A visual Brain-Computer Interface for gaze-free communication

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The Locked-in Syndrome

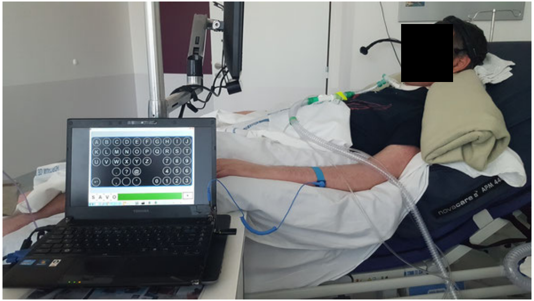
Complete paralysis,
impaired communication

Due to

- Stroke
- Traumatic brain injury
- Neurodegenerative diseases
- …

Assistive technology

A Brain-Computer Interface (BCI)
bypasses muscle activity



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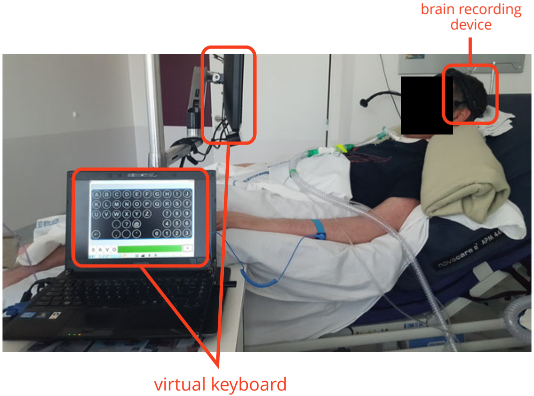
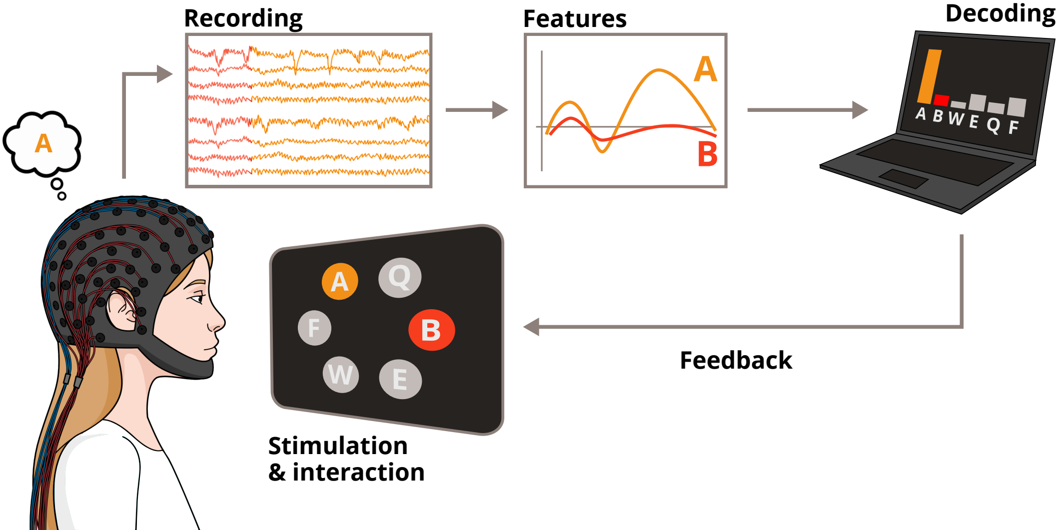


