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Non-binary codes for c-VEP-based BCI systems

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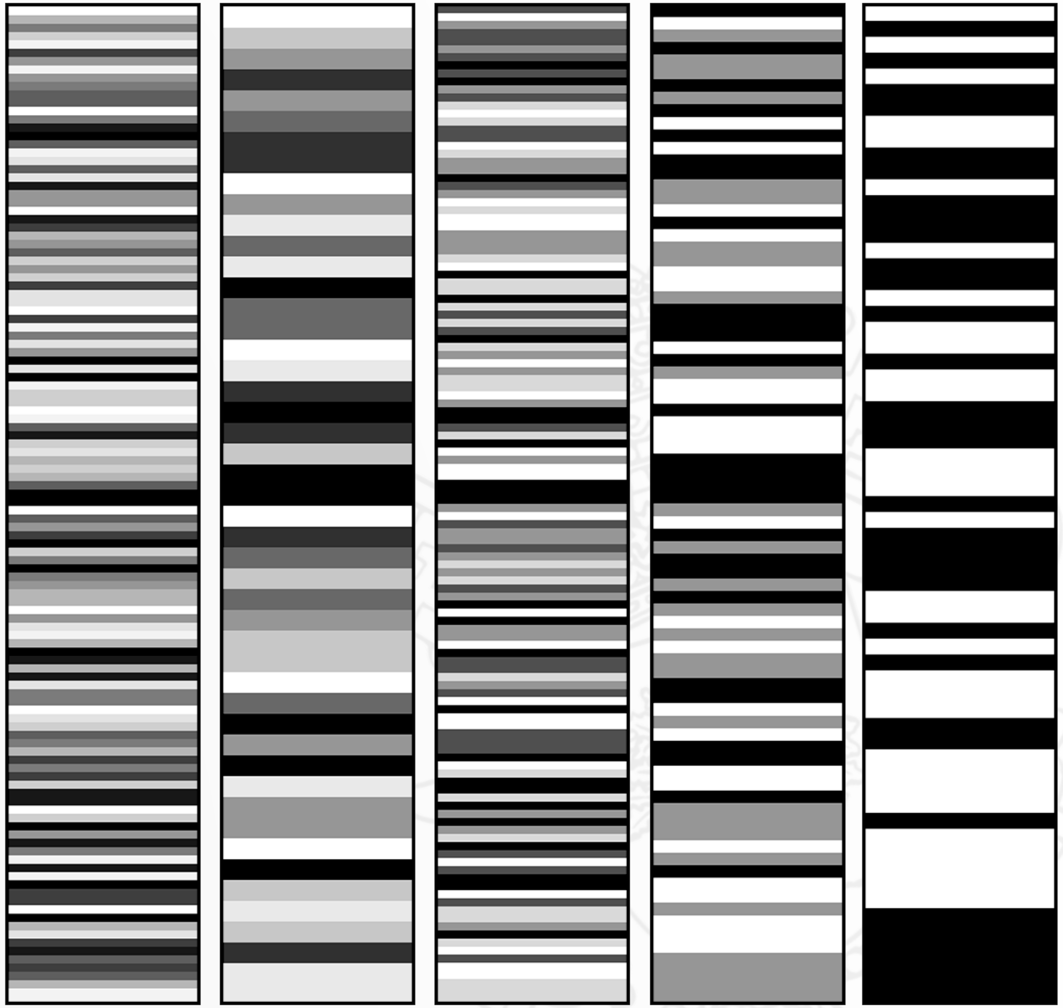
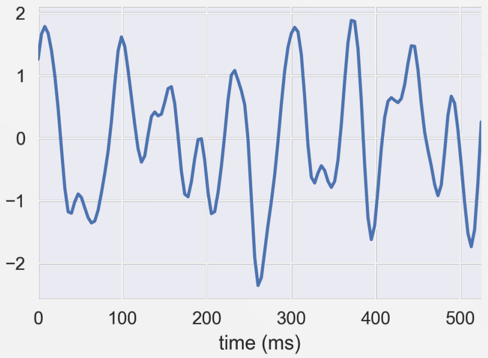
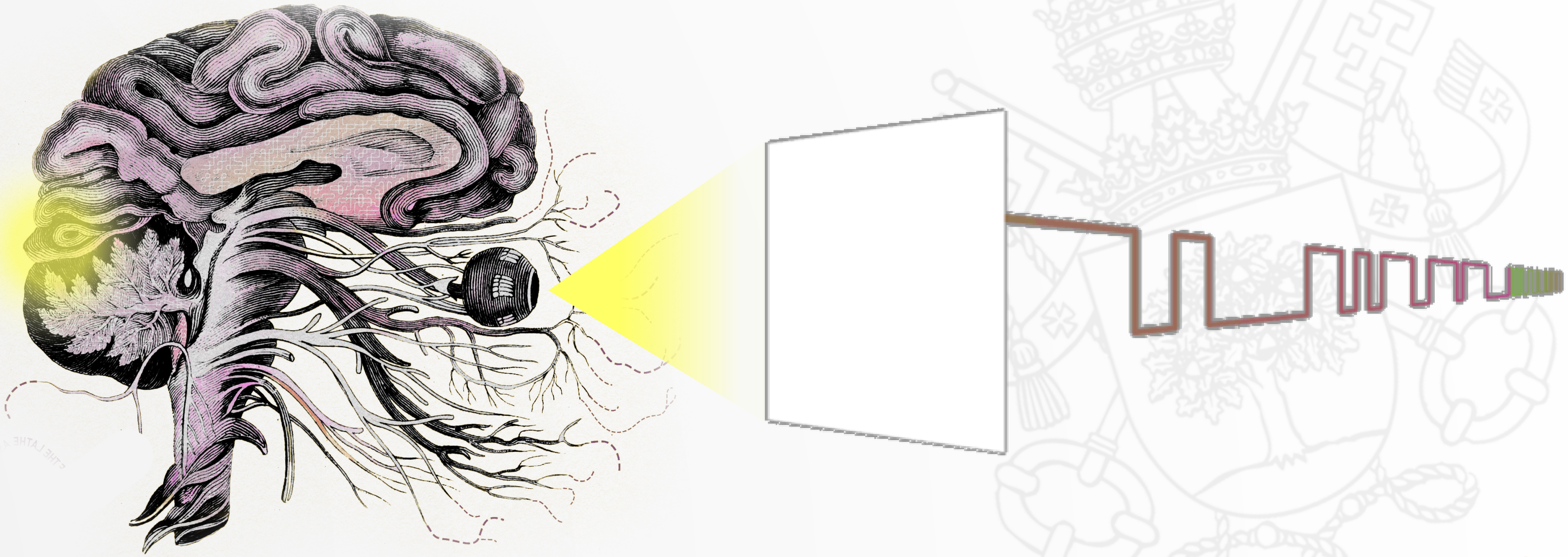
Contents



