

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



The Locked-in Syndrome

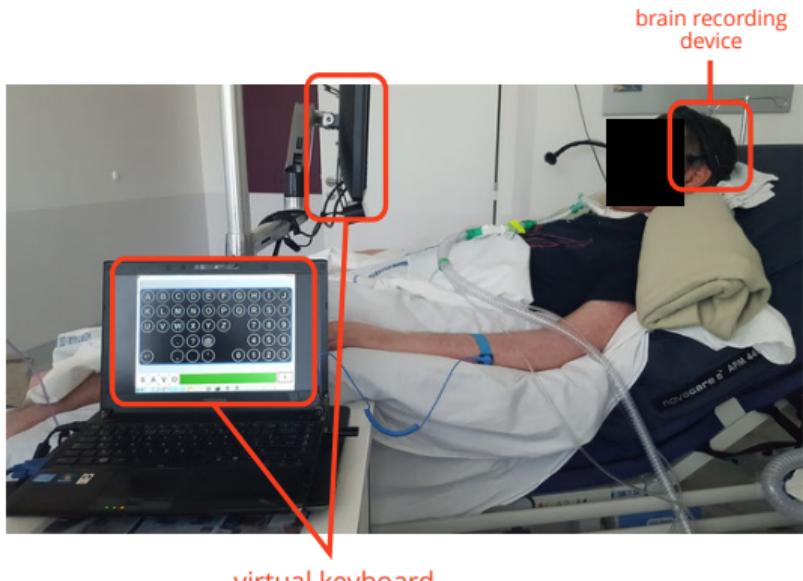
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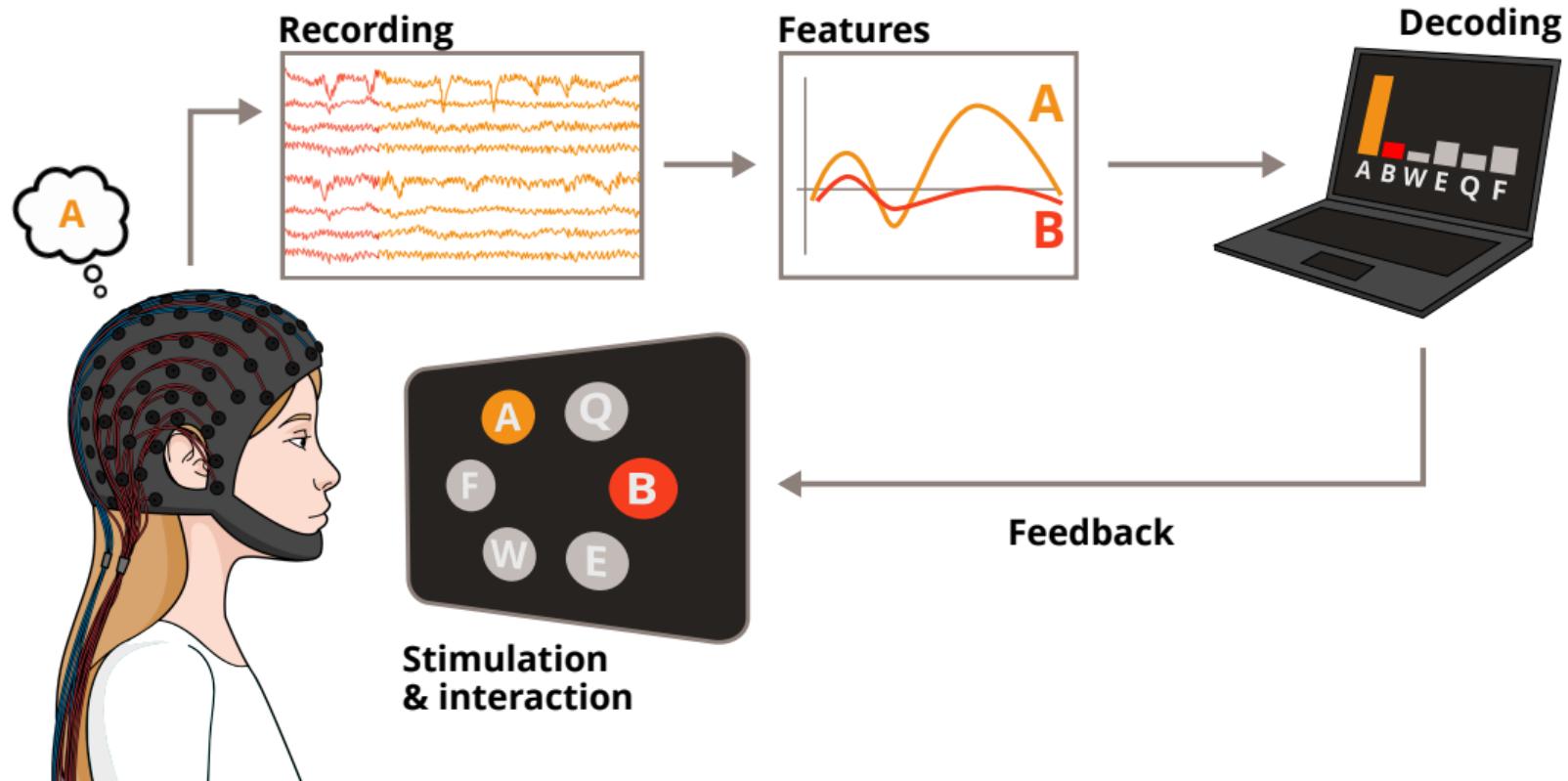
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Assistive technology