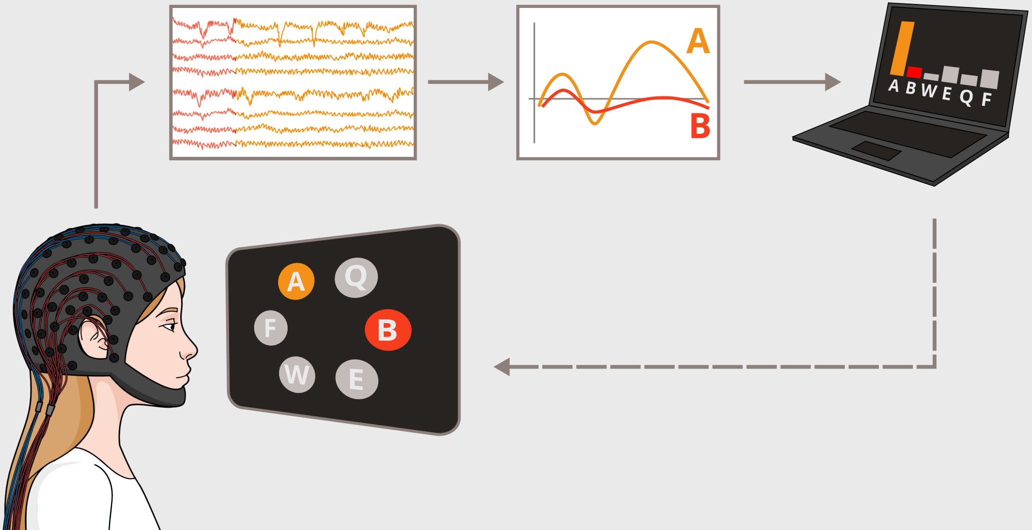
The Brain-Computer Interface



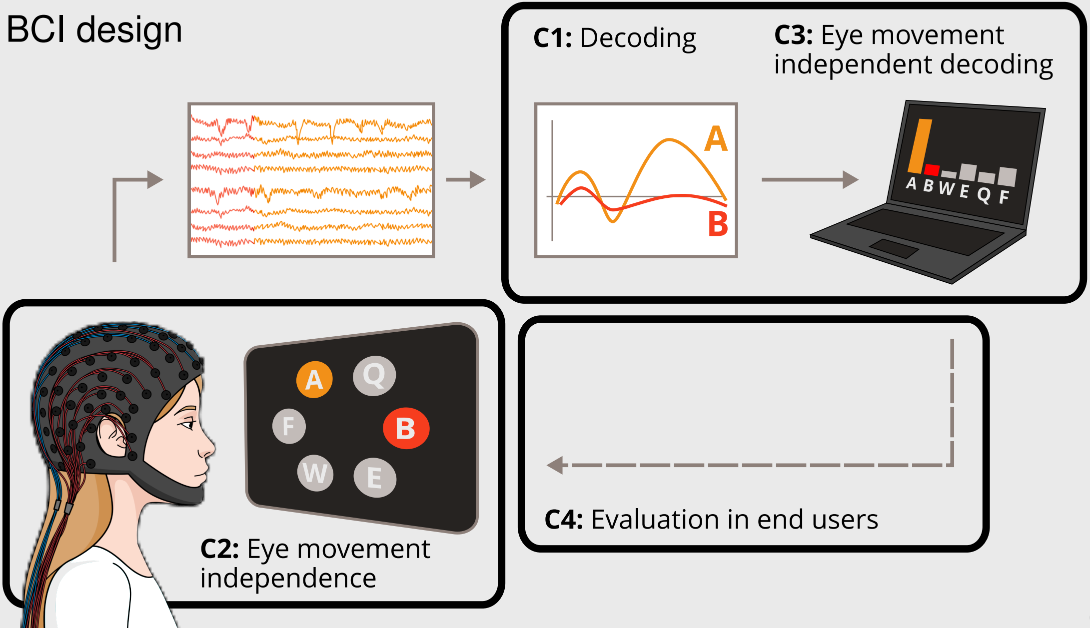
Research question

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

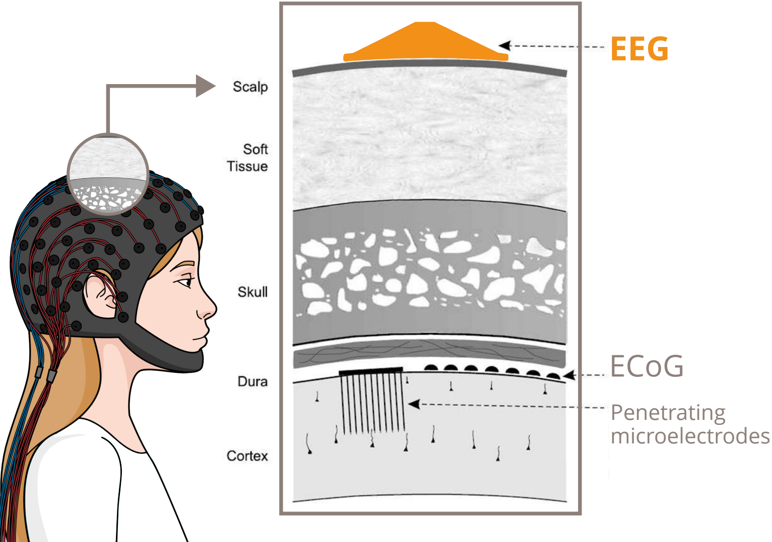
BCI design



BCI design


C1: Decoding
C3: Eye movement independent decoding
A
B
A B W E Q F
A
Q
F
B
W
E
C2: Eye movement independence
C4: Evaluation in end users

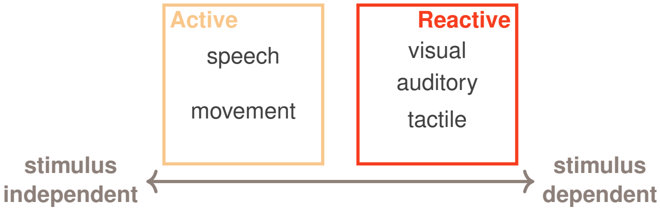
Recording the brain activity