Introduction

- **Code-modulated visual evoked potentials (c-VEP)**
  - Visual evoked potentials in response to pseudorandom codes
  - Binary codes are usually encoded with black & white flashes
    - Maximal amplitude depth → stronger response at occipital cortex





Introduction

Cons

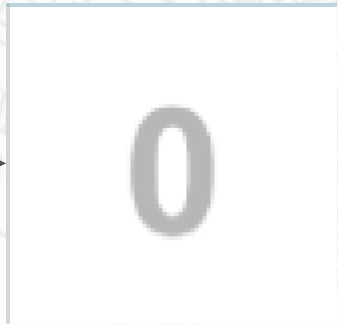
Pros

Eyestrain for some users

High accuracy (>90%)

Brief calibration (~30s)

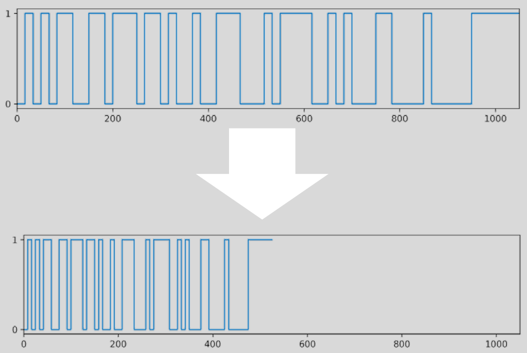
Visual fatigue may be caused by high-contrast stimuli!