A **Brain-Computer Interface** (BCI)
bypasses muscle activity



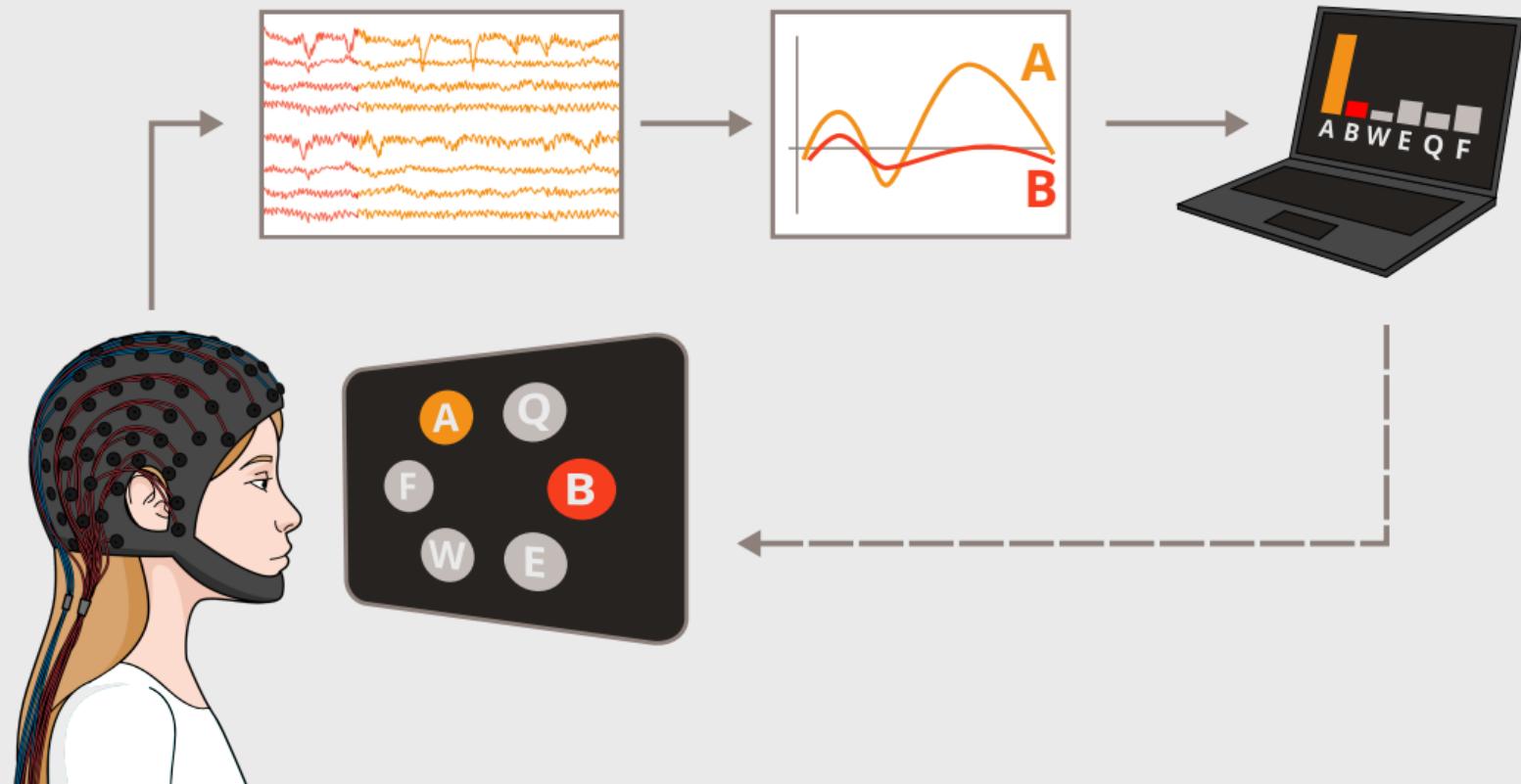
The Brain-Computer Interface



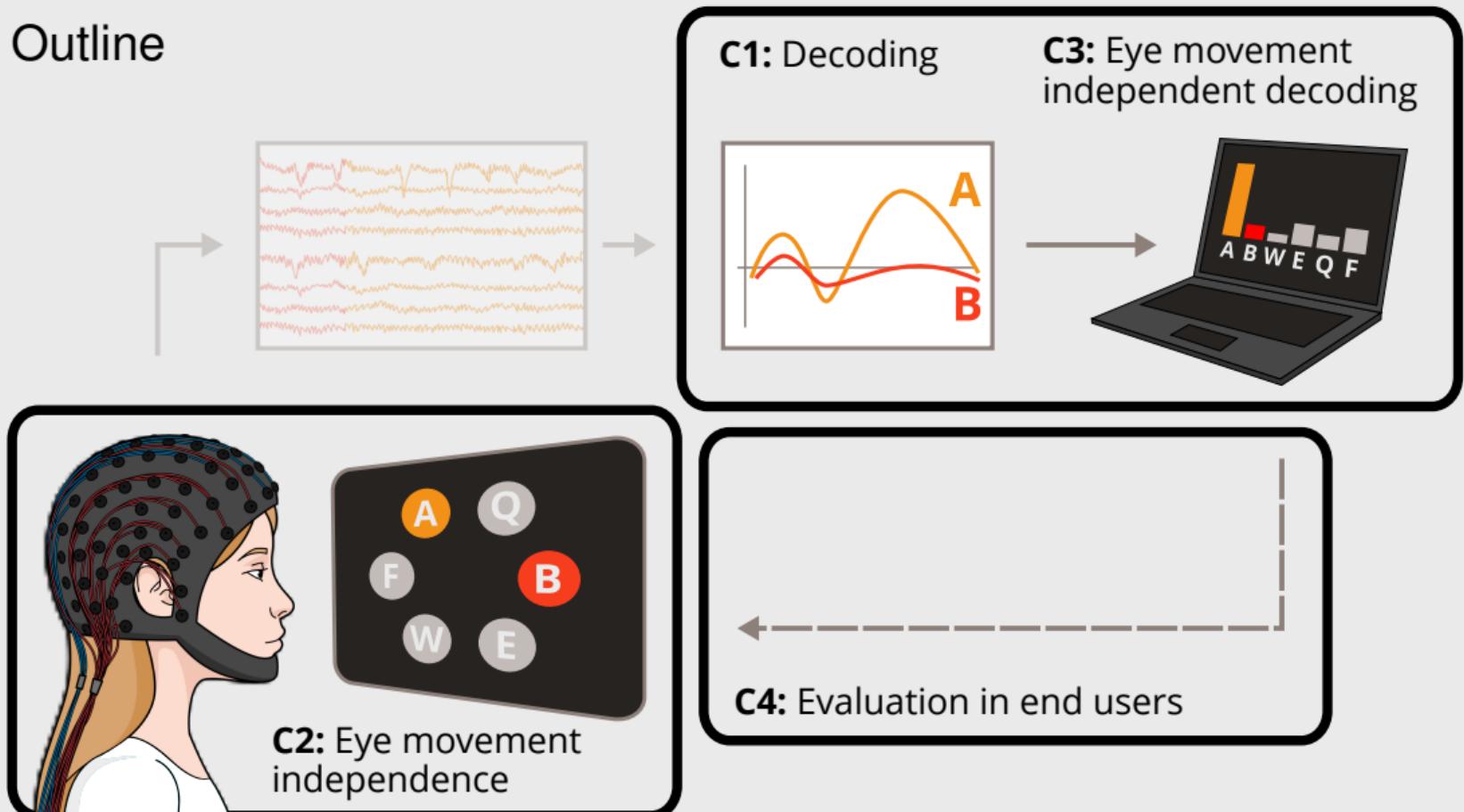
Research question

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

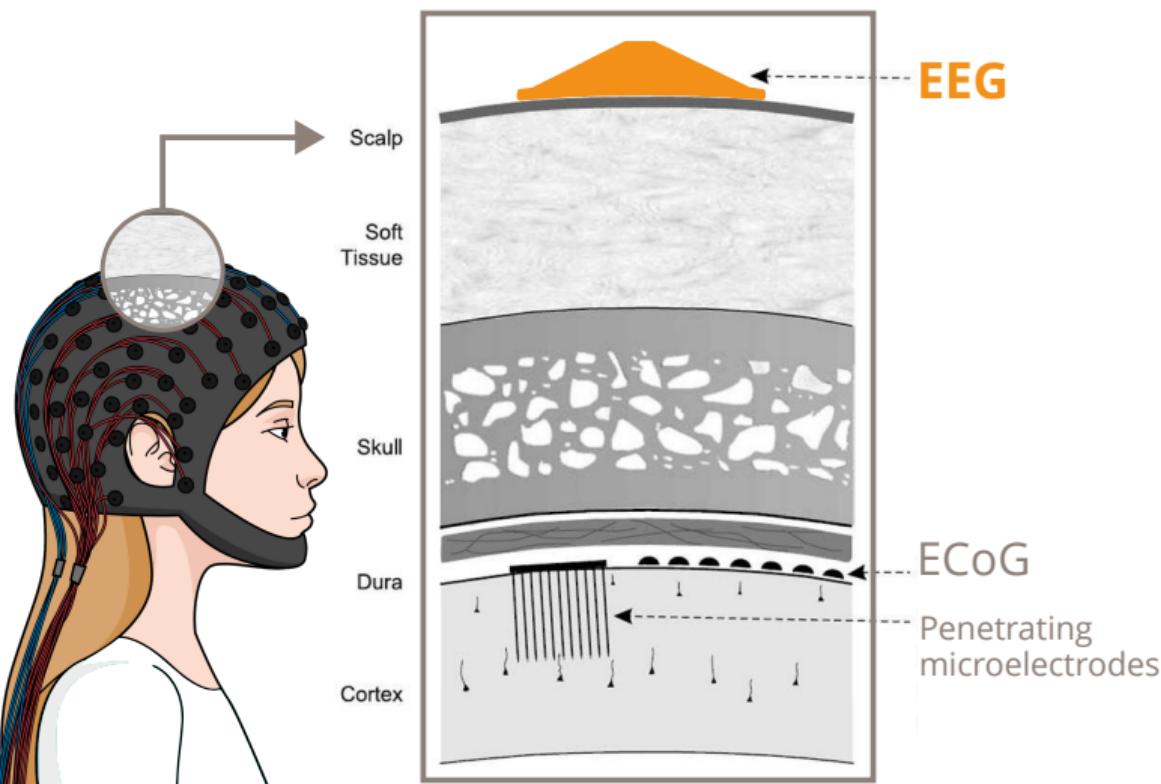
Outline



Outline



Recording the brain activity

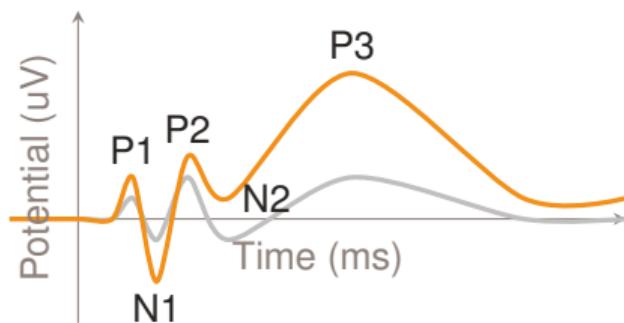
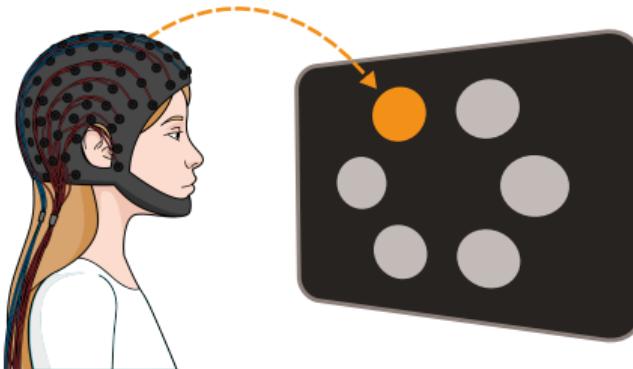


EEG measures the electrical field on the scalp:

