A visual Brain-Computer Interface for gaze-free communication

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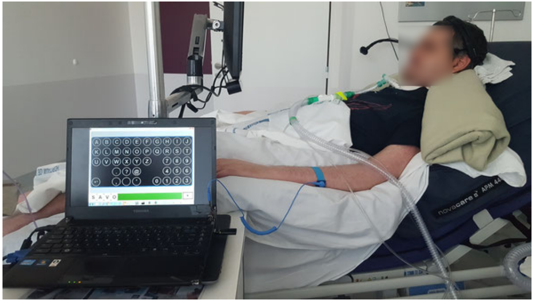
The Locked-in Syndrome



Paralysis with impaired speech: the **Locked-in Syndrome**

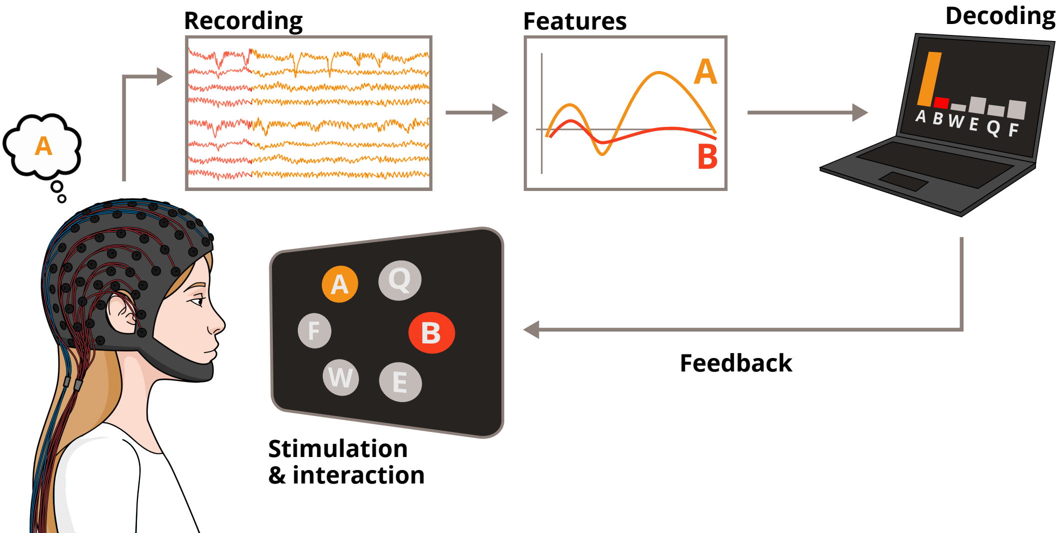
Due to

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

Communication requires **assistive technology**

What if muscle control is insufficient?