EEG measures the electrical field on the scalp:

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

BCI paradigms for communication



Active BCIs

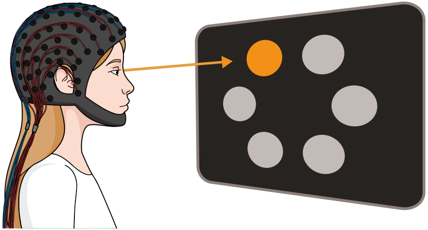
+ Natural
– Invasive for high speed

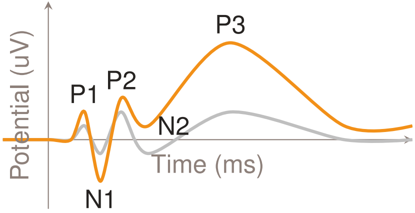
Reactive

– Continuous stimulation
+ Fast stimulation
+ Suited for EEG

Fast communication with **visual reactive** paradigm

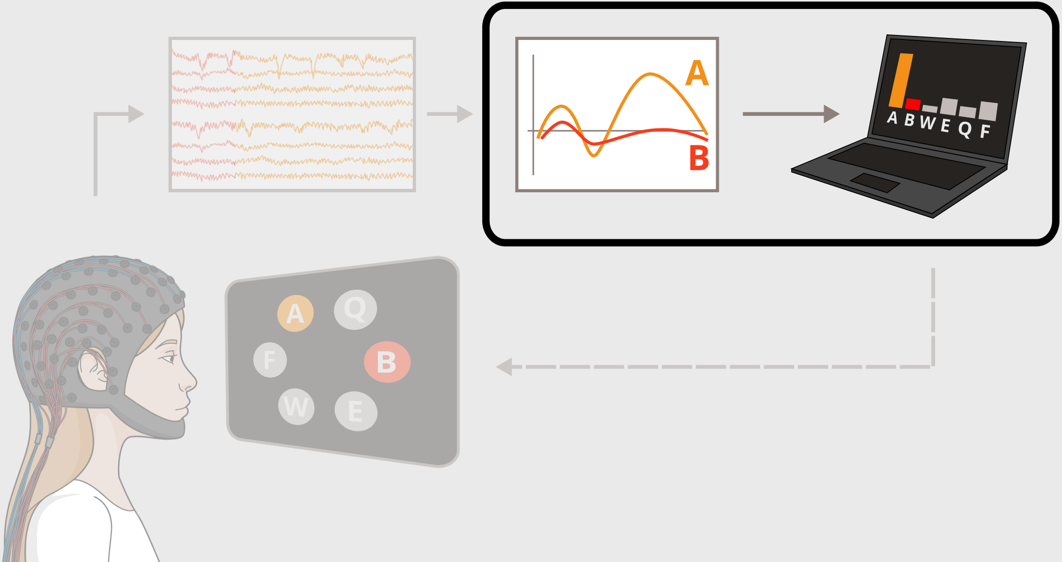
The visual event-related potential (ERP) paradigm