- + Non-invasive
- + Cheap
- Large scale activity
- High noise

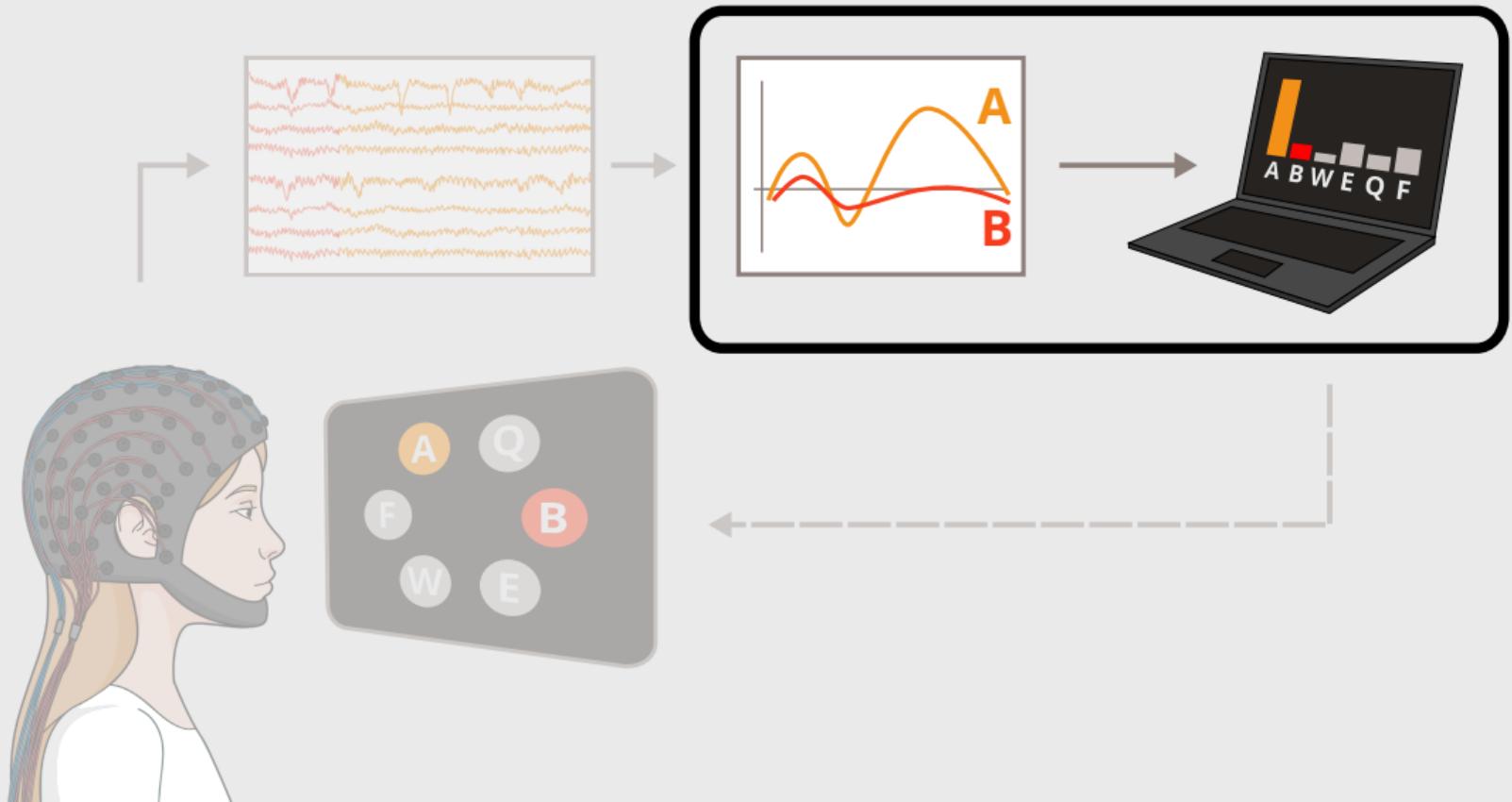
► Account for this in task and decoder design

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



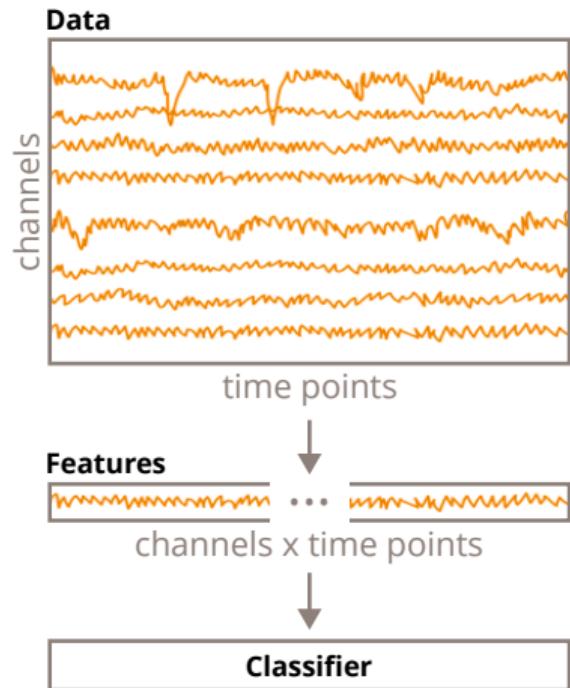
Problem: ERP responses can be difficult to extract

Strong noise ▶ machine learning decoders

- High number of features
- Calibration: low sample size

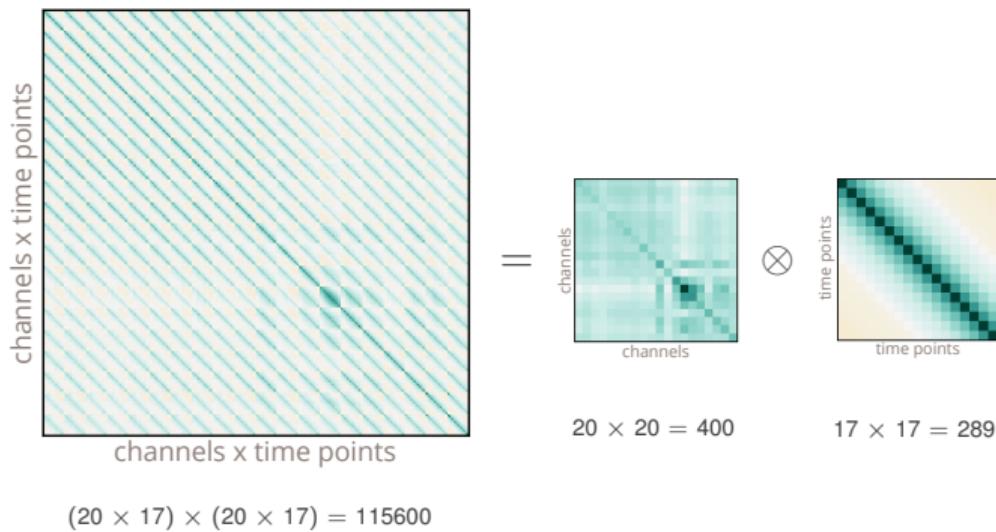
Solution: incorporate original data structure

- + Regularization
- + Fast training



Covariance matrix regularization

Van Den Kerchove et al. 2022



Spatial temporal linear decoders

Imprecise due to high number of features

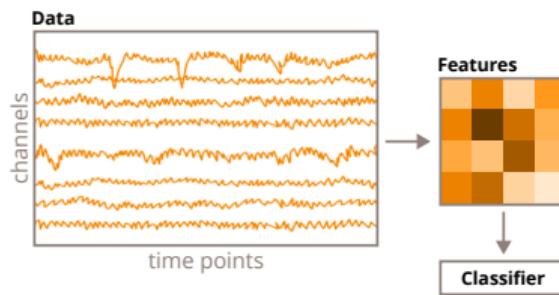
Repetitive structure in channels and time