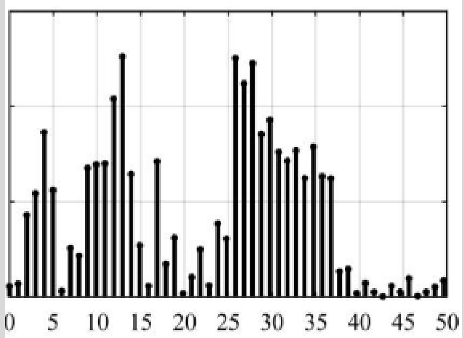
Introduction

- Addressing user convenience in c-VEP-based BCIs

1 Higher stimulation rates



2 High-frequency codes

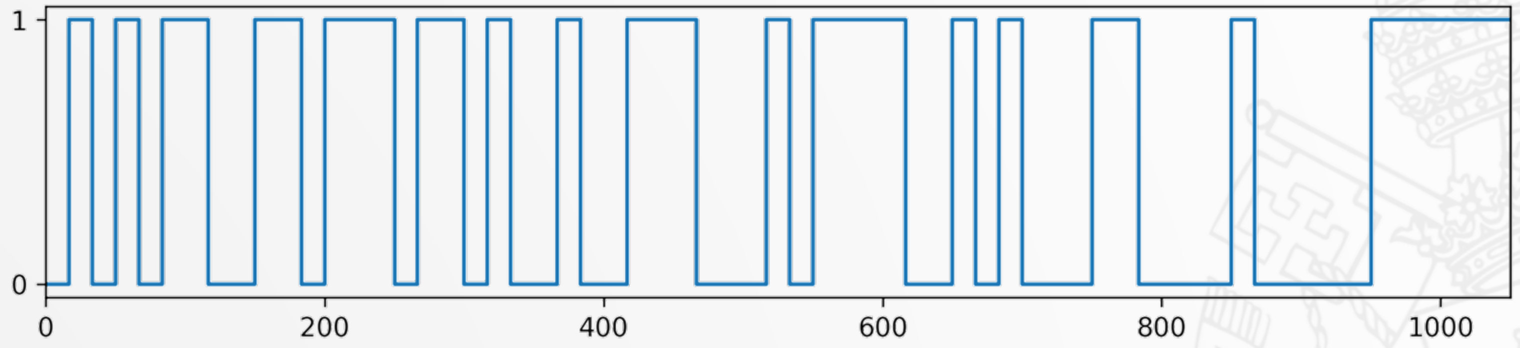


3 Non-binary codes

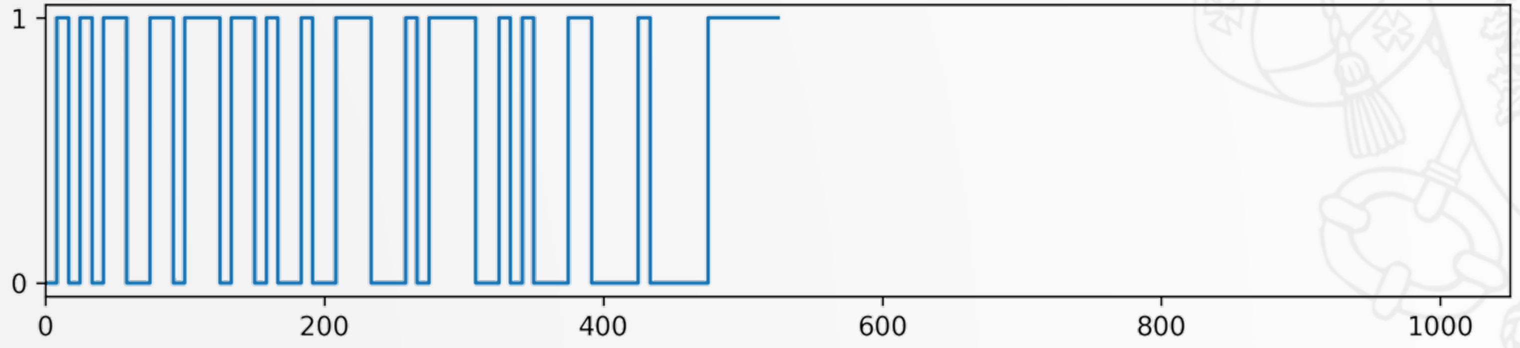
Introduction

- **Addressing user convenience in c-VEP-based BCIs**
  1. Higher stimulation rates
     - Many studies claimed that 120 Hz stimulation is less fatiguing than 60 Hz → 📖 Martínez-Cagigal et al., 2023
     - Although decreases in performance reported for >120 Hz rates (e.g. 240 Hz) → 📖 Gembler et al., 2018