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. Spatial-temporal ERP decoding



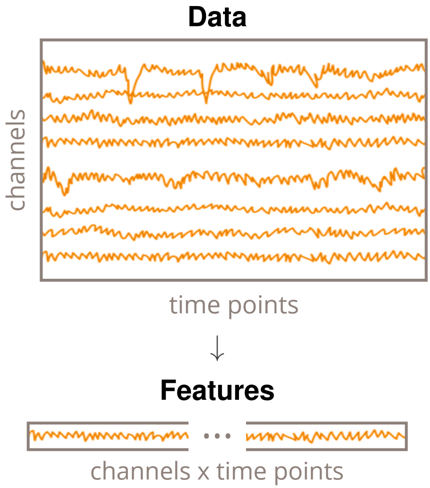
Problem: ERP responses can be difficult to extract

Strong noise ▶ machine learning decoders

- – High number of features
- – Low sample size for short calibration

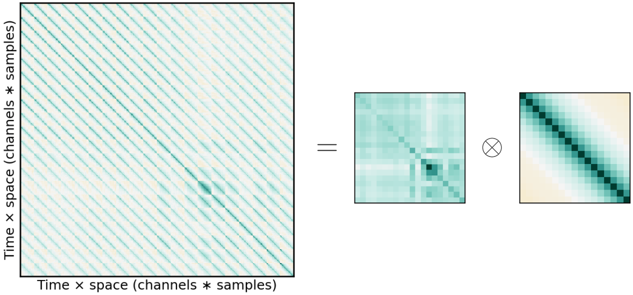
Solution: incorporate original data structure

- + Regularization
- + Fast training



Covariance matrix regularization

Van Den Kerchove, Libert, et al., 2022



Linear decoders require covariance estimation

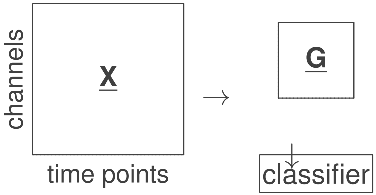
Imprecise due to high number of features