Lightweight computation

LCMV-beamformer and LDA: improvement for short calibration time

Wittevrongel et al. 2017

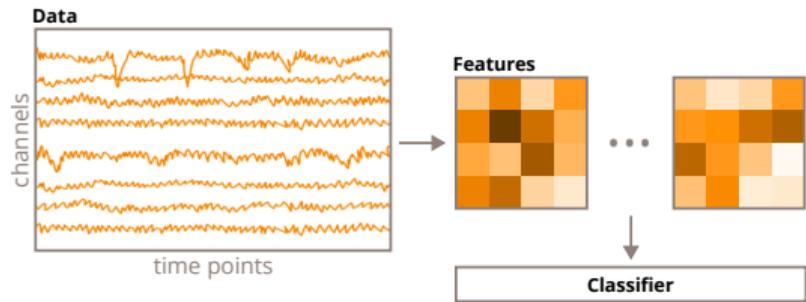
Spatial-temporal feature extraction



Directly operates on structured data

- ▶ Extract features separately in space and time

Phan et al. 2010

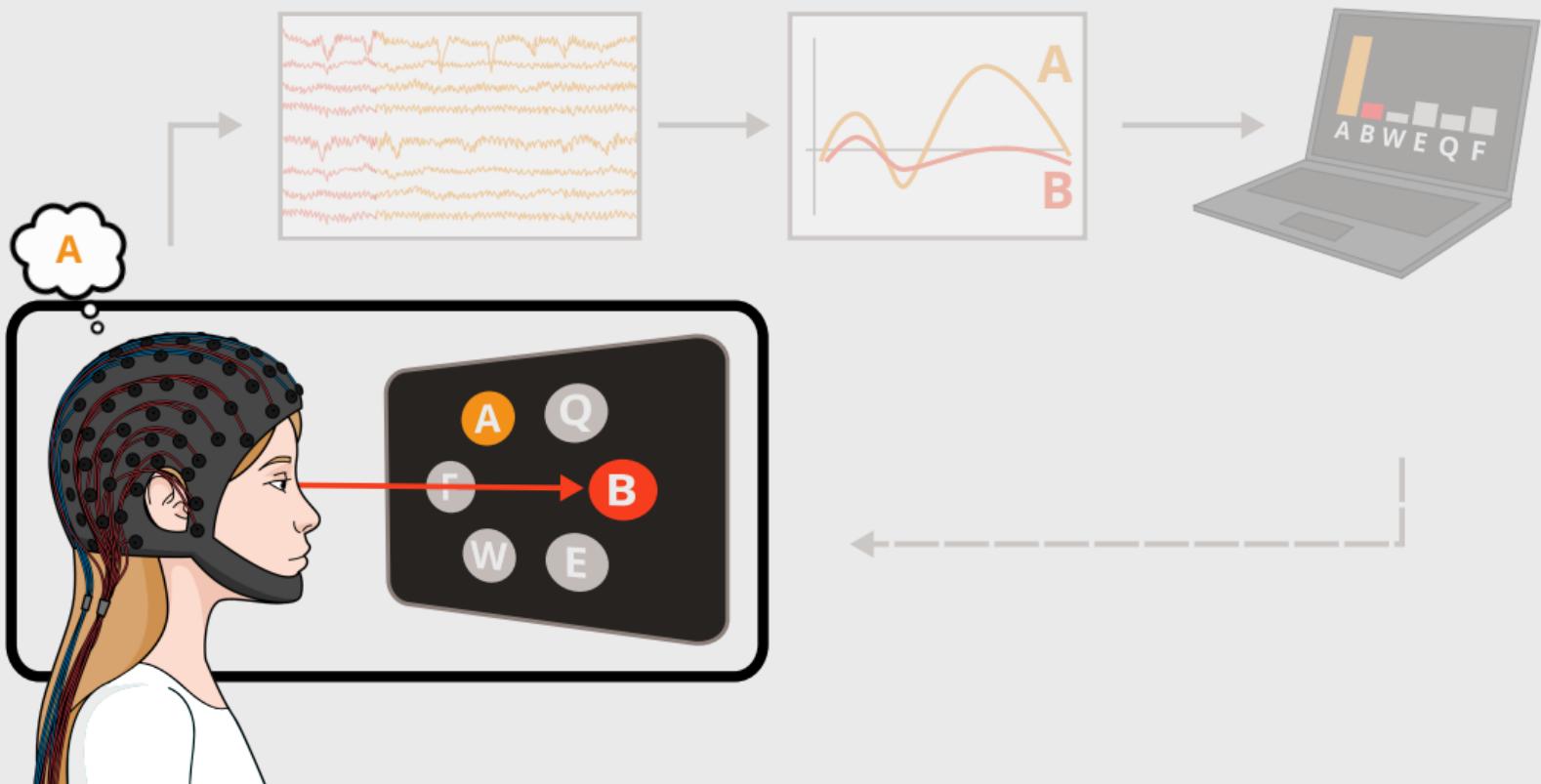


- + More flexible
- + Retains structure
- More parameters
- ▶ Heuristic model selection

Van Den Kerchove et al. submitted

Validated with benchmarking datasets

C2. Eye movement independence



Problem: Eye motor impairment prevents gazing at targets

Impairment affects BCI operation

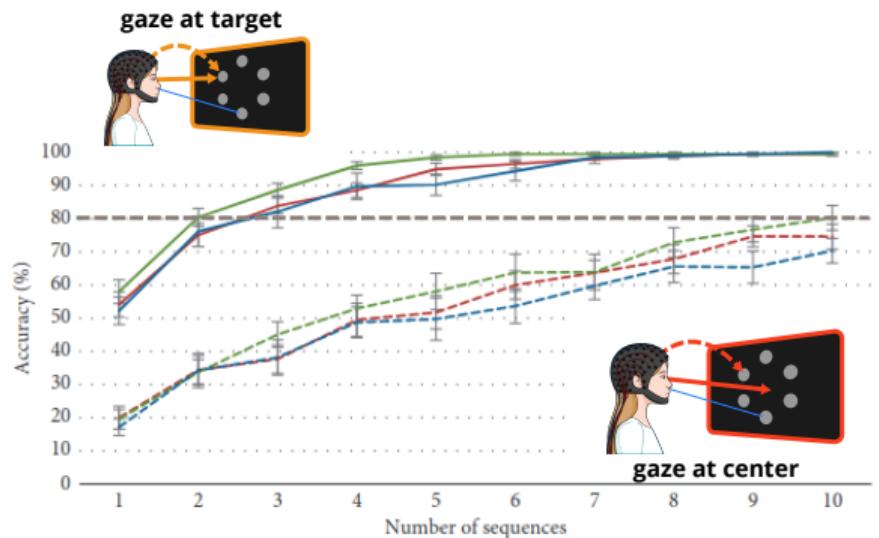
Fried-Oken et al. 2020

- ▶ Discomfort fixating
- ▶ Restricted movement
- ▶ Involuntary movements

No direct gaze

Decoding relies on **visual ERP** components

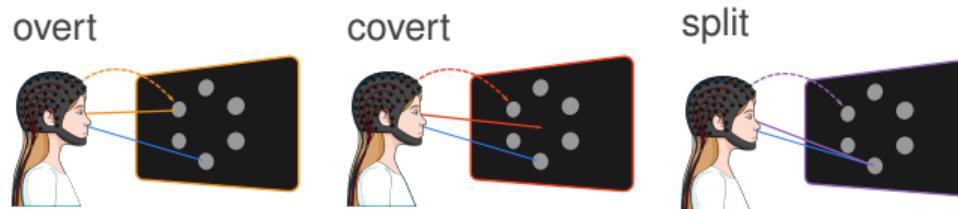
Treder et al. 2010



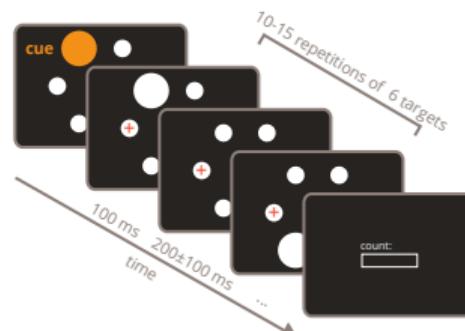
Ron-Angevin et al. 2019

Covert visuospatial attention experiment

Van Den Kerchove et al. 2024

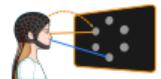


Hex-o-Spell Treder et al. 2010



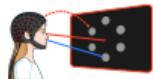
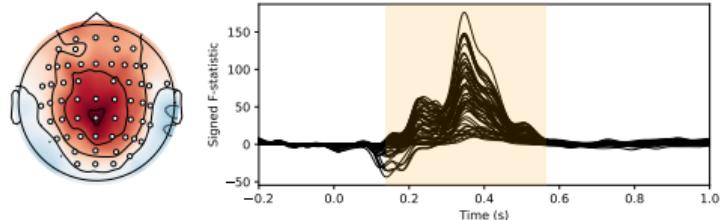
- ▶ simulate with 15 healthy control subjects
- ▶ randomized dual attention and gaze task

