

Effects of stimulus sequences on brain-computer interfaces using code-modulated visual evoked potentials: an offline simulation

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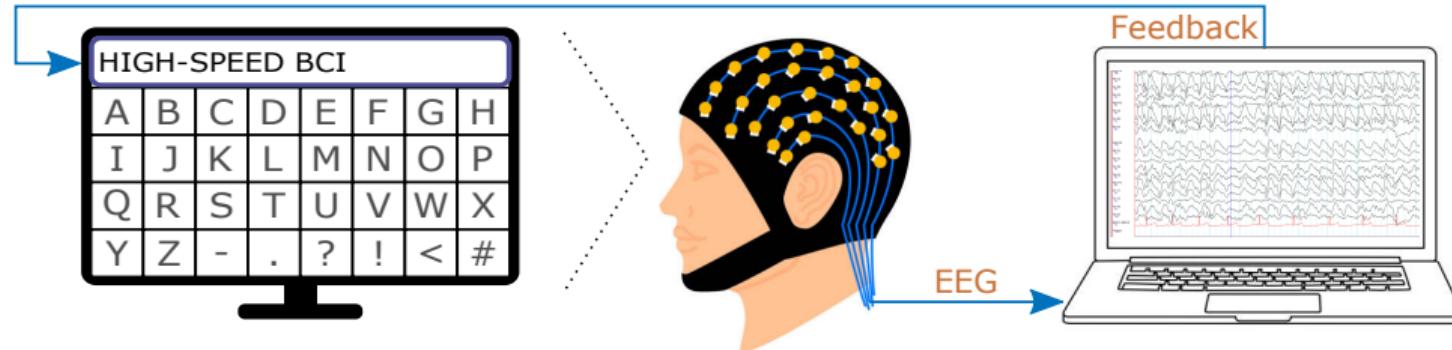
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Background: brain-computer interfacing (BCI)

Translate brain activity into digitized commands

- Electroencephalography (EEG): non-invasive
- Communication and control



Background: BCI control signals

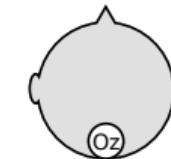
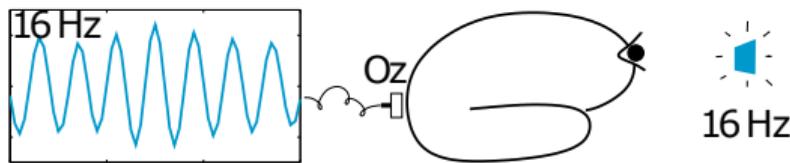
- **(Spontaneous) oscillations**

- Not time-locked, internally generated (endogenous)
- Change in power at a specific frequency, e.g., SMR



- **Evoked responses**

- Time-locked to an external event (exogenous)
- Change in amplitude at a specific latency, e.g., P300



[Blankertz (2014) BBCI Winter School]

Background: evoked responses

• Transient responses

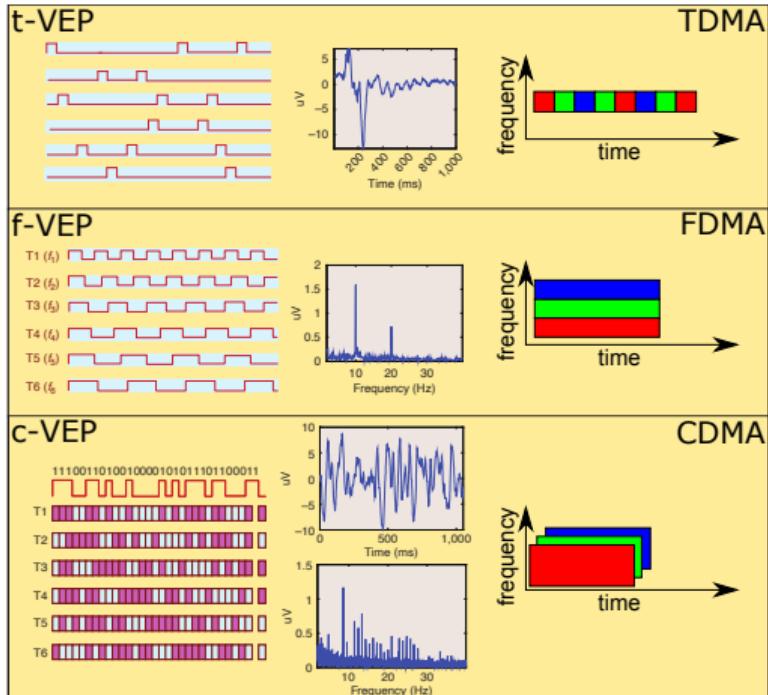
- Response to a *single* event
- Protocol: e.g., oddball
- Examples: P300, ERN, MMN