Repetitive structure in channels and time

Fast computation

Improvement for short calibration time

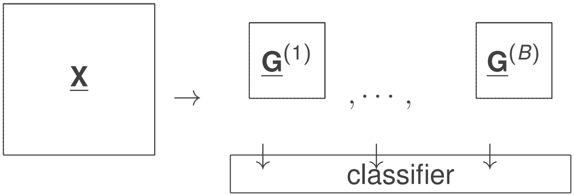
Spatial-temporal feature extraction



Directly operates on structured data

- Extract features separately in space and time

Phan et al., 2010



+ More flexible
+ Retains structure

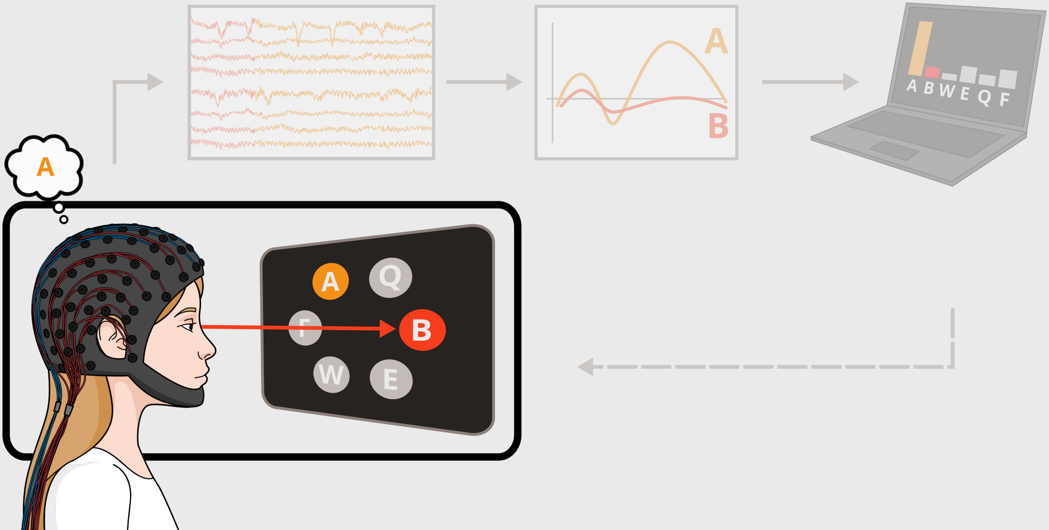
Van Den Kerchove, Si-Mohammed, et al., submitted

– More parameters

- Heuristic model selection

Validated with 4 open datasets, improvement over base model

C2. Eye movement independence



Problem: Eye motor impairment prevents gazing at targets

Impairment affects BCI operation

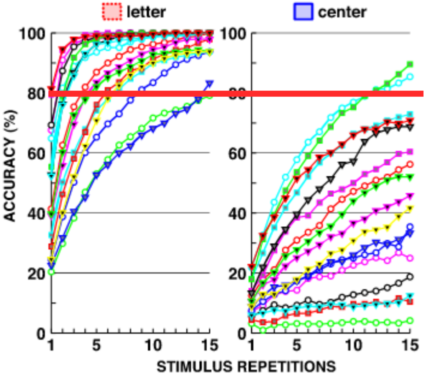
Fried-Oken et al., 2020

- Discomfort fixating
- Restricted movement
- Involuntary movements

No direct gaze

Decoding relies on **visual ERP** components

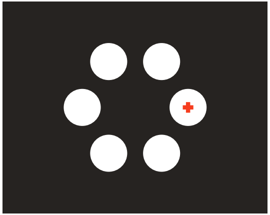
Treder et al., 2010



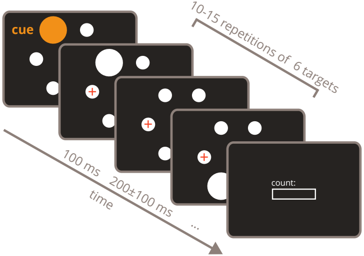
Ron-Angevin et al., 2019

Covert visuospatial attention experiment

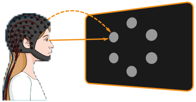
Van Den Kerchove, Si-Mohammed, et al., 2024



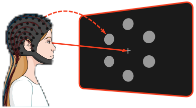
Hex-o-Spell Treder et al., 2010



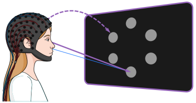
overt



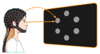
covert



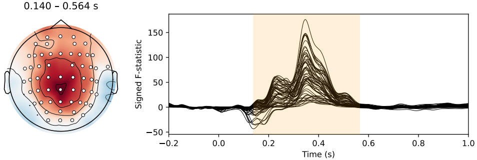
Split

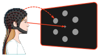


Evoked ERP components



Overt VSA





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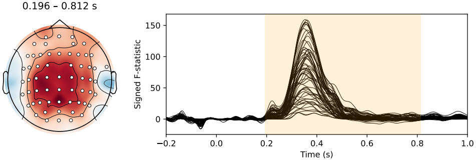
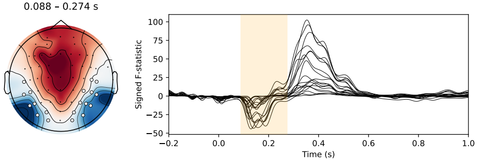
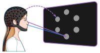
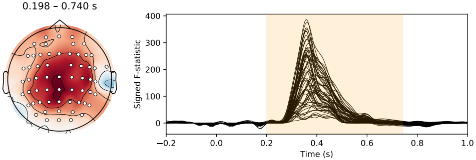