Absence of visual ERP components



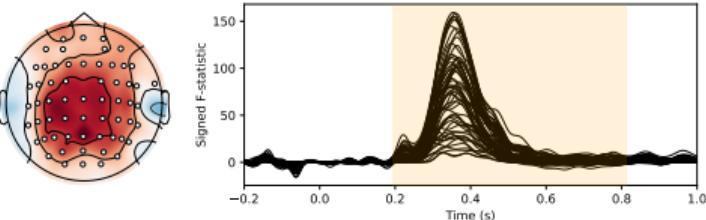
overt

0.140 - 0.564 s

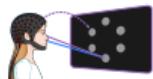
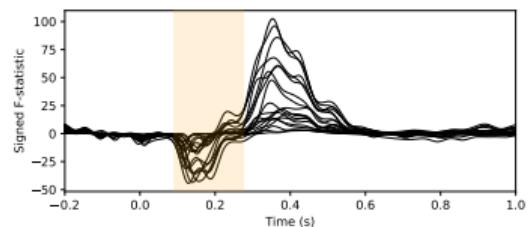
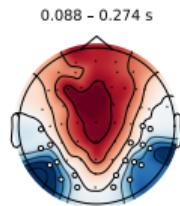


covert

0.196 - 0.812 s

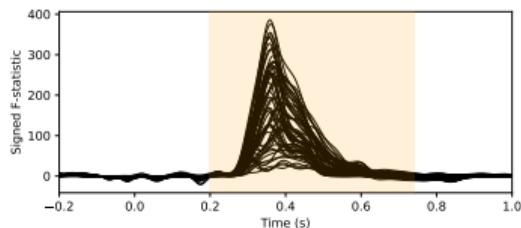
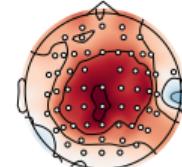


Attention-based P3 (central-parietal)



split

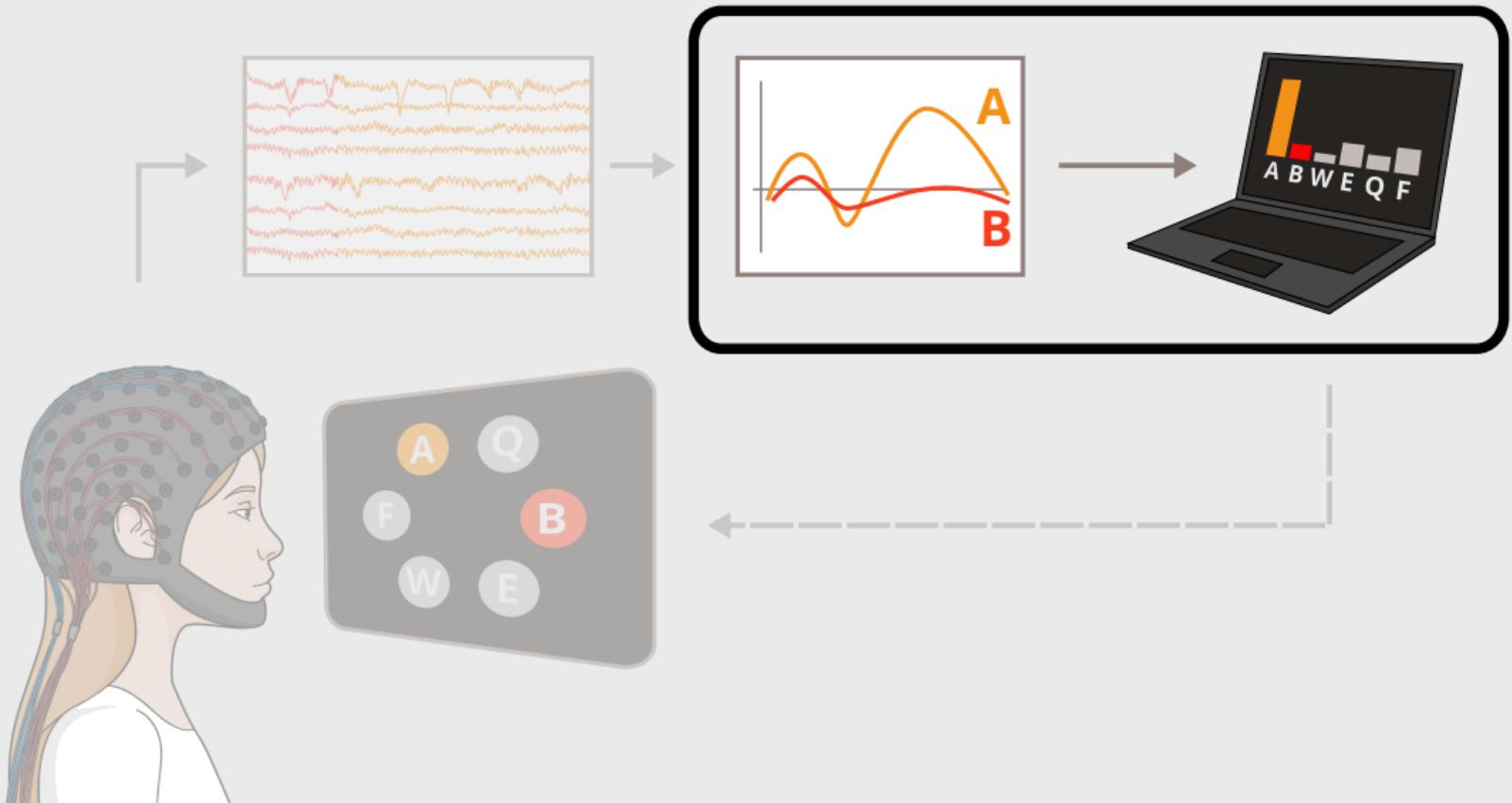
0.198 - 0.740 s



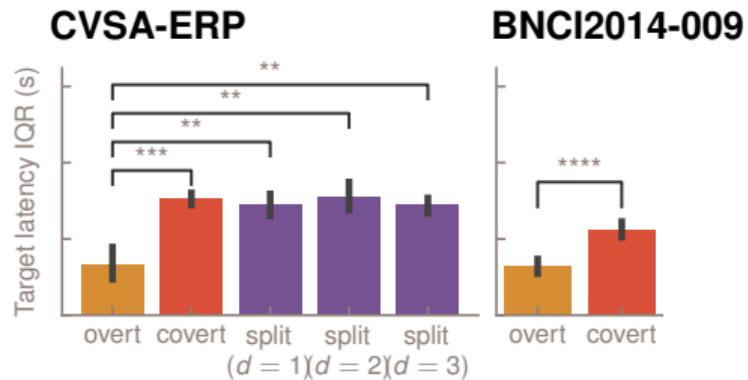
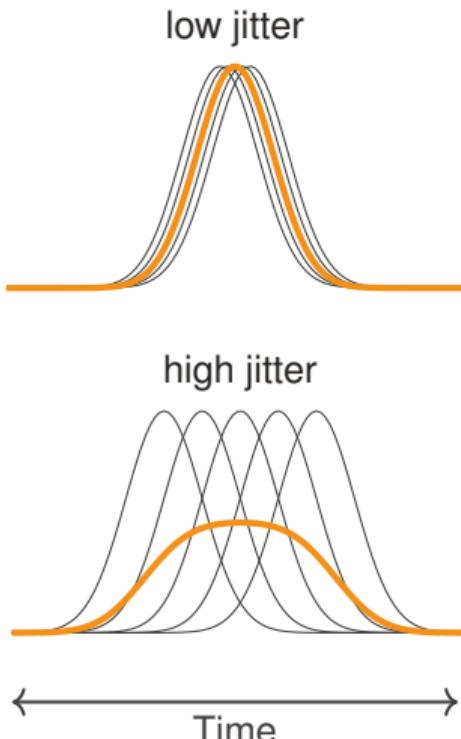
Visual early components (occipital)

F-statistic cluster-based permutation tests

C3. Eye movement independent decoding

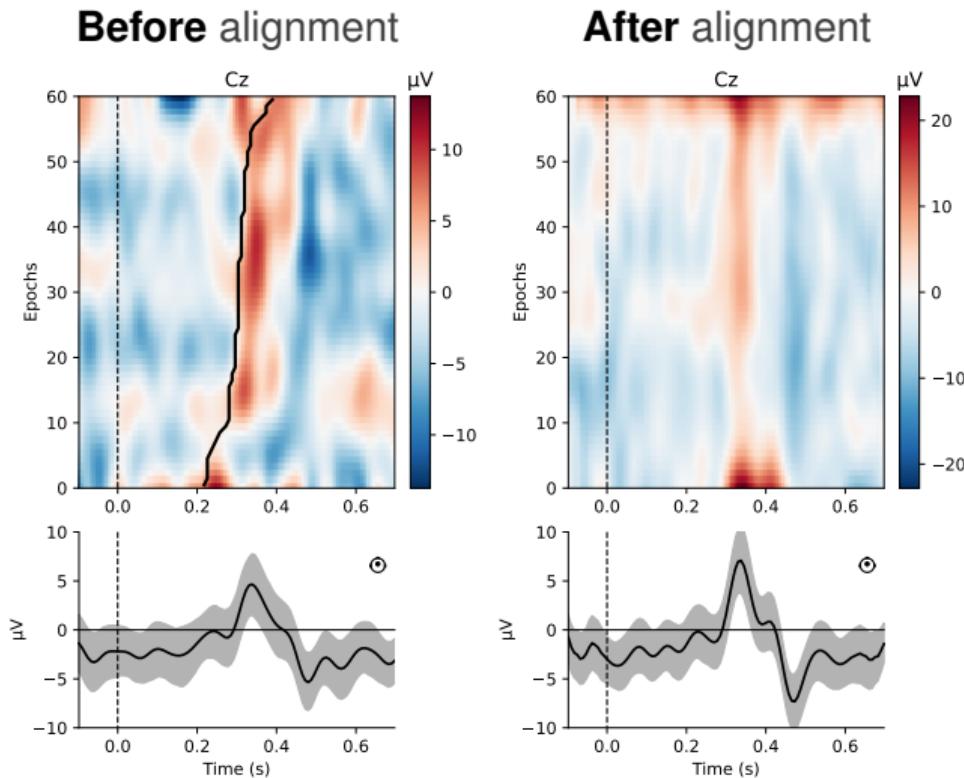


Problem: Latency jitter decreases performance in covert and split attention



- ▶ Higher jitter when eye movement independent
- ▶ Contributes to low accuracy
- ▶ Aricò et al. 2014
- ▶ Can this be **accounted for?**