• Steady-state responses

- Response to *periodic sequence* of events
- Protocol: frequency-tagging
- Examples: SSVEP, ASSR, SSSEP

• Broad-band responses

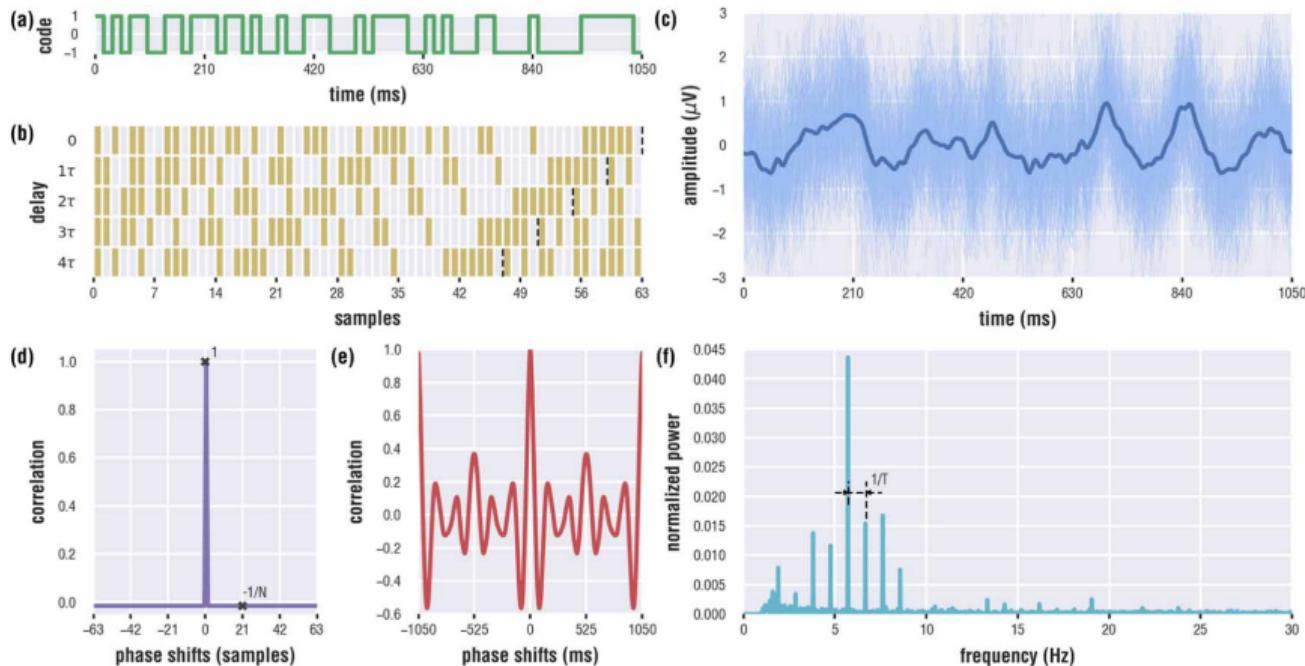
- Response to *pseudo-random sequence* of events
- Protocol: noise-tagging
- Examples: c-VEP, c-AEP, c-SEP