Attention-based P3 (central-parietal)





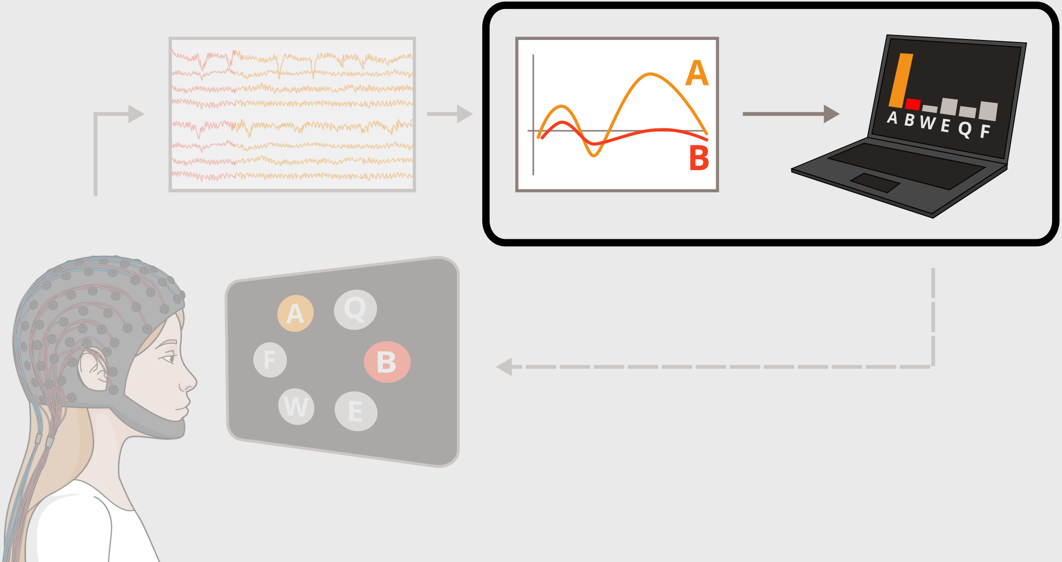
Split VSA



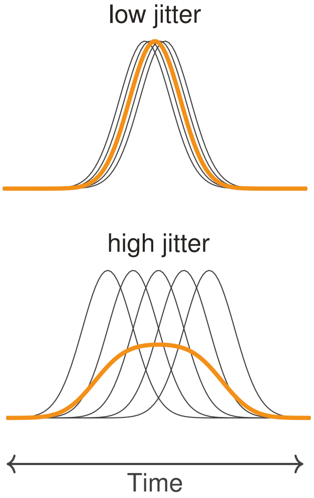
Visual early components (occipital)

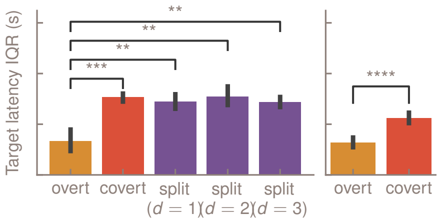
F-statistic cluster-based permutation tests