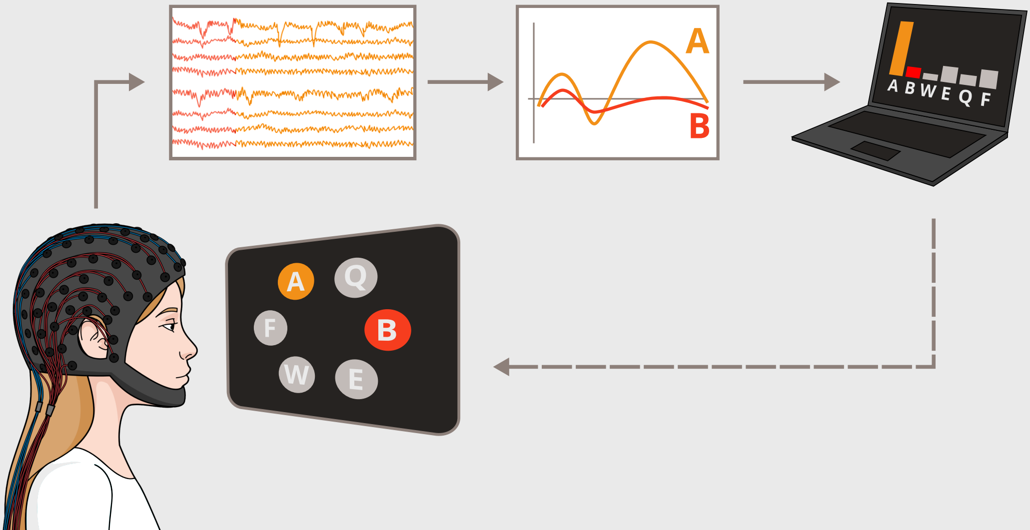
The Brain-Computer Interface



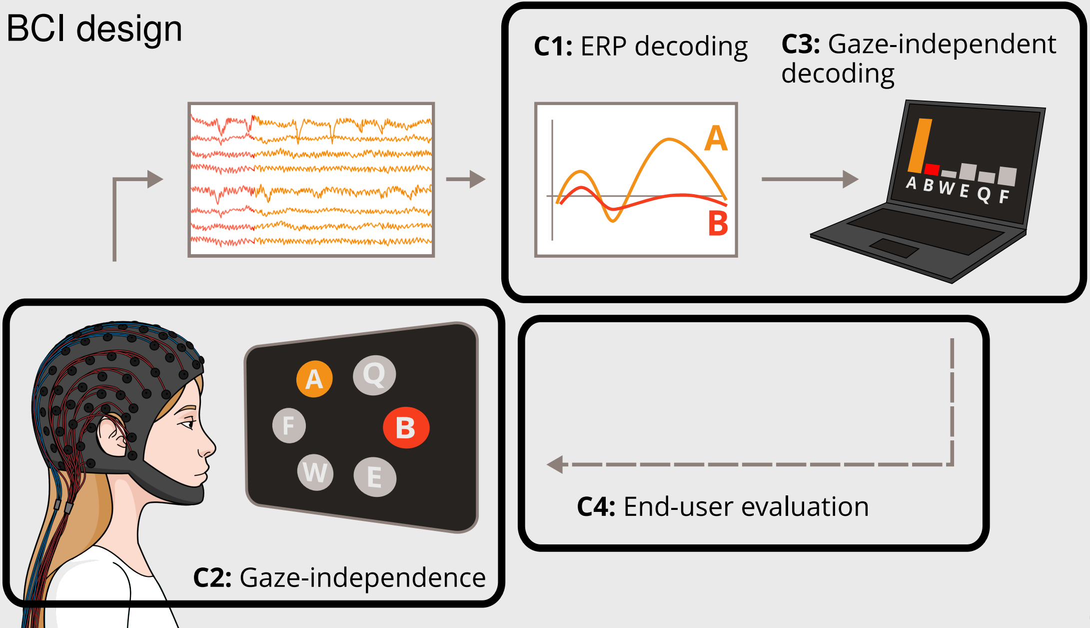
Research question

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

BCI design

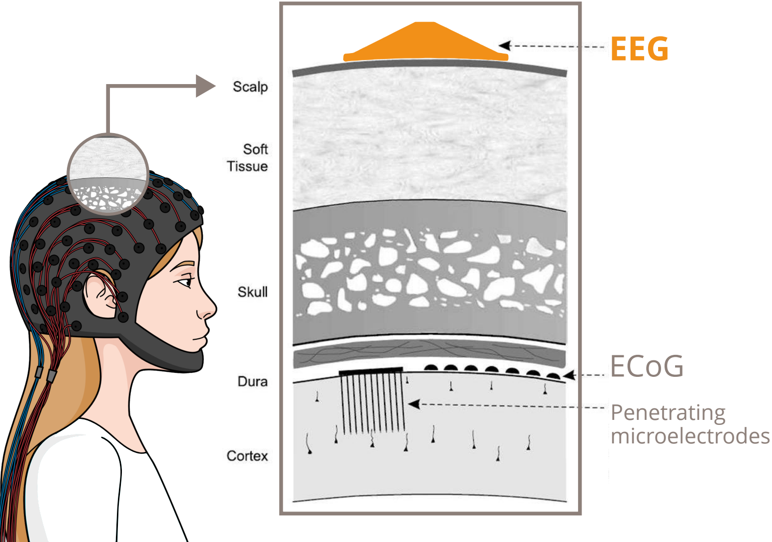


BCI design



C1: ERP decoding
A
B
C3: Gaze-independent decoding
A B W E Q F
A
Q
F
B
W
E
C2: Gaze-independence
C4: End-user evaluation

