 1$
minimize $w^T(r_3) * l(r_3)$
minimize $w^T(r_4) * l(r_4)$



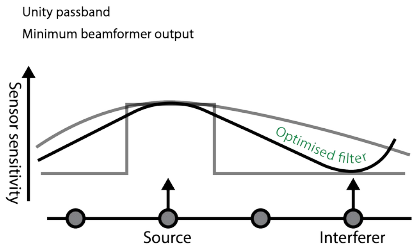
Beamformer

$$\boldsymbol{w}(\boldsymbol{r}) = \underset{\boldsymbol{w}(\boldsymbol{r})}{\operatorname{argmin}}\ \boldsymbol{w}^{\boldsymbol{T}}(\boldsymbol{r})\boldsymbol{R}\boldsymbol{w}(\boldsymbol{r}), \text{ subject to } \ \boldsymbol{w}^{\boldsymbol{T}}(\boldsymbol{r})\boldsymbol{L}(\boldsymbol{r}) = 1$$

Minimization of variance: $\underset{\boldsymbol{w}(\boldsymbol{r})}{\operatorname{argmin}}\ \boldsymbol{w}^{\boldsymbol{T}}(\boldsymbol{r})\boldsymbol{R}\boldsymbol{w}(\boldsymbol{r})$

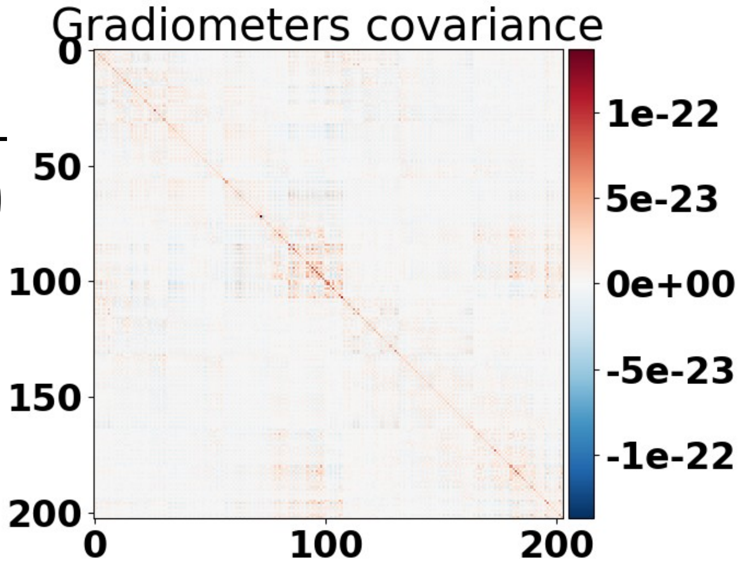
Unit-gain constraint: $\boldsymbol{w}^{\boldsymbol{T}}(\boldsymbol{r})\boldsymbol{L}(\boldsymbol{r}) = 1$

Beamformer



Data covariance matrix (*R*)

$$\boldsymbol{w}(\boldsymbol{r}) = \frac{\boldsymbol{R}^{-1}\boldsymbol{L}(\boldsymbol{r})}{\boldsymbol{L}^{T}(\boldsymbol{r})\boldsymbol{R}^{-1}\boldsymbol{L}(\boldsymbol{r})}$$



***w(r)* =** spatial filter
L(r) = lead field or forward model
R = data covariance matrix

Derivation

$\mathscr{L}(\boldsymbol{w}, \kappa)=\boldsymbol{w}^{\boldsymbol{T}}\boldsymbol{R}\boldsymbol{w}+\kappa(\boldsymbol{w}^{\boldsymbol{T}}\boldsymbol{L}(\boldsymbol{r})-1)$ (eq 1)

$\dfrac{\delta\mathscr{L}(\boldsymbol{w}, \kappa)}{\delta\boldsymbol{w}}=2\boldsymbol{R}\boldsymbol{w}+\kappa\boldsymbol{L}(\boldsymbol{r})$ (eq 2)

Finding the minimum

$2\boldsymbol{R}\boldsymbol{w}+\kappa\boldsymbol{L}(\boldsymbol{r})=0$ (eq 3)

$\boldsymbol{w}=-\kappa\boldsymbol{R}^{-1}\boldsymbol{L}(\boldsymbol{r})/2$ (eq 4)

From substituting $\boldsymbol{w}$ into: $\boldsymbol{w}^{\boldsymbol{T}}\boldsymbol{L}(\boldsymbol{r})=1$

follows: $\kappa=\dfrac{-2}{\boldsymbol{L}^{\boldsymbol{T}}(\boldsymbol{r})\boldsymbol{R}^{-1}\boldsymbol{L}(\boldsymbol{r})}$ (eq 5)

Then subtistuting κ into eq 4 we get:

$$\boldsymbol{w}(\boldsymbol{r})=\frac{\boldsymbol{R}^{-1}\boldsymbol{L}(\boldsymbol{r})}{\boldsymbol{L}^{\boldsymbol{T}}(\boldsymbol{r})\boldsymbol{R}^{-1}\boldsymbol{L}(\boldsymbol{r})}$$