C3. Eye movement independent decoding



Problem: Latency jitter decreases performance in covert and split attention



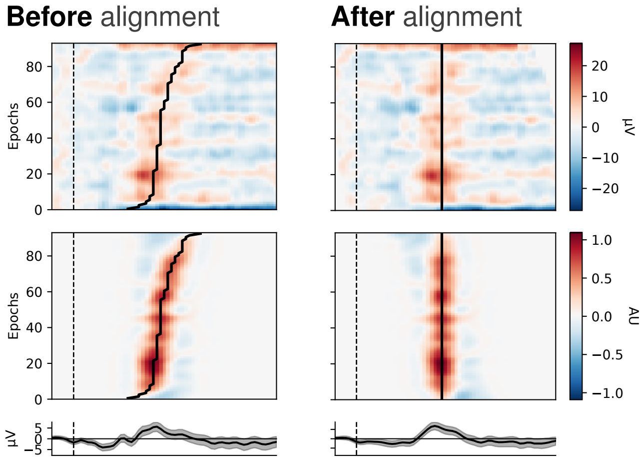


- Higher jitter when eye movement independent
- Contributes to low accuracy

  Aricò et al., 2014

- Can this be **accounted for**?

Latency estimation and alignment



Developed enhanced ERP latency estimation method

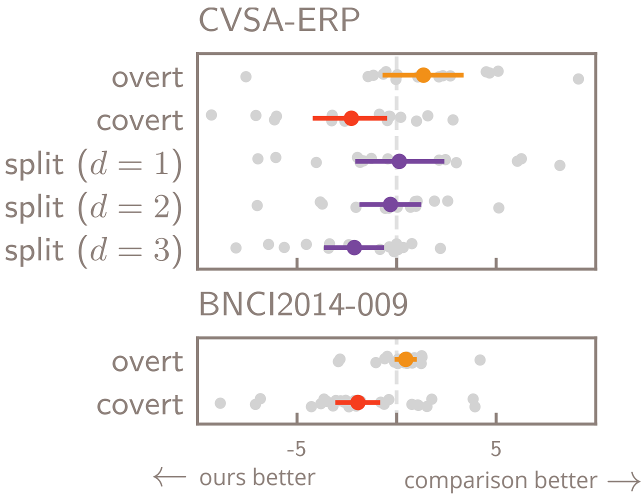
Van Den Kerchove, Si-Mohammed, et al., 2024; Mowla et al., 2017

Iterative alignment

Alignment improves SNR in simulated data

Transfer to real data?

Application to eye movement independent decoding



Applicable as decoder

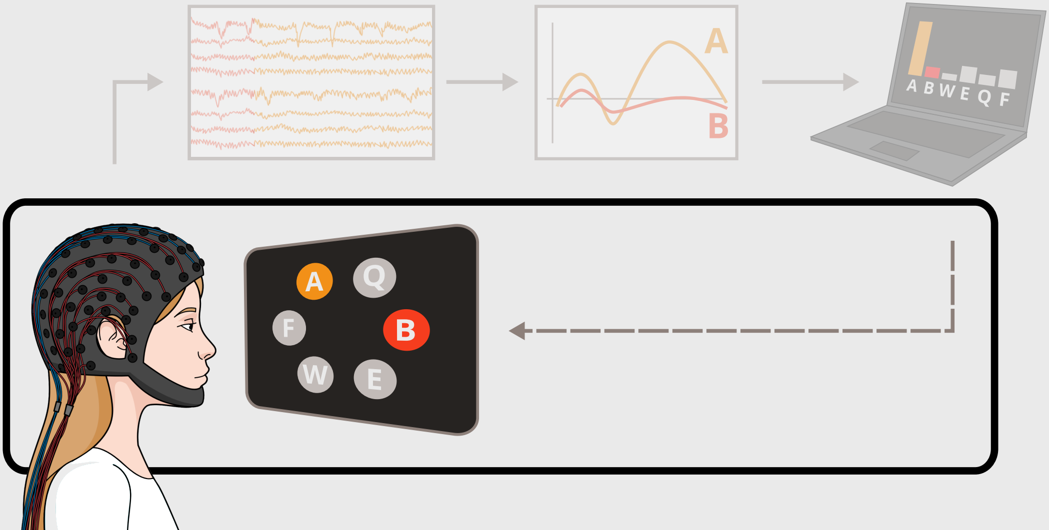
Within-subject, cross-validated single-trial evaluation (ROC-AUC), 2 datasets