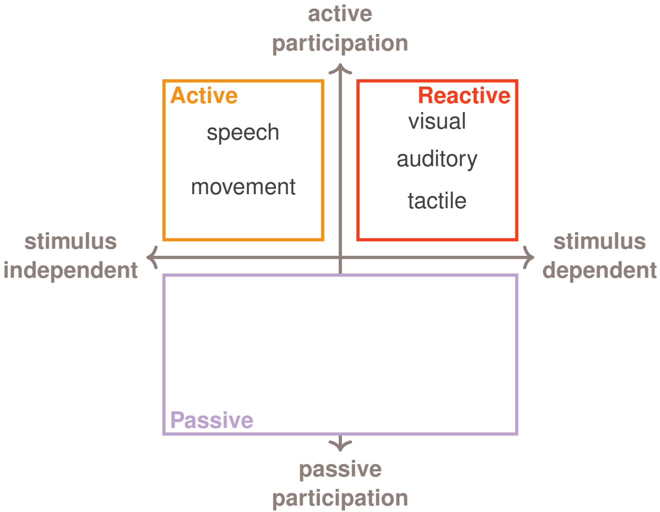
Recording the brain activity



EEG measures the electrical field on the scalp:

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

BCI paradigms for communication



Active BCIs

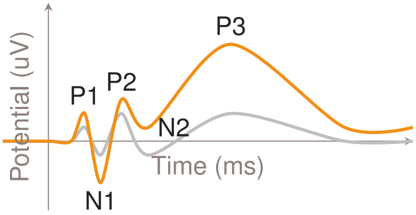
- + Intuitive, self-paced
- – High speed requires invasive

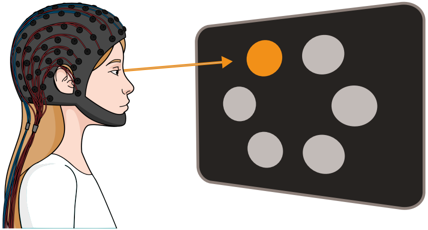
Reactive BCIs decode reactions to attended stimuli

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

Visual reactive BCIs are a good candidate.

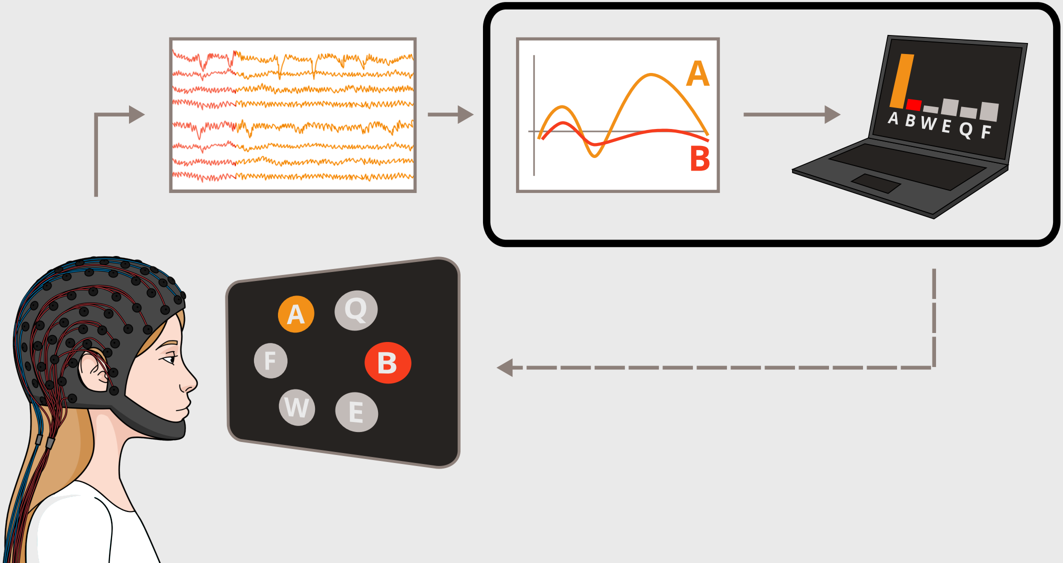
The visual event-related potential paradigm