60 Hz

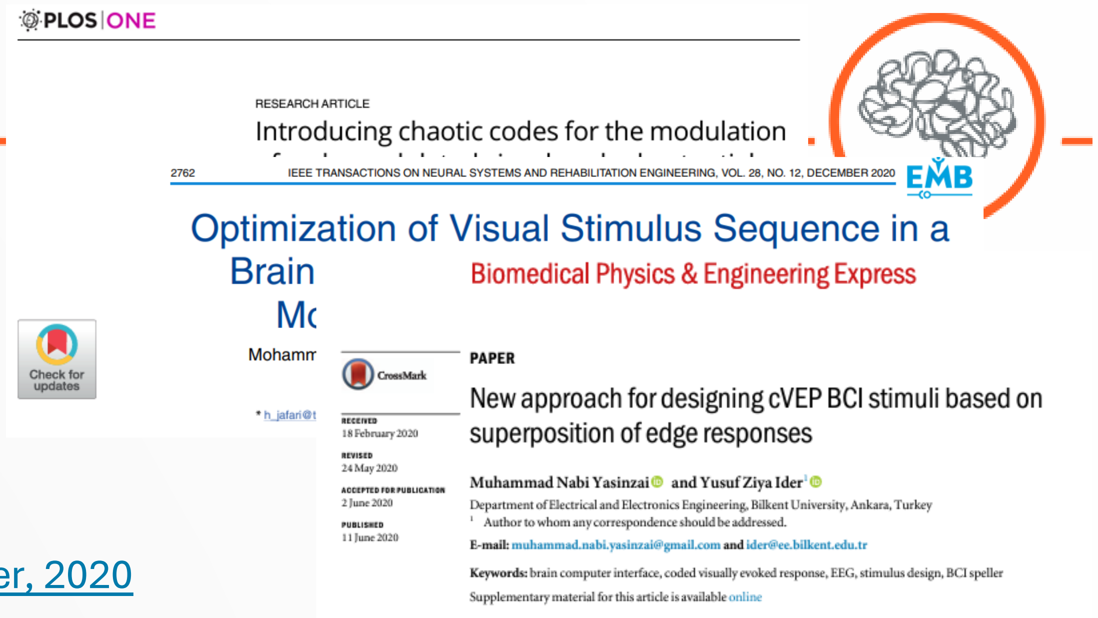


120 Hz



Introduction

- **Addressing user convenience in c-VEP-based BCIs**
    2. High-frequency codes
        - Chaotic codes → 📖 Shirzhiyan et al., 2019
        - Optimum sequences → 📖 Behboodi et al., 2020
        - Superposition optimized pulses → 📖 Yasinzai & Ider, 2020


PLOS ONE

RESEARCH ARTICLE

Introducing chaotic codes for the modulation

Check for updates

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Optimization of Visual Stimulus Sequence in a Brain Mc

Mohamm

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Biomedical Physics & Engineering Express

CrossMark

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PAPER

New approach for designing cVEP BCI stimuli based on superposition of edge responses

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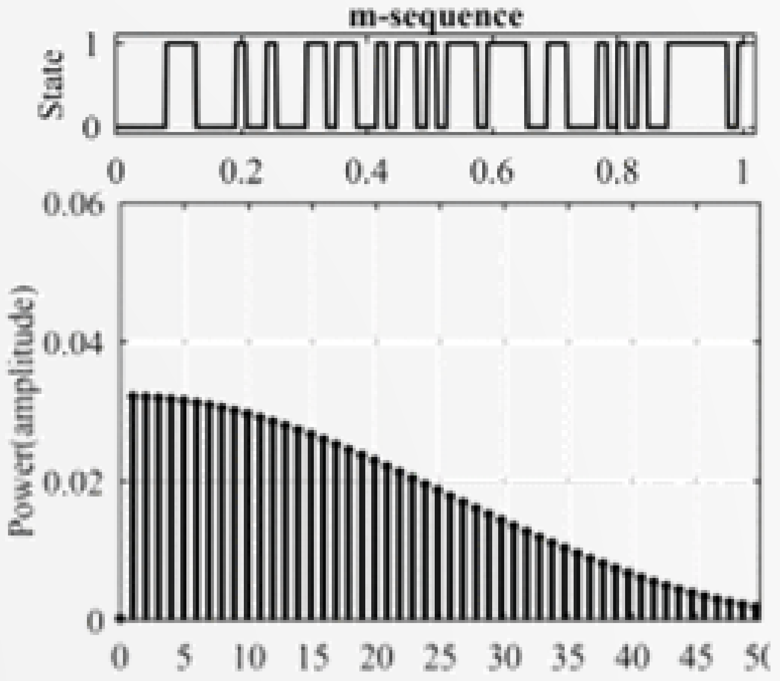