[Bin et al. (2009) *IEEE Comput Intell M*] [Gao et al. (2014) *IEEE T Bio-Med Eng*]

Background: code-modulated visual evoked potential (c-VEP)

23	24	25	26	27	28	29	30	31	0
31	0	1	2	3	4	5	6	7	8
7	8	9	10	11	12	13	14	15	16
15	16	17	18	19	20	21	22	23	24
23	24	25	26	27	28	29	30	31	0
31	0	1	2	3	4	5	6	7	8



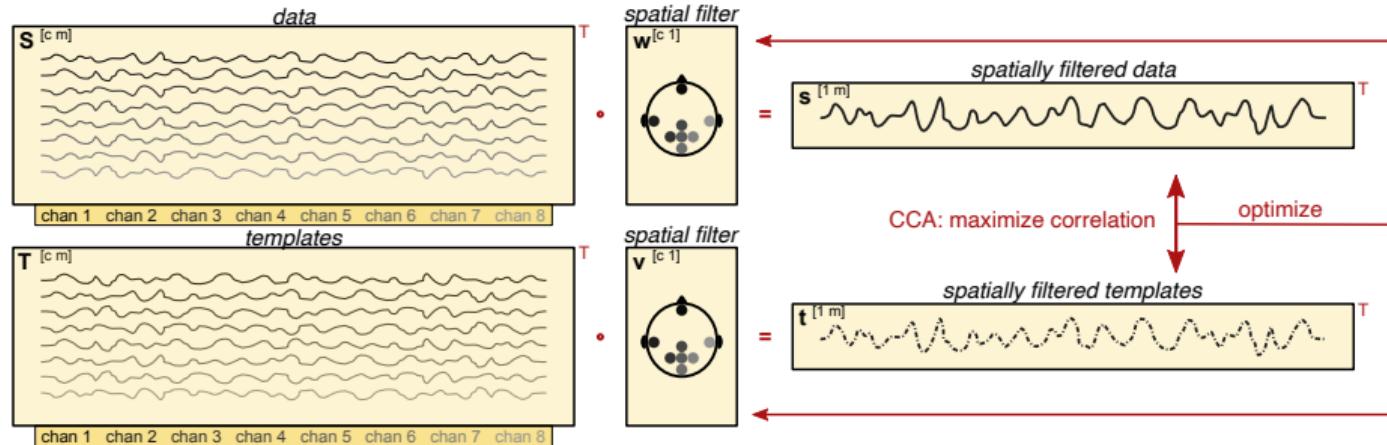
[Spüler et al. (2012) PLOS ONE]

[Martinez-Cagigal et al. (2021) J Neural Eng]

Background: reference pipeline

Template matching classifier: $\hat{y} = \arg \max_i \rho(\mathbf{w}^\top \mathbf{X}, \mathbf{w}^\top \mathbf{T}_i)$

Canonical correlation analysis: $\arg \max_{\mathbf{w}, \mathbf{v}} \rho(\mathbf{w}^\top \tilde{\mathbf{X}}, \mathbf{v}^\top \tilde{\mathbf{T}})$



[Martinez-Cagigal et al. (2021) *J Neural Eng*]

[Hotelling (1936) *Biometrika*] [Spüler et al. (2012) *ESANN*] [Spüler et al. (2013) *IEEE T Neur Sys Reh*]

[Thielen et al. (2021) *J Neural Eng*]

Aim: enhanced BCI performance without more training

The challenge: BCIs require **calibration** before use

- Time-consuming and costly
- Prevents immediate use
- Infeasible to explore hyperparameters, e.g., potential sequences
 - From telecommunication: m-sequence, Gold codes, etc. [Bin et al. (2009) *IEEE Comput Intell M*]
 - Hand-crafted sequences [Yasinzai & Ider (2020) *Biomed Phys Eng Express*]