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

C1. Spatiotemporal ERP decoding



Problem: ERP responses can be difficult to extract

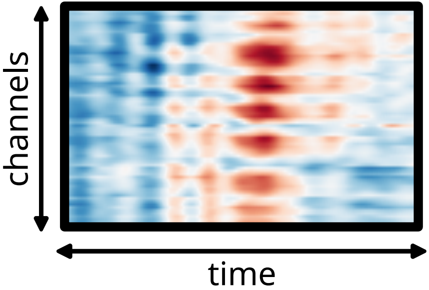
Low single-trial signal-to-noise ratio

- Machine learning models must be trained to decode ERPs

Each response is a sample with
features $=$ # channels $\times$ # time points

- High number of features (channels $\times$ times)
- Short calibration time results in low sample size

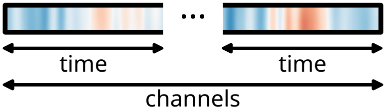
 # features $>>$ # samples



Retaining space-time structure enhances performance

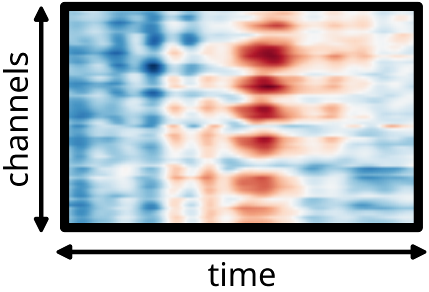
Data are ususally flattened
before classification

- ignores channel-time point structure



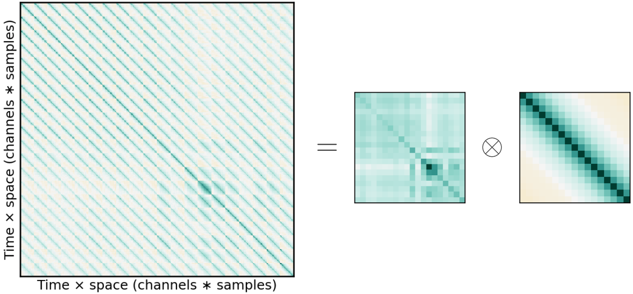
Assumptions on **data structure**

- yield strong regularization
- speed up training



Covariance matrix regularization

Van Den Kerchove, Libert, et al., 2022



Linear decoders require covariance estimation and inversion

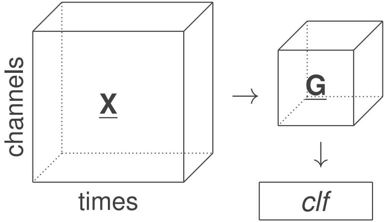
Imprecise due to high dimensionality

Repetitive structure can be expressed as separate space and time covariance

Saves computation time and improves accuracy for low data availability

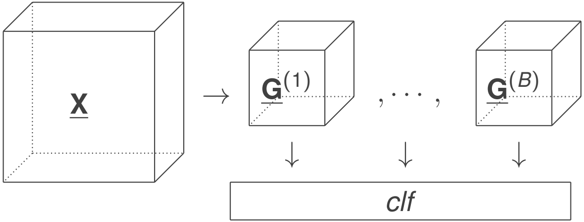
Tensor feature extraction Van Den Kerchove, Si-Mohammed, et al., submitted