Latency estimation and alignment



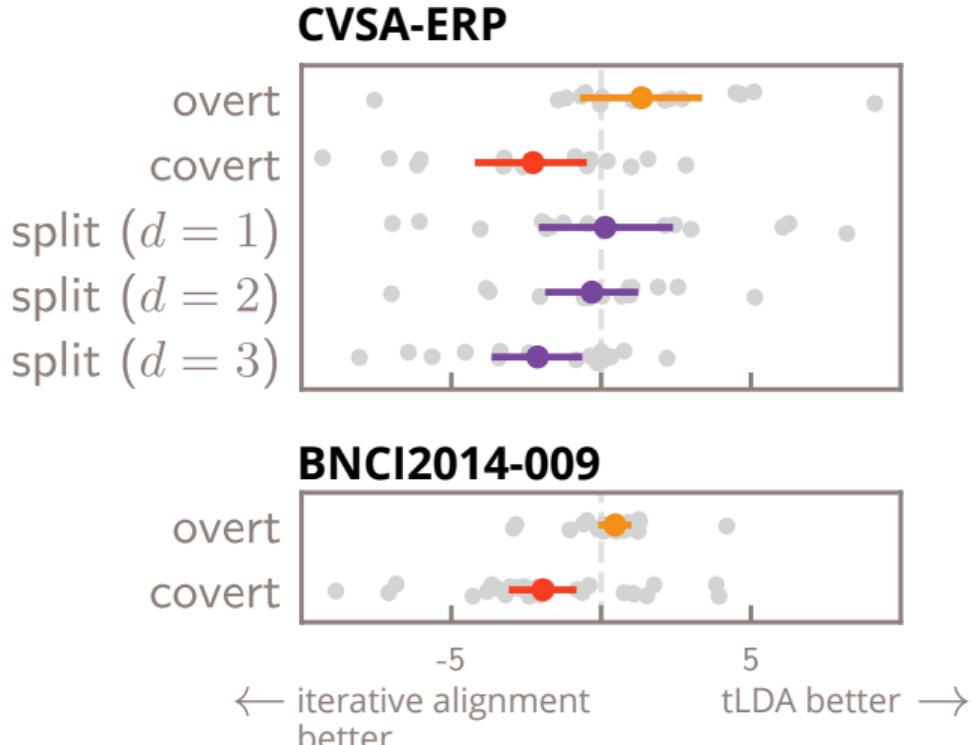
Developed enhanced ERP latency estimation method
Van Den Kerchove et al. 2024; Mowla et al. 2017

Iterative alignment

Improves latency estimation in simulated data

Useful in BCI setting?

Application to eye movement independent decoding



Applicable as decoder

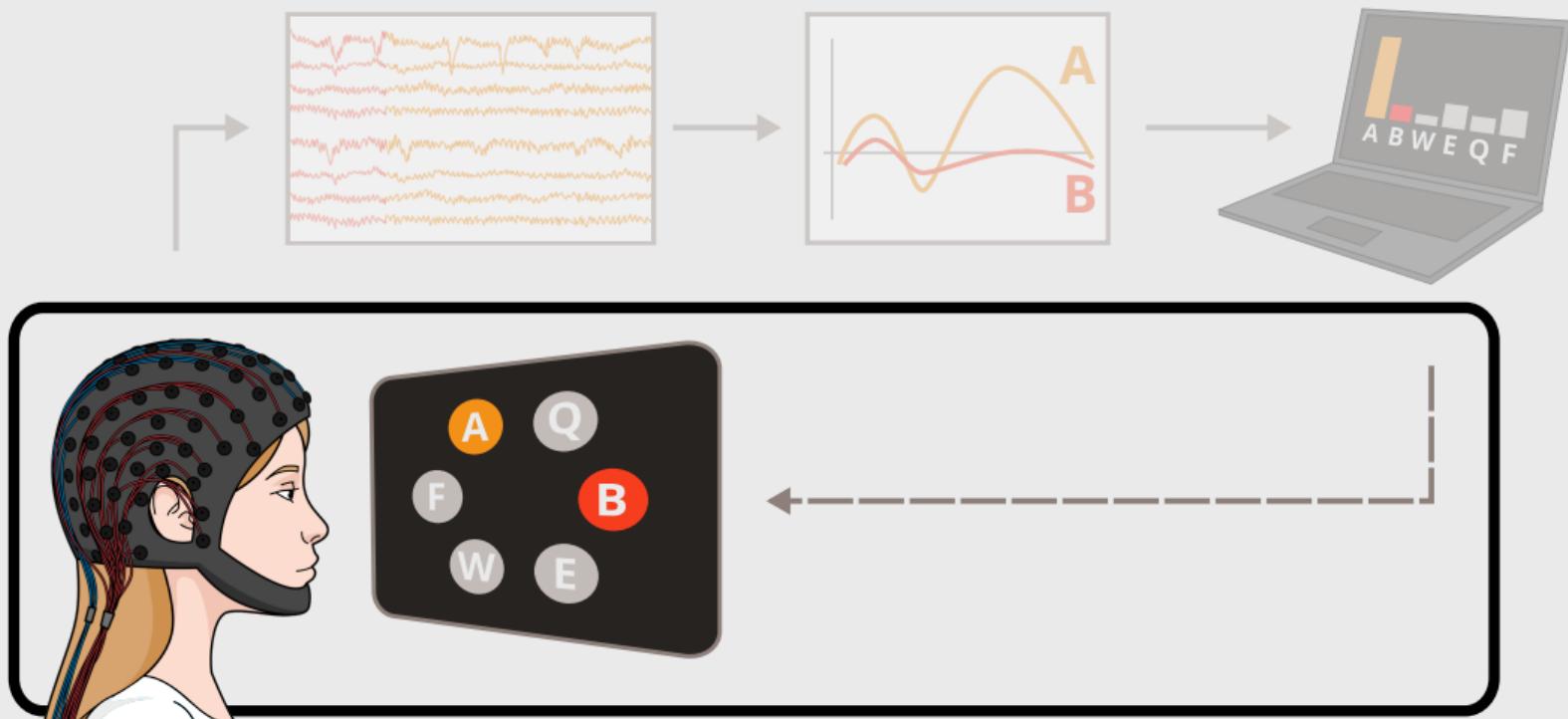
Within-subject,
cross-validated ROC-AUC

Compared with state-of-the art decoder (tLDA)

Sosulski et al. 2022

Improves covert and split decoding performance

C4: Evaluation in end-users



Participants with physical, speech and eye movement impairment

Large **individual variety** in preserved skills

3 Friedreich's **ataxia**

- ▶ impaired speech
- ▶ involuntary eye movements
- ▶ discomfort fixating

1 bulbar onset **ALS**

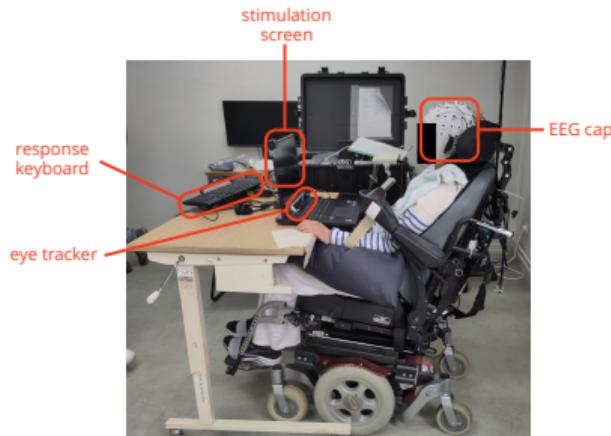
- ▶ no speech
- ▶ minor eye movement impairment