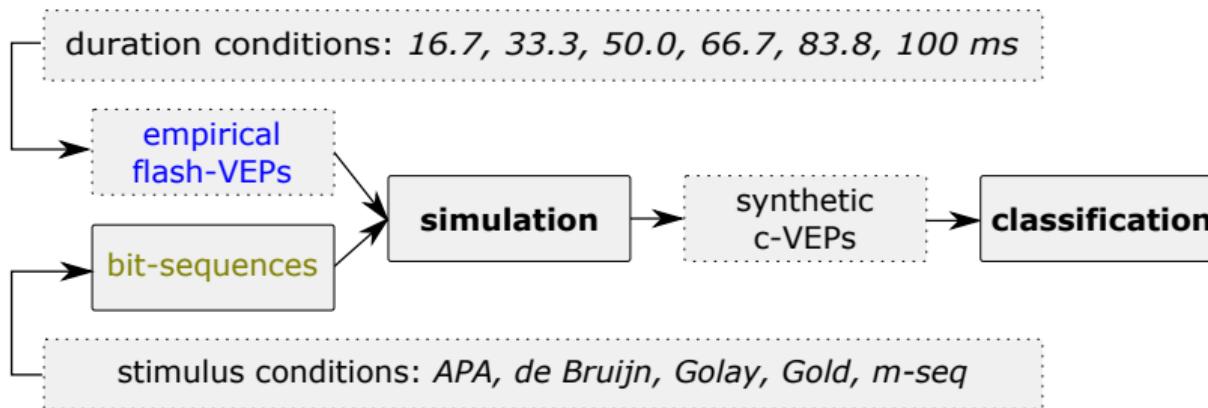
The solution: use **simulated** data

- Generate simulated data to explore hyperparameters
- Include biologically plausible forward model [Capilla et al. (2011) *PLOS ONE*]
 - Improved over [Torres & Daly (2021) *J Neural Eng*]

Methods: processing pipeline

Single-trial **c-VEP**: $x(t) = s(t) + n(t)$

- Signal: $s(t) = \sum_j^6 \sum_{\tau}^e l_j(t) r_j(t - \tau)$
- Noise: $n(t)$ includes white and pink ($1/f$) noise, and eye blinks and movements

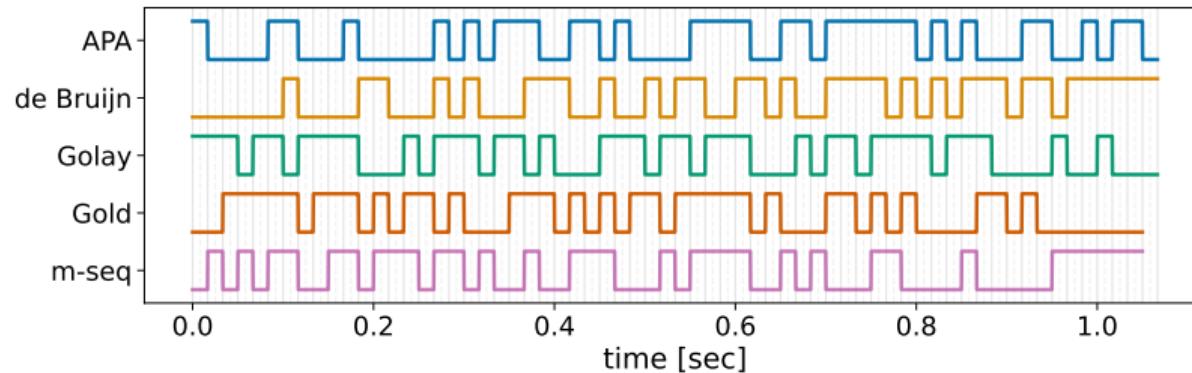


[Thielen et al. (2015) *PLOS ONE*] [Thielen et al. (2021) *J Neural Eng*]