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Key aspects

OBJECTIVES

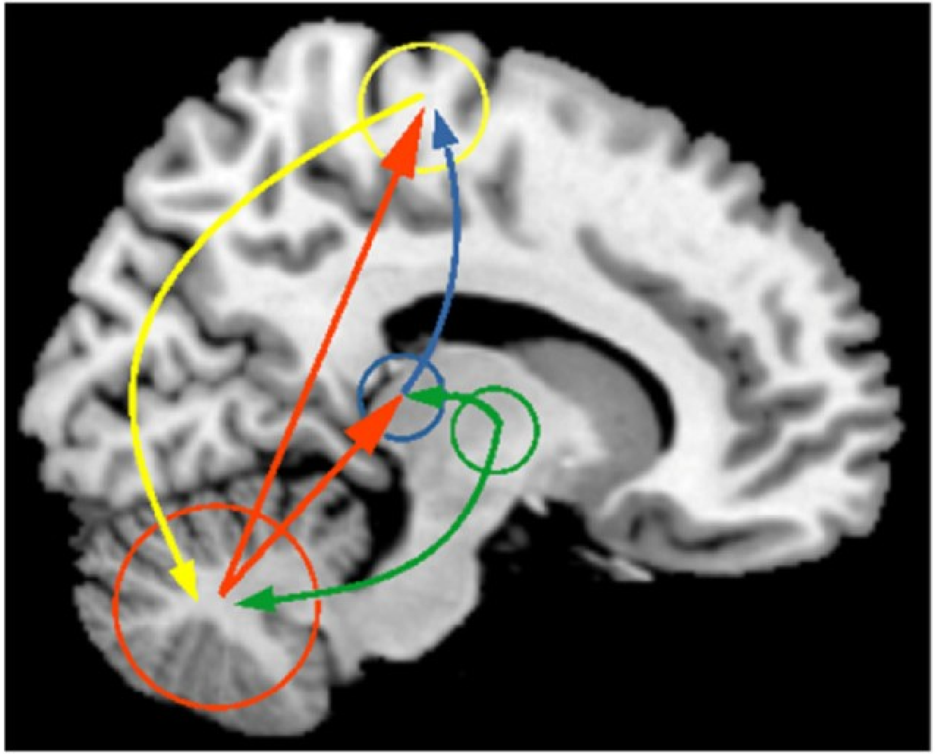
1) To show that the cerebellum is integrated with the cerebrum, mid-brain and the body
   - How is timing represented in the cerebellum?
   - Cesario et al. 2020: *Your Brain Is Not an Onion With a Tiny Reptile Inside*
2) To show that it is possible to measure its activity reliably in a non-invasive manner
   - AKA: please do not cut the cerebellum from your “whole brain”-analyses

Cerebellar summary

- We can measure the cerebellum using MEG and EEG
- The cerebellum builds sensory and temporal expectations
- These expectations are functionally relevant, making informed behaviour possible (through thalamus)
- Timing responses in basala ganglia and cerebellum, are different in Parkinson’s disease
- Cerebellar-basal-ganglia-thalamic disruptions in connectivity underlie differences in Parkinson’s disease patients?
- Further questions for the future:
  - Do optically pumped magnetomers allow for better cerebellar MEG? (Barbara)
  - Does respiration modulate cerebellar timing-related activity? (Laura)
  - Can we causally change my proposed timing network by turning on and off DBS?

Proposed network of timing

OBJECTIVES



Current Opinion in Behavioral Sciences

Proposed model for the cerebellum's involvement in timing action:

- *Basal ganglia passes timing information on to cerebellum*
- *Sensory expectations in the cerebellum then inform thalamus that inform primary motor cortex*
- *At the same time sensory predictions and feedback are sent back and forth between cerebellum and primary motor cortex*

(Andersen and Dalal, 2024a)

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WHAT WILL WE BE COVERING?

Background

- Respiration

Ongoing study investigating how breathing affects processing of temporally predict
tactile stimulation

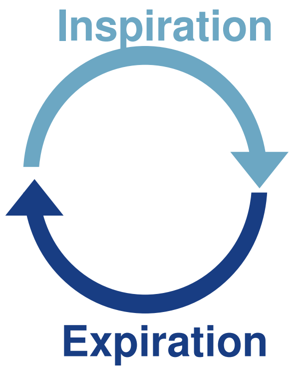
- Methods — how to preprocess and analyse respiration data
- Pilot results