3 brain stem or cerebellar **stroke**

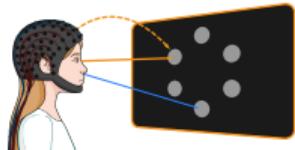
- ▶ no speech
- ▶ partial eye paralysis



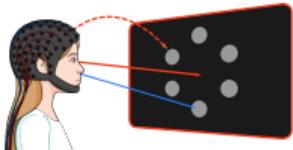
Covert visuospatial attention experiment



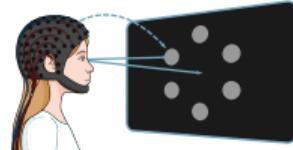
overt



covert



free



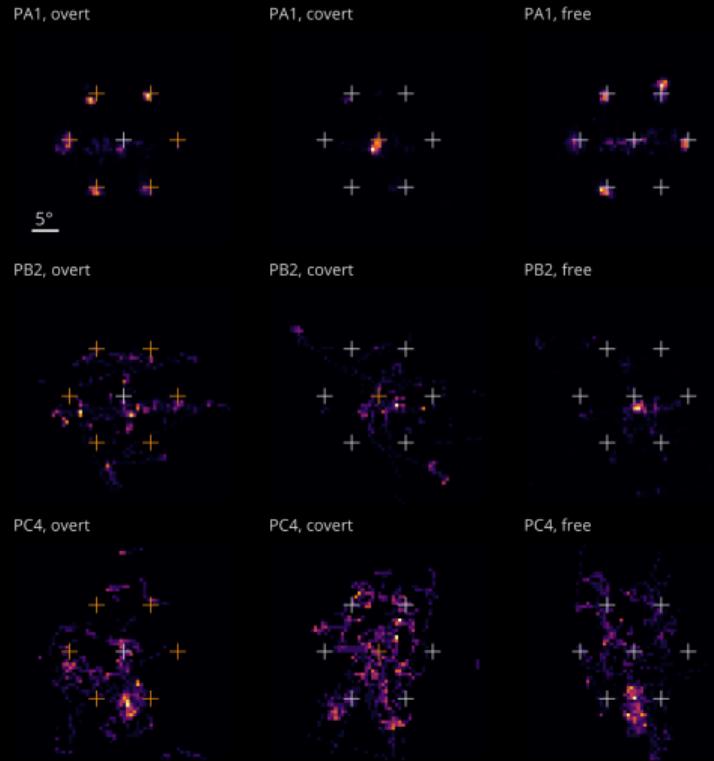
EEG, EOG and
eye-tracking

Adapted stimulation
parameters

Few studies investigating
abilities

Replace *split* by natural
free

Eye tracking

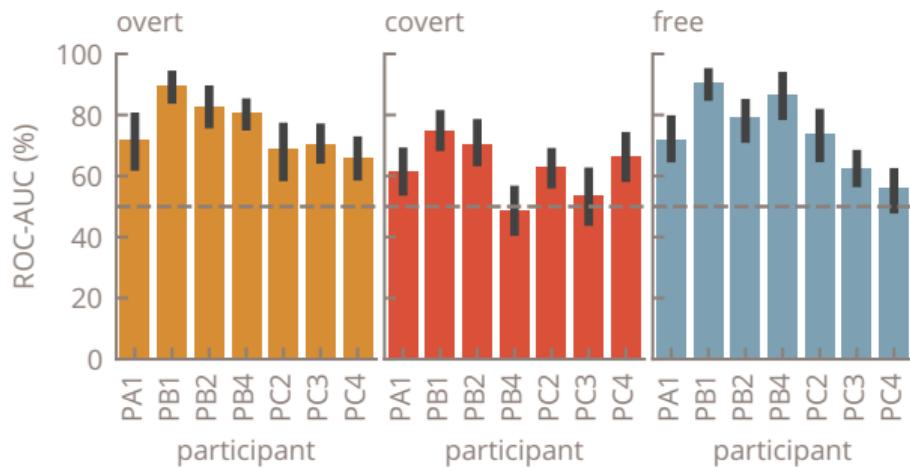


Most used overt attention

1 participant covert

1 participant split

Subject decoding performance



Off-line decoder
comparison, similar
performance

Most above chance,
positive effect for some

Covert lower than overt

Contribution of gaze

Recap

Make BCI-AT more **efficient** and **accessible** using the **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

- ▶ Libert, A. et al. (2022). "Analytic beamformer transformation for transfer learning in motion-onset visual evoked potential decoding". In: *Journal of Neural Engineering* 19.2, p. 026040.
- ▶ Van Den Kerchove, A. et al. (2022). "Classification of Event-Related Potentials with Regularized Spatiotemporal LCMV Beamforming". In: *Applied Sciences* 12.6, p. 2918.
- ▶ Van Den Kerchove, A. et al. (2024). "Block-Term Tensor Discriminant Analysis for Brain-Computer Interfacing". In: *Journal of Neural Engineering*. Submitted for publication.
- ▶ Van Den Kerchove, A. et al. (2024a). "Correcting for ERP latency jitter improves gaze-independent BCI decoding". In: *Journal of Neural Engineering*.
- ▶ Van Den Kerchove, A. et al. "Case studies of the impact of eye motor impairment on visual ERP BCI usage". In preparation.

Conclusions

- ▶ Improved decoders enhance BCI **efficiency**
- ▶ Improvements in eye movement independent decoding improve **accessibility** for some
- ▶ Occasionally impacts end-users, need for holistic approach beyond decoder design
- ▶ Gained insight in requirements of BCI users with impaired eye movement

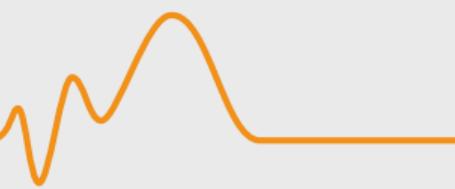
Perspectives

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

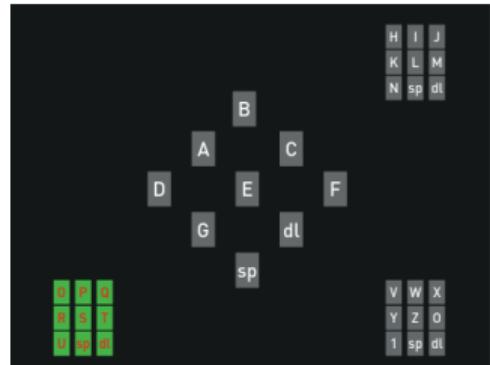
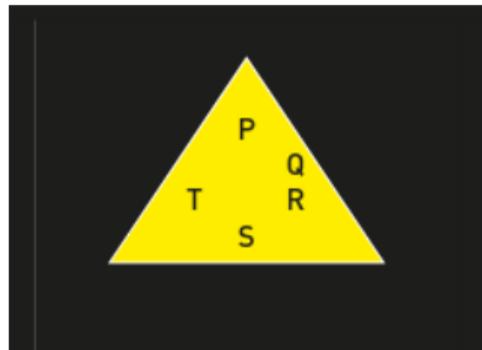
KU LEUVEN

Université
de Lille



Gaze-independent visual reactive BCIs

- ▶ Auditory
- ▶ Tactile
- ▶ Visual
- ▶ ERP
- ▶ SSVEP
- ▶ Localized covert attention shift



Kronecker-Toeplitz structured spatiotemporal covariance matrix estimation

$$\tilde{\mathbf{S}}_{k+1} = \frac{1}{N} \sum_{n=1}^N \mathbf{x}_n^\top \hat{\mathbf{T}}_k^+ \mathbf{x}_n$$

$$\tilde{\mathbf{T}}_{k+1} = \frac{1}{N} \sum_{n=1}^N \mathbf{x}_n \hat{\mathbf{S}}_k^+ \mathbf{x}_n^\top$$

$$\tilde{\mathbf{S}}_{k+1}^{(\beta)} = (1 - \beta_{k+1}) \tilde{\mathbf{S}}_{k+1} + \beta_{k+1} \frac{\text{Tr}(\tilde{\mathbf{S}}_{k+1})}{C} \mathbb{I}$$

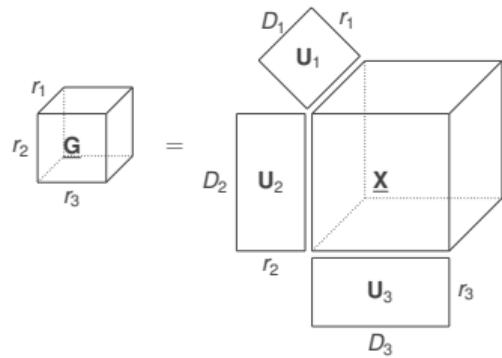
$$\tilde{\mathbf{T}}_{k+1}^{(\gamma)} = (1 - \gamma_{k+1}) \tilde{\mathbf{T}}_{k+1} + \gamma_{k+1} \frac{\text{Tr}(\tilde{\mathbf{T}}_{k+1})}{S} \mathbb{I}$$

$$\hat{\mathbf{S}}_{k+1} = \frac{C}{\text{Tr}[\tilde{\mathbf{S}}_{k+1}^{(\beta)}]} \tilde{\mathbf{S}}_{k+1}^{(\beta)}$$