Methods: stimulus sequences

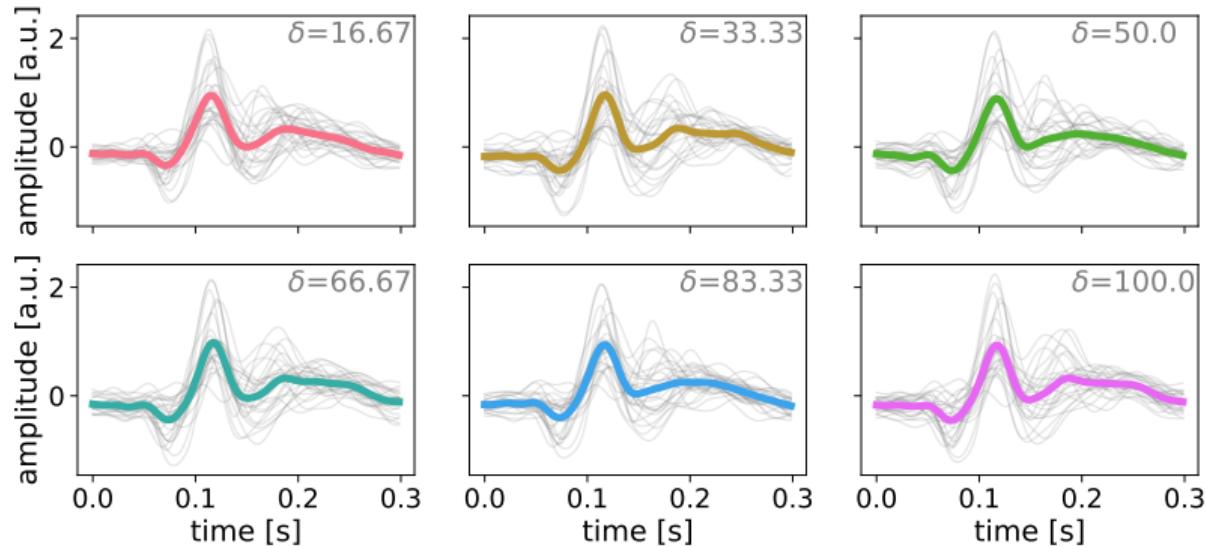
Frame rate 120 Hz while presentation rate 60 Hz