Compared with state-of-the art decoders

Sosulski2022; Mowla et al., 2017

Improves decoding performance independent from eye movement

C4: Evaluation in end-users



Recruited individuals with physical, speech and eye movement

3 Friedreich's **ataxia**

- impaired speech
- involuntary eye movements
- discomfort fixating

1 bulbar onset **ALS**

- no speech
- minor eye movement impairment

3 brain stem or cerebellar **stroke**

- no speech
- partial eye paralysis

Large **individual variety** in preserved skills

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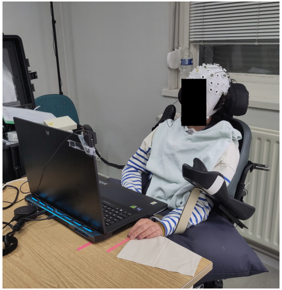
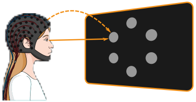
TRAINM neuro rehab clinics

FONDATION PARTAGE & VIE

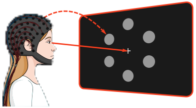
Covert visuospatial attention experiment



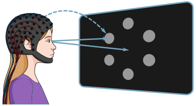
Overt VSA



Covert VSA



Free VSA



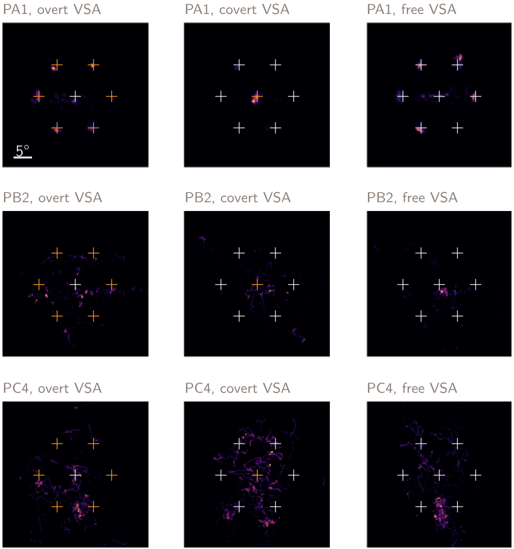
EEG, EOG and eye-tracking

Adapted stimulation parameters

Few studies investigating abilities

Replace *split* by natural *free*

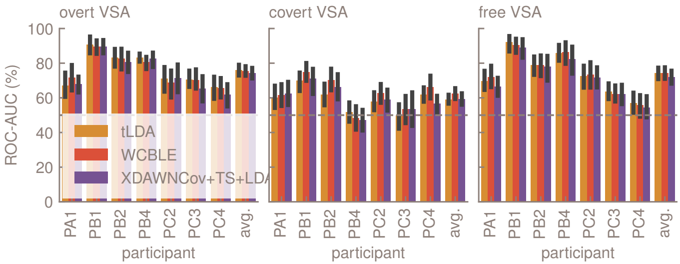
Eye tracking



Most prefered to perform overtly

Voluntary covert and split did occur

Subject decoding performance



Off-line decoder comparison

All but one subject above chance

Covert was lower than overt, free generally on par

Contribution of eye movement

Recap

Visual ERP paradigm

C1: Decoders exploiting spatial-temporal structure

C2: Covert attention study with healthy subjects

C3: Decoder for eye movement independence accounting for jitter

C4: Validation with eye movement impaired subjects

Publications

Conclusions

- Improved decoders enhance BCI **efficiency**
- Improvements in gaze independent decoding improve **accessibility** for some
- Gained insight in requirements of BCI users with impaired eye movement

Perspectives

1. Integrate BCI and eye-tracking
   for impaired eye movement
2. On-line experiments
3. User-centered design study
4. 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

WCBLE training procedure

WCBLE test procedure

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

Visual skill and eye movement 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	
Visual acuity (logMAR)	0.0	0.0	0.6	0.2	0.0	0.7	0.6

x: impaired, o: severely impaired

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