Tensor discriminant analysis



Phan et al., 2010

Block-term tensor discriminant analysis

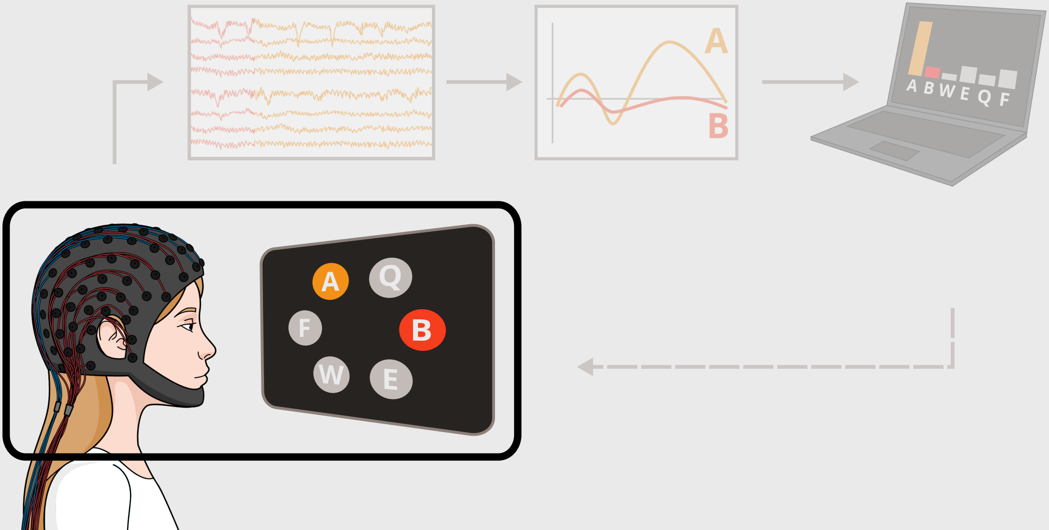


- \+ More flexible
- \+ Retains structure
- – More parameters

Heuristic model selection

Validated with 4 open datasets

C2. Gaze-independence

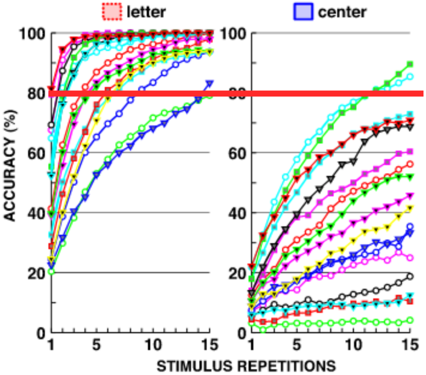


Problem: Eye motor impairment prevents gazing at targets

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

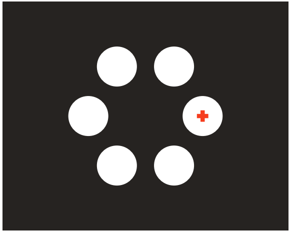
- Discomfort fixating
- Restricted movement
- Involuntary movements

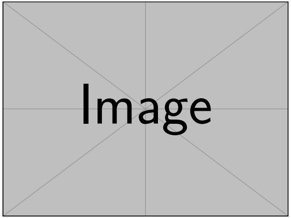
Decoding relies on **visual ERP** components Treder et al., 2010



Ron-Angevin et al., 2019

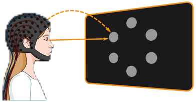
Covert visuospatial attention experiment