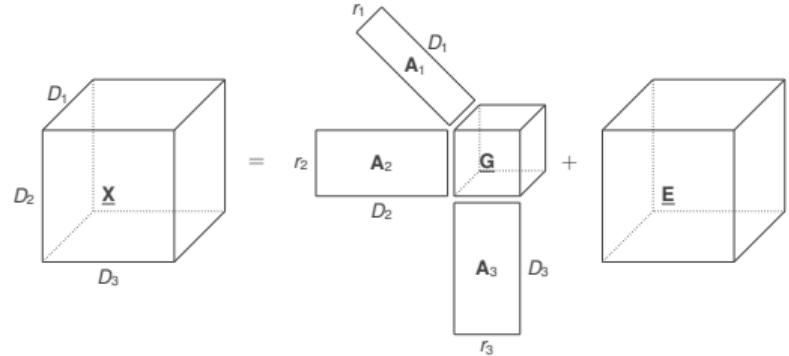
$$\hat{\mathbf{T}}_{k+1} = \frac{S}{\text{Tr}[\tilde{\mathbf{T}}_{k+1}^{(\gamma)}]} \tilde{\mathbf{T}}_{k+1}^{(\gamma)}$$

Block-term tensor discriminant analysis procedure

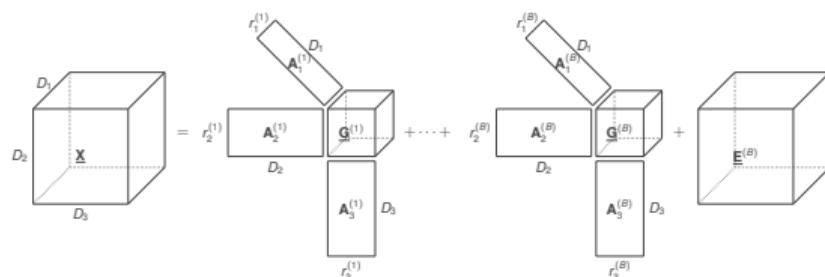
HODA **backward** model



HODA **forward** model



BTTDA forward model

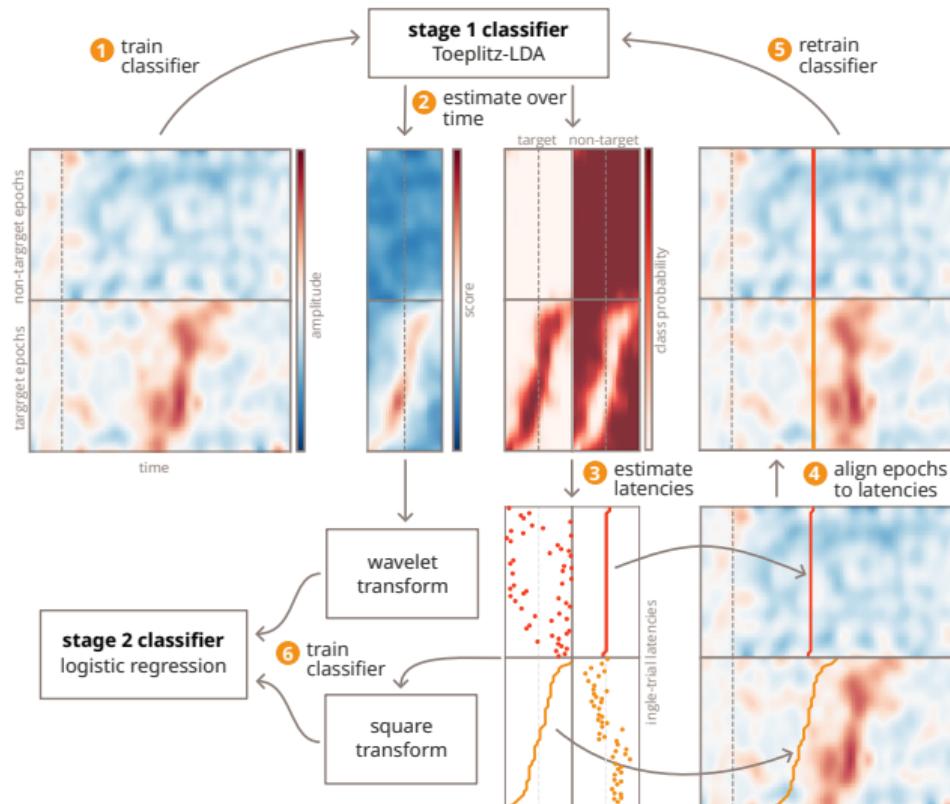


$$\{\mathbf{U}^*\} = \frac{\sum_c^C N_c \|\bar{\mathbf{G}}(c) - \bar{\mathbf{G}}\|_F^2}{\sum_n^N \|\underline{\mathbf{G}}(n) - \bar{\mathbf{G}}(c_n)\|_F^2}$$

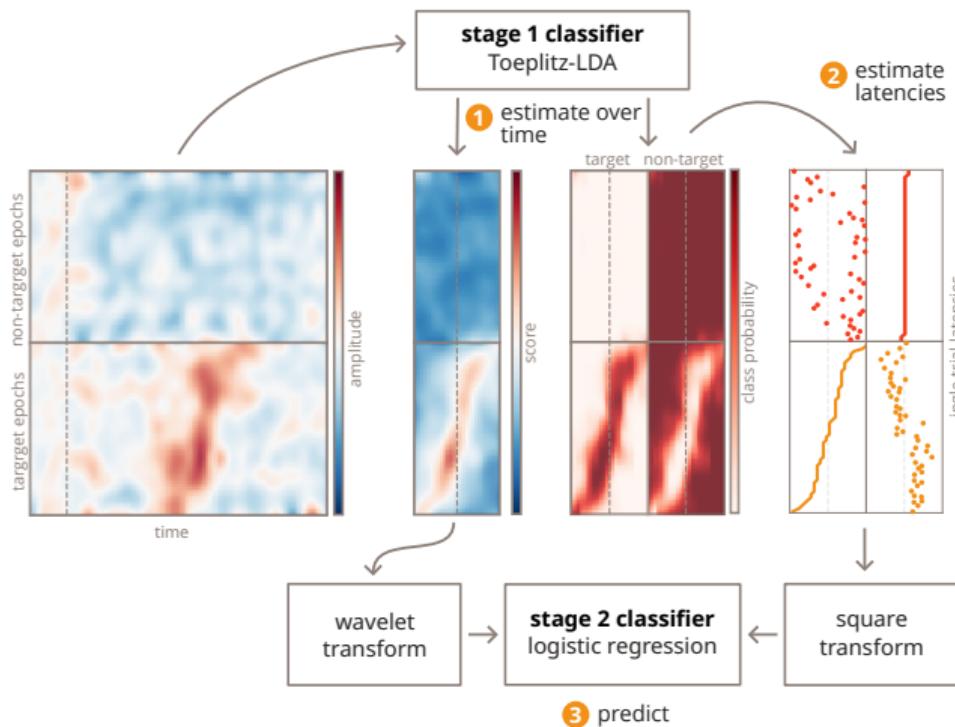
$$\mathbf{A}_k = \underset{\mathbf{A}_k}{\operatorname{argmin}} \sum_n^N \left[\mathbf{X}_k(n) - \mathbf{A}_k (\underline{\mathbf{G}}(n) \times_{-k} \{\mathbf{A}\})_k \right]^2$$

$$\underline{\mathbf{G}}^{(b)} = \underline{\mathbf{E}}^{(b-1)} \times \{\mathbf{U}^{(b)}\}$$

Classifier-based latency estimation with Woody iterations (train)



Classifier-based latency estimation with Woody iterations (test)



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

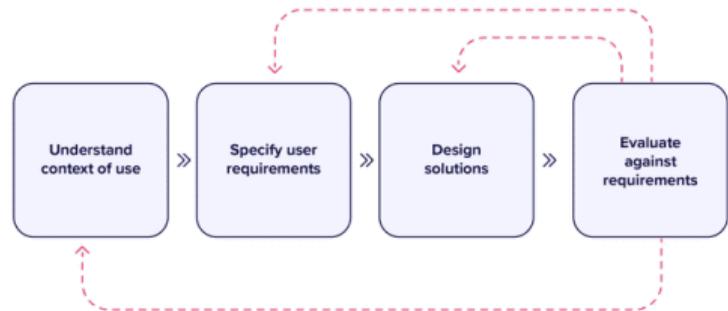
Visual skill and eye movement impairment

	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	address holistic experience
P6	multidisciplinary design



Evaluate

- ▶ effectiveness
- ▶ efficiency
- ▶ user satisfaction