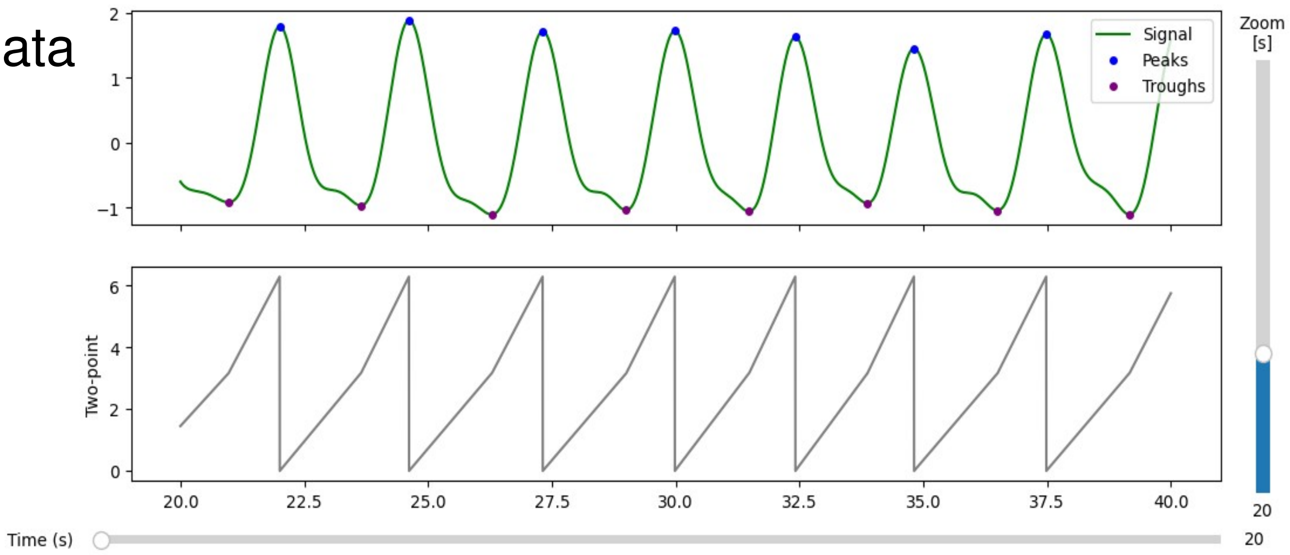
Working on respiration and behavioural data from the MEG lab

- *Pyriodic* — python module under development for MSc thesis

PREPROCESSING

- Bandpass filter
- Smoothing kernel (average within a window)
- Transforming to circular data





BREATHING SHAPES BRAIN OSCILLATIONS

Respiration-modulated brain oscillations (RMBOs) at rest

- Respiration modulates the global power of all frequencies between 2-150 Hz
- Localised to widespread network of cortical and subcortical regions
- Brain regions show modulation in different frequency bands and at different respiratory phases

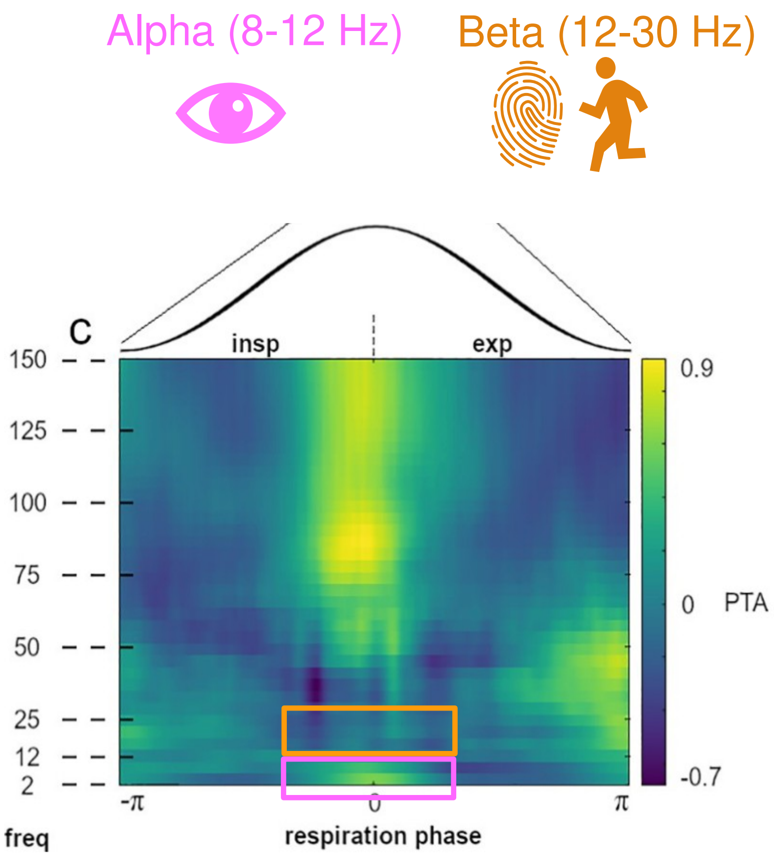


Figure from Kluger & Gross (2021)

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We will get the slides

Presentations

– The visual system, as understood through MEG

– The auditory system, as understood through MEG

– The somatosensory system, as understood through MEG

– Cognitive components and change detection

– Links between respiration, behaviour and MEG

– Development as understood through MEG

– Language comprehension as understood through MEG

– Subjective experience as understood through MEG

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Thank you!

- It has been a pleasure teaching you MEG.
  - I have never had a group of students as eager, as inquisitive and as curious as you
  - I promise I will learn from you to make the course (even) better