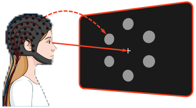


timeline

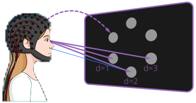
Overt VSA



Covert VSA



Split VSA



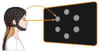
CVSA-ERP dataset

- 15 subjects, $\pm$ 11h stimulation
- Hex-o-Spell interface

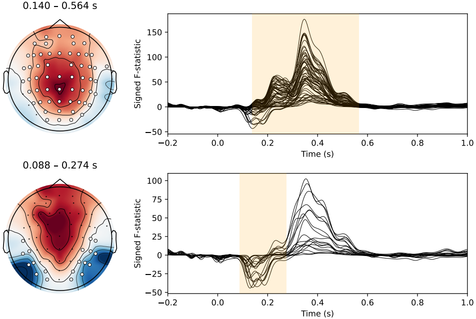
  Treder et al., 2010
- Discrete gaze-independence conditions

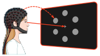
Van Den Kerchove, Si-Mohammed, et al., 2024

Evoked ERP components

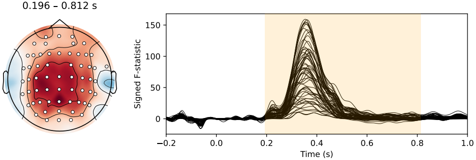


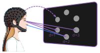
Overt VSA



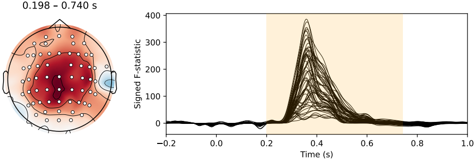


Covert VSA



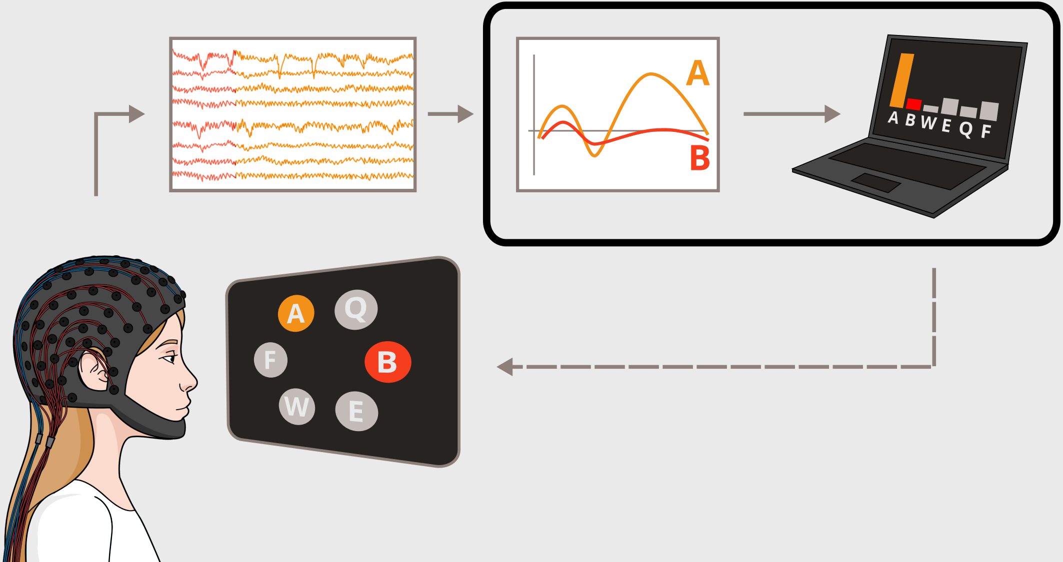


Split VSA

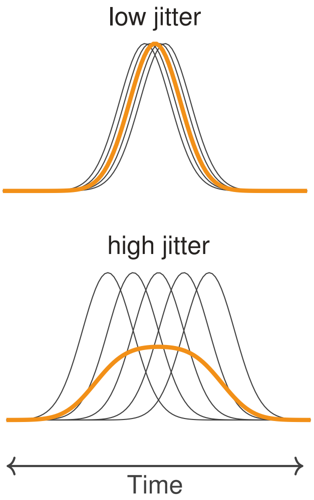


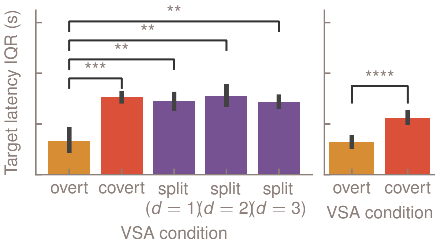
F-statistic cluster-based permutation tests, target vs. non-target