Simulate a 32-class speller BCI by circular shifting codes with a lag of 2 bits



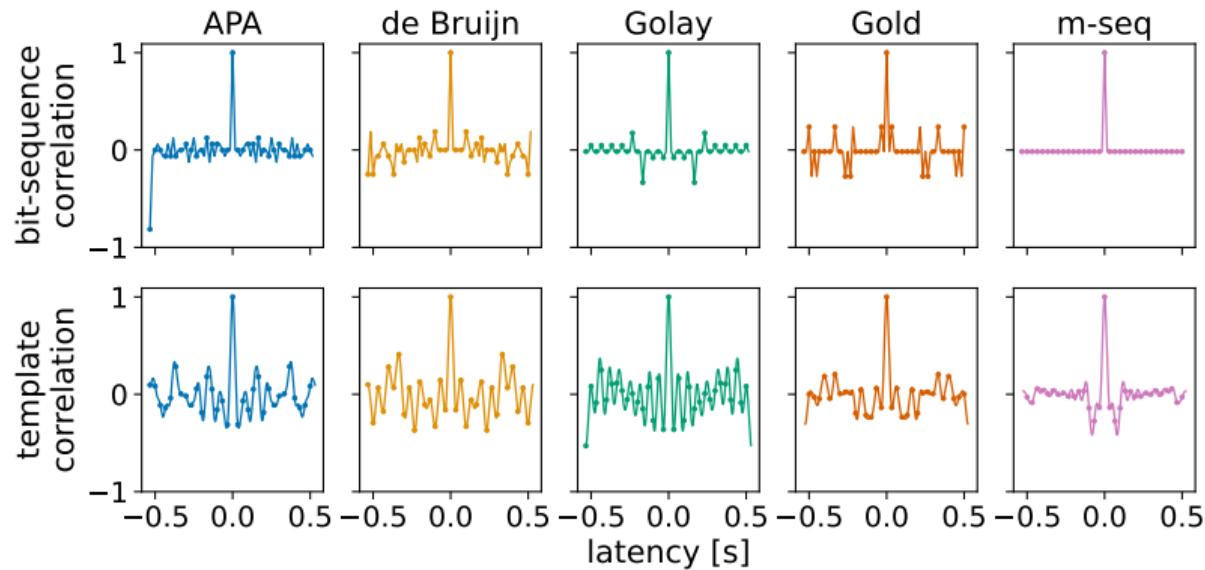
Results: empirical flash-VEP

Participant-specific ($N=26$) and duration-specific flash-VEPs



Results: synthetic c-VEP

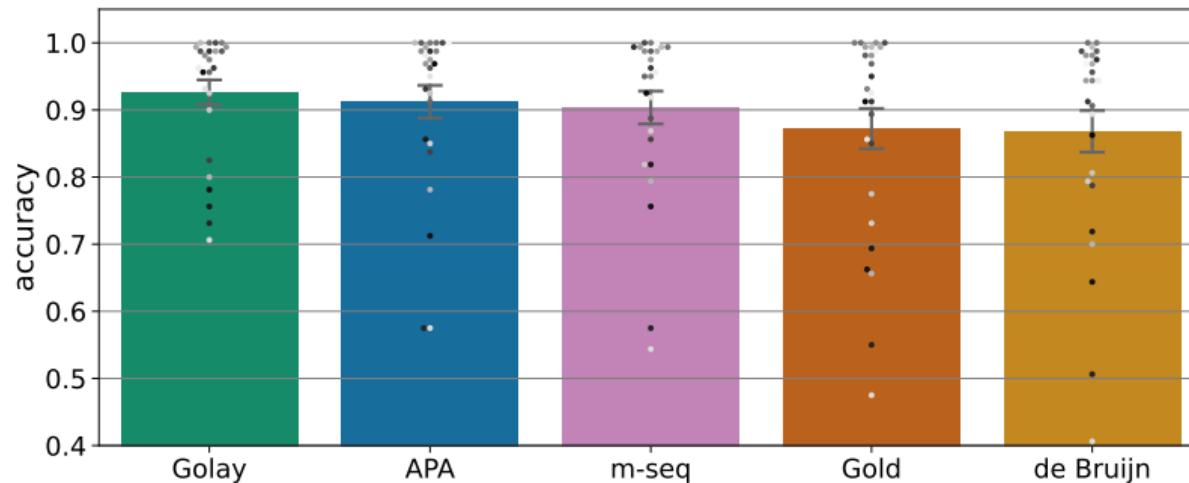
Autocorrelation properties of sequences do not carry over from stimulus to response domain



Results: decoding accuracy

Average best: Golay sequence (0.926 ± 0.018)

Individual best: mostly Golay and APA (0.937 ± 0.017)



Conclusion

Improved biologically plausible **forward model**

- Includes the flash-VEP
- Can model inter-individual differences

Initial step towards **optimizing stimulus parameters** using synthetic data

- One-size-fits-all: Golay sequence (and APA sequence)
- Individual optimization allows enhanced BCI tailored to the individual

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The role of code-modulated evoked potentials in next-generation brain-computer interfacing

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Acknowledgements

Data-Driven Neurotechnology Lab (<https://neurotechlab.socsci.ru.nl/>)

- Michael Tangermann
- Sara Ahmadi

BCI Lab

- Peter Desain
- Jason Farquhar
- Pieter Marsman
- Philip van den Broek

Resources and tutorials on: <https://neurotechlab.socsci.ru.nl/resources/cvep/>