A visual Brain-Computer Interface for gaze-free communication

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The Locked-in Syndrome

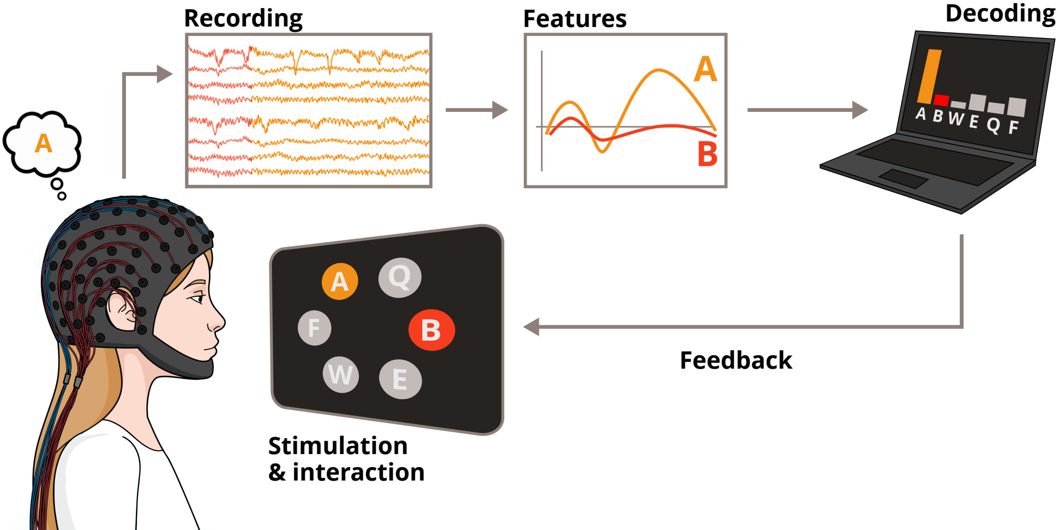
A functioning mind trapped in a paralyzed body

Severe paralysis leads to **Locked-in Syndrome**, due to

- Stroke
- Traumatic brain injury
- Neurodegenerative diseases
- . . .

Communication requires **assistive technology**

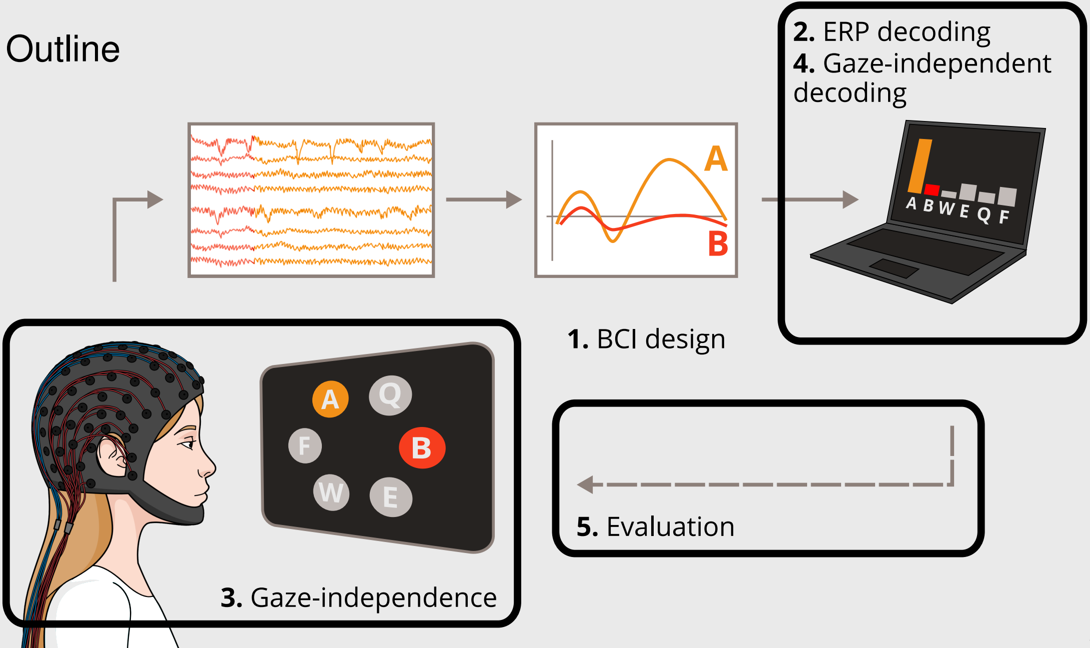
The Brain-Computer Interface



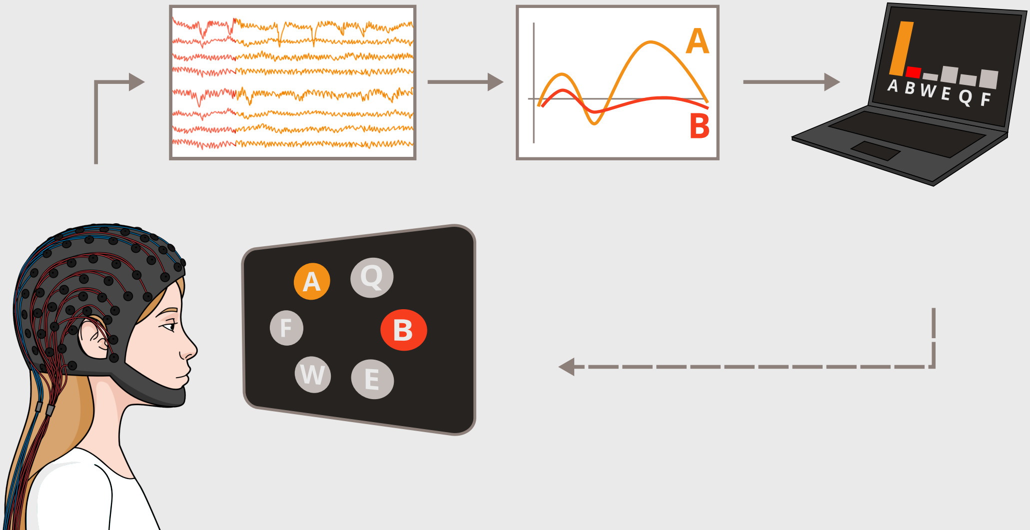
Research question

How can we optimize **BCI** assistive technology design to make it more **efficient** and **inclusive**?

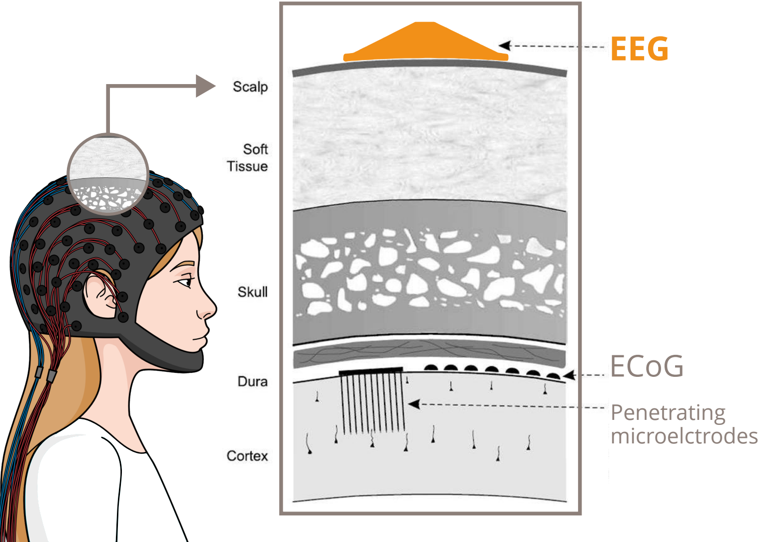
Outline


2. ERP decoding
4. Gaze-independent decoding
A
B
A B W E Q F
1. BCI design
A
Q
F
B
W
E
3. Gaze-independence
5. Evaluation

1. BCI design



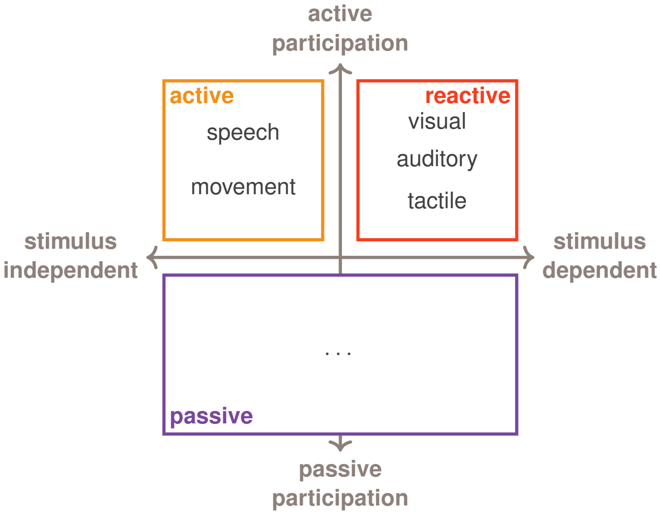
Recording the brain activity



EEG measures the electrical field on the scalp:

- \+ Non-invasive
- \+ Cheap
- – Limited resolution
- – Low signal-to-noise ratio

BCI paradigms



Passive BCIs

- – Less practical

Active BCIs

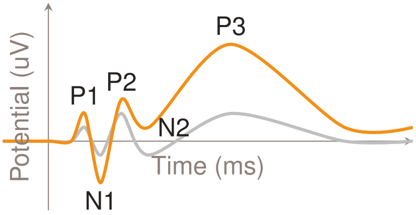
- + Intuitive, self-paced
- – High speed requires invasive

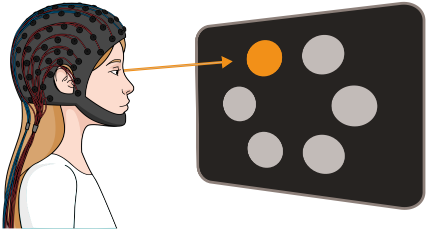
Reactive BCIs decode reactions to attended stimuli

- – Less intuitive
- + Fast stimulation
- + Suited for EEG

Visual is fastest

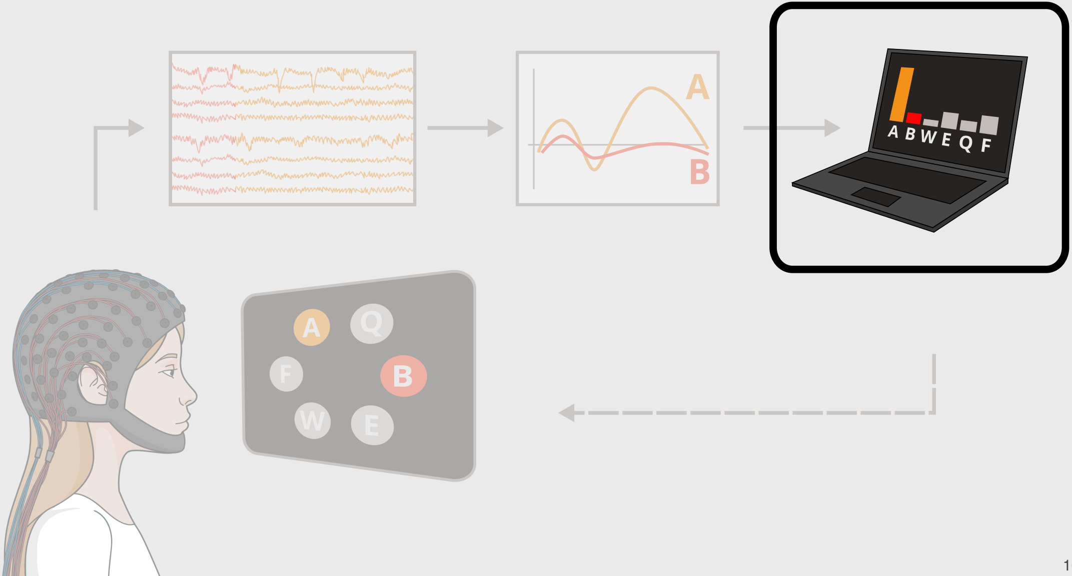
The visual event-related potential paradigm





1. Stimuli flash one by one
2. Flashes evoke ERPs
3. User attends a stimulus
4. ERP components are modulated by attention
5. Decode target based on timing and components

3. Spatiotemporal ERP decoding

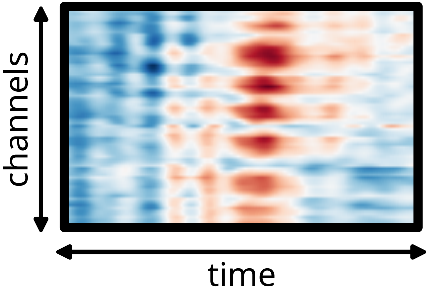


Problem: ERPs are high dimensional features

Machine learning models must be trained to decode ERPs

- Low single-trial signal-to-noise ratio
- High number of features (channels $\times$ times)
- Short calibration time results in low sample size

 # features $>>$ **# samples**

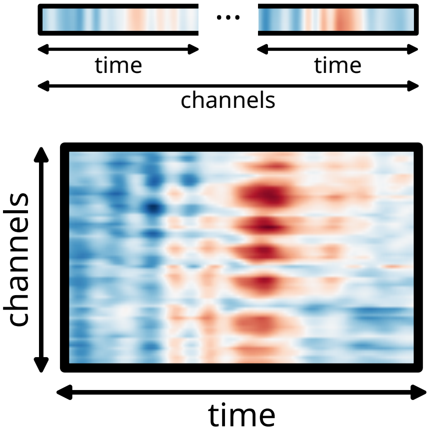


Retaining space-time structure enhances performance

- Data are ususally flattened before classification
- Spatiotemporal structure is often ignored

Assumptions on **data structure**

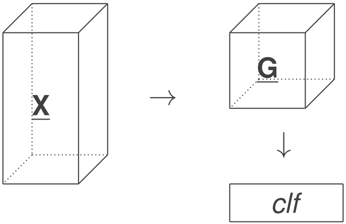
- yield strong regularization
- speed up training



Covariance matrix regularization Van Den Kerchove, Libert, et al., 2022

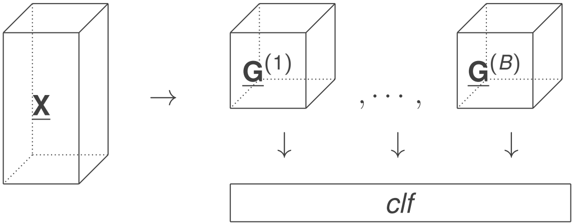
Tensor feature extraction Van Den Kerchove, Si-Mohammed, et al., submitted

Tensor discriminant analysis



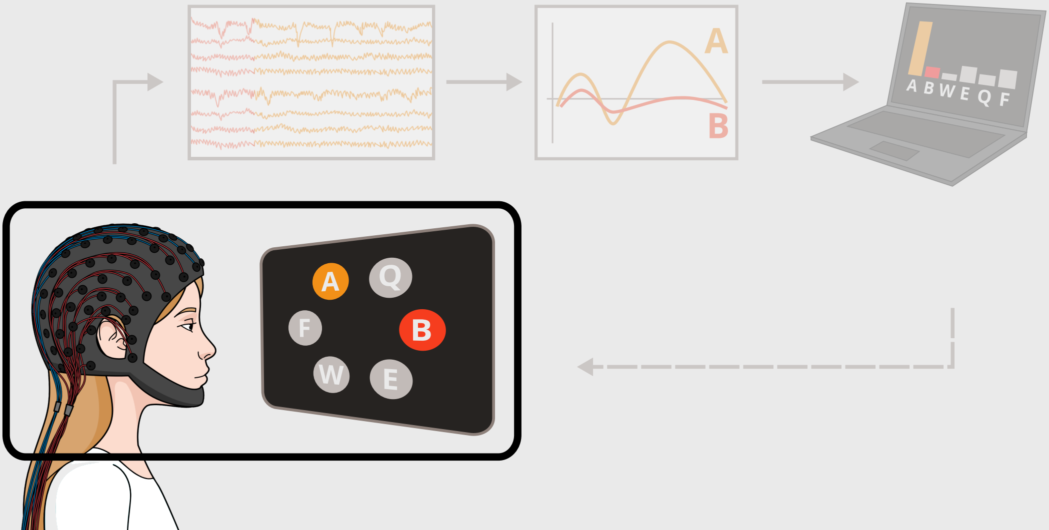
Phan et al., 2010

Block-term tensor discriminant analysis



- \+ More flexible
- \+ Still retains structure
- – More hyperparameters
- ▶ Heuristic model selection
- ▶ Validated with 4 open datasets

4. Gaze-independence

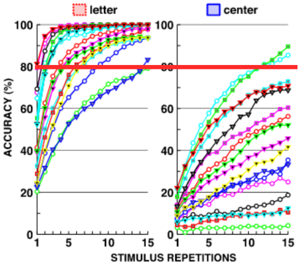


Problem: Eye motor impairment prevents gazing at targets

Visual skills related to disease affect BCI operation Fried-Oken et al., 2020

- Discomfort fixating
- Restricted movement
- Involuntary movements

Decoding relies on **visual ERP** components Treder et al., 2010



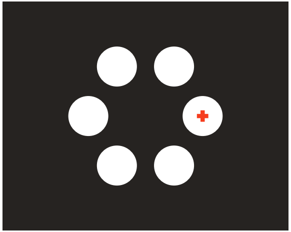
Ron-Angevin et al., 2019

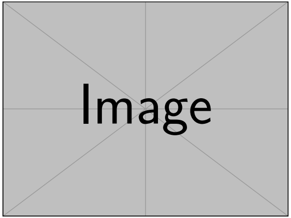
Those who can’t use eye tracking need BCIs

but

Visual BCIs perform poorly

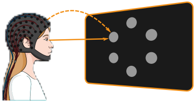
Covert visuospatial attention experiment



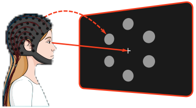


timeline

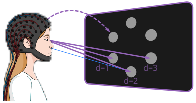
Overt VSA



Covert VSA



Split VSA

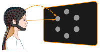


CVSA-ERP dataset

- 15 subjects, $\pm$ 11h stimulation
- Hex-o-Spell interface
  Treder et al., 2010
- Discrete gaze-independence conditions

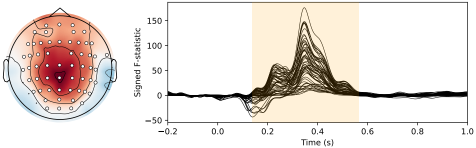
Van Den Kerchove, Si-Mohammed, et al., 2024

Evoked ERP components

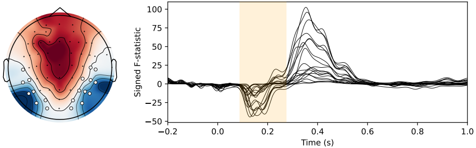


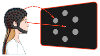
Overt VSA

0.140 – 0.564 s



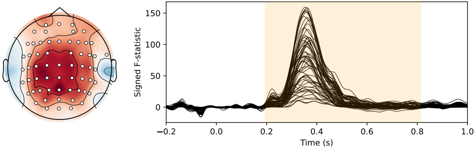
0.088 – 0.274 s

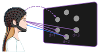




Covert VSA

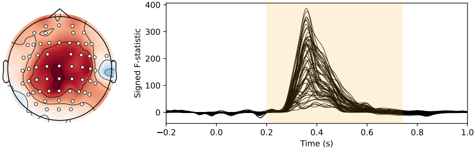
0.196 – 0.812 s





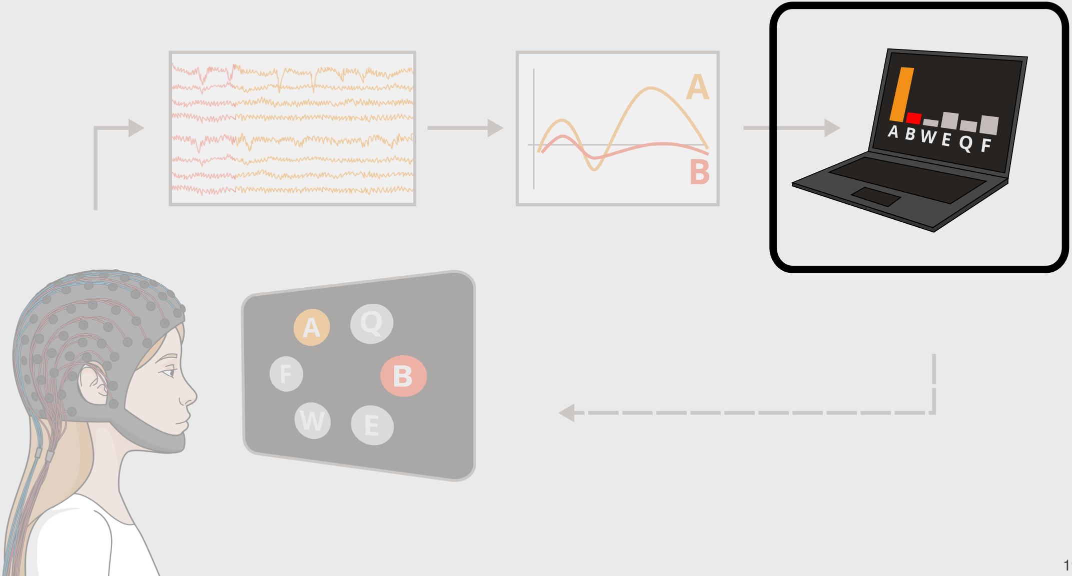
Split VSA

0.198 – 0.740 s

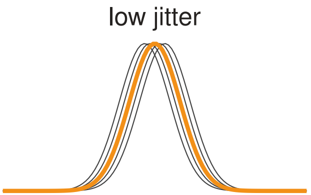


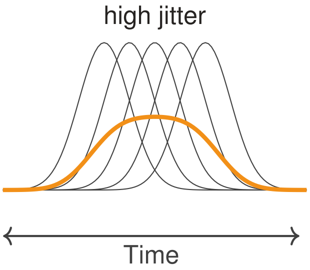
F-statistic cluster-based permutation tests, target vs. non-target

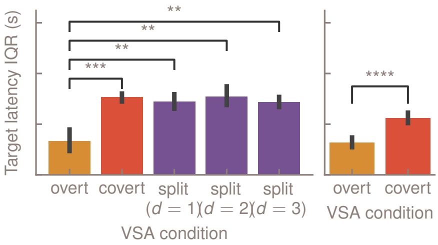
5. Gaze-independent decoding



Problem: Latency jitter decreases performance in covert and split attention





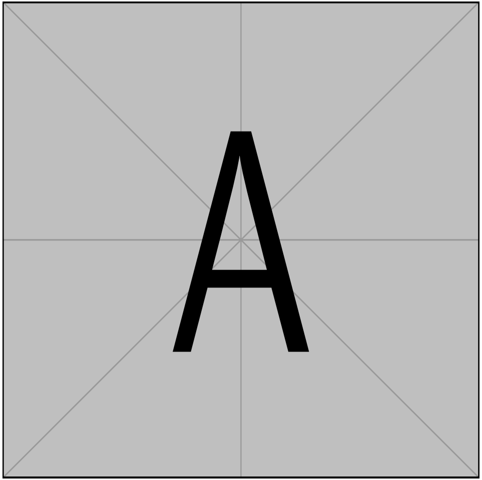


- Classifier-based latency estimation Mowla et al., 2017
- Jitter of discriminative information is higher for gaze-independent settings
- Contributes to low accuracy Aricò et al., 2014
- **Can this be exploited?**

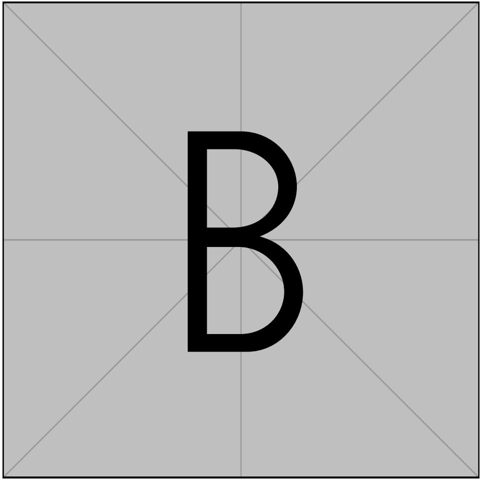
Latency estimation and alignment

Alignment of simulated data

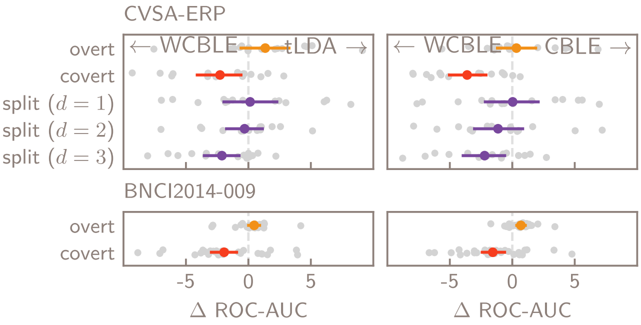
Before alignment



After alignment



Application to gaze-independent decoding



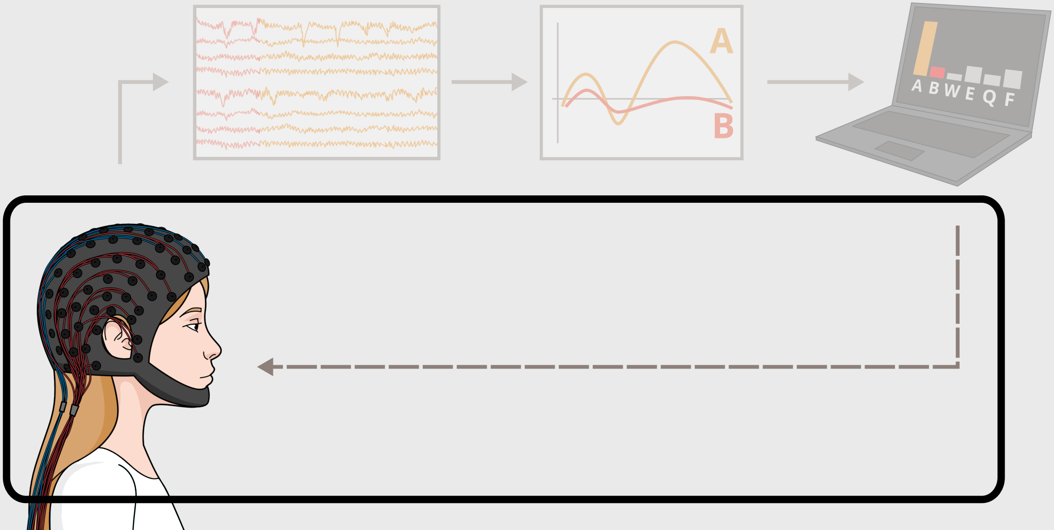
WCBLE can function with unseen data and is applicable as decoder

Within-subject, cross-validated single-trial ROC-AUC (%)

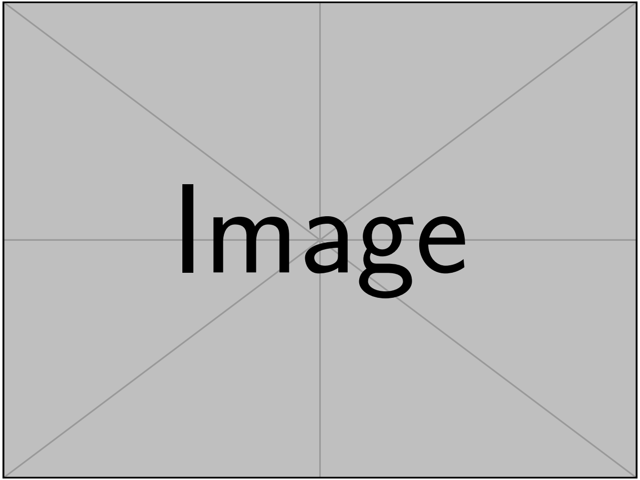
Within and across VSA conditions to establish independence

Improves decoding performance in gaze-independent settings

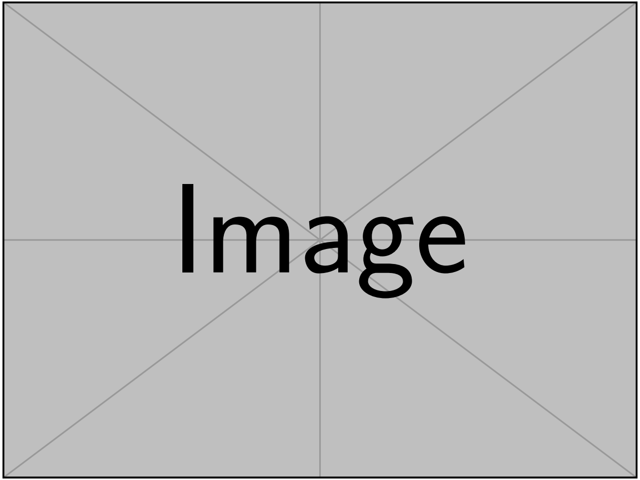
6.Evaluation in end-users



Subjects with physical, speech and gaze impairment



Eye motor impairment



Off-line covert vsa experiment

photo of setup
pictures of conditions

Gaze tracking analysis

Most prefered to perform overt VSA, despite severe eye motor impairment
Eye tracking with portable eye tracker could not properly be established due to eye motor impairments

Subject decoding performance

Who/how many performed above chance? Did WCBLE matter? -> not that much, only when TODO

Recap

1. Visual, spatial ERP paradigm
2. 2 decoders exploiting spatiotemporal structure
3. Alignment decoder for gaze independence
4. Covert attention study with healthy subjects
5. Off-line study with eye-motor impaired patients

TODO: main takeaway of each

Conclusions

- Improved decoders enhance BCI **efficiency**.
- Applications to gaze-independent decoding improve **inclusivity**.
- Limited effect on end-users
- Gained insight in requirements of BCI users with gaze-impairment

Perspectives

- On-line experiments
- User experience study
- Models capturing multi-component and non-stationary aspect of (covert) ERPs

Q&A

Experimental procedure
CVSA-ERP

hardware, locations, timings, nr of blocks, ...

Experimental procedure
end-user study

hardware, locations, timings, nr of blocks, ...

Block-term tensor discriminant analysis procedure

backward model image and equation
forward model image and equation
deflation image and equations
model selection procedure

Block-term tensor discriminant analysis procedure

backward model image and equation
forward model image and equation
deflation image and equations
model selection procedure

User-Centered Design

	Principles
P1	understand user, task, environment
P2	early and active user involvement
P3	driven by user-centered evaluation
P4	iterative design
P5	adress holistic experience
P6	multidisciplinary design

TODO: schematic with stages
TODO: reference