C3. Gaze-independent decoding



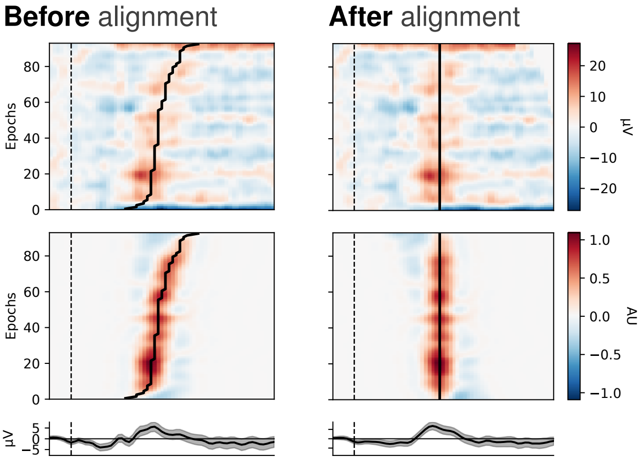
Problem: Latency jitter decreases performance in covert and split attention





- 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

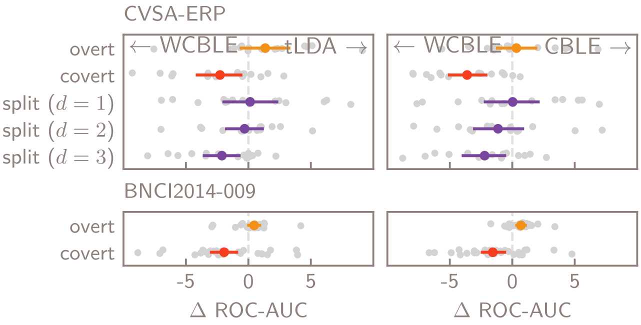


Developed iterative method based on CBLE

Enhances latency es-timagion and SNR in simulated data

Does this transfer to real data?

Application to gaze-independent decoding



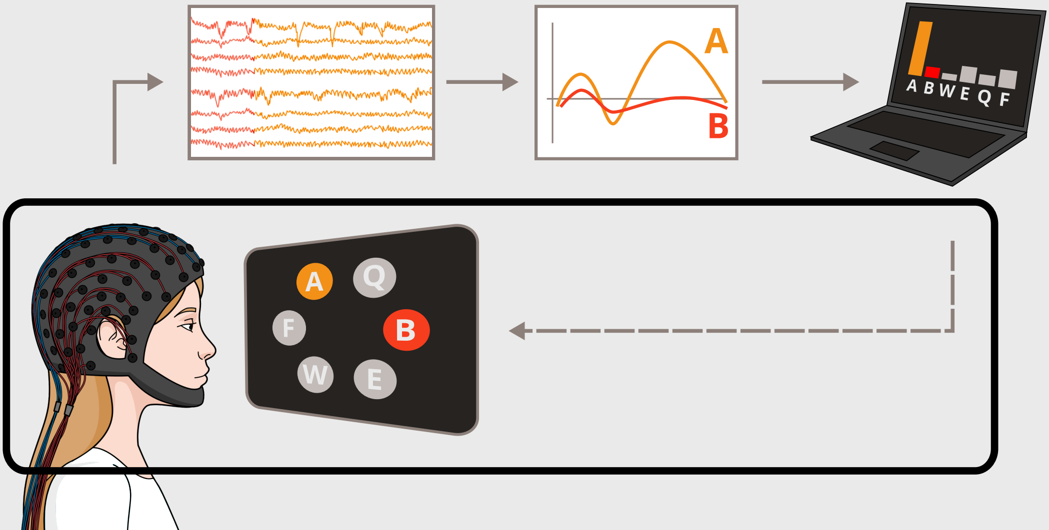
Iterative CBLE can function with unseen data and is applicable as decoder

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

Within and across VSA conditions to establish independence

Improves decoding performance in gaze-independent settings

C4: Evaluation in end-users



Subjects with physical, speech and gaze impairment

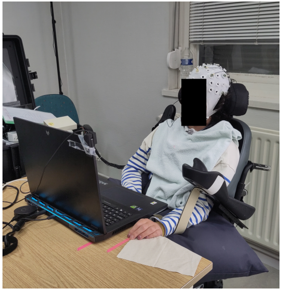
ID	Diagnosis	Age	Speech	Trach.	Communication
PA1	bulbar-onset ALS	58	absent	no	tablet
PB1	Friedreich's ataxia	41	impaired	no	verbal
PB2	Friedreich's ataxia	43	impaired	no	verbal
PB4	Friedreich's ataxia	48	impaired	no	verbal
PC2	brainstem stroke	43	absent	yes	eye movement
PC3	brainstem stroke	43	absent	yes	letterboard
PC4	cerebellar stroke	54	absent	yes	letterboard

Eye motor impairment

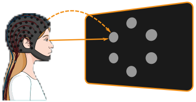
	PA1	PB1	PB2	PB4	PC2	PC3	PC4
Visual fixation	x	x	x	x	x	x	x
Eyelid function						x	x
Ocular motility		x		x	o	o	x
Binocular vision					x	o	o
Field of vision						x	x
Involuntary movement		x	o	x	x	x	

x: impaired, o: severely impaired

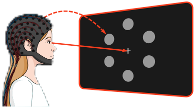
Off-line covert vsa experiment



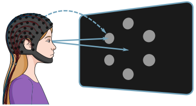
Overt VSA



Covert VSA



Free VSA



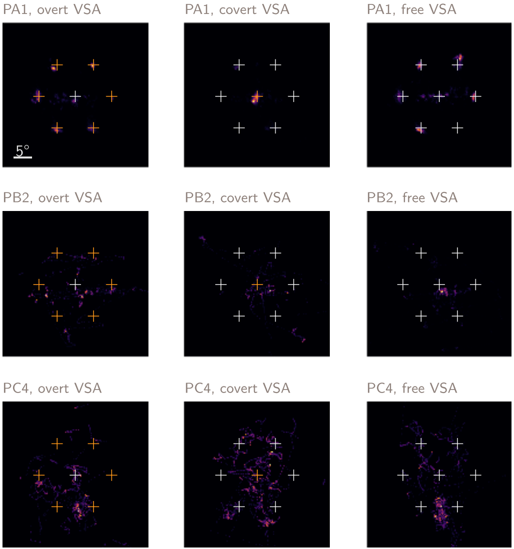
EEG, EOG and eye-tracking

Adapted stimulation parameters

Few studies investigating VSA abilities of end-users

Replace *split* by *free* to study comfort

Eye tracking

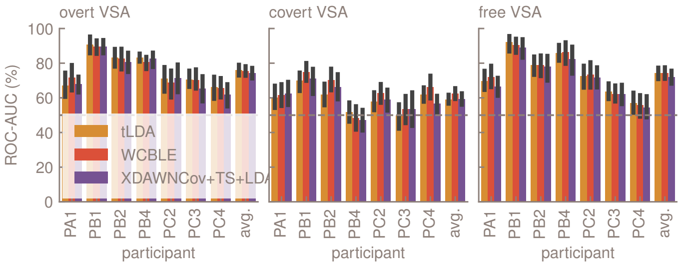


Most prefered to perform overt VSA

Voluntary covert and split VSA did occur

Portable eye tracker not always suited

Subject decoding performance



Off-line decoder comparison

All but one subject above chance

Covert was lower than overt, free generally on par

Limited impact of gaze-independent decoding

Contribution of gaze, break with limits of overt and covert

Recap

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

Publications

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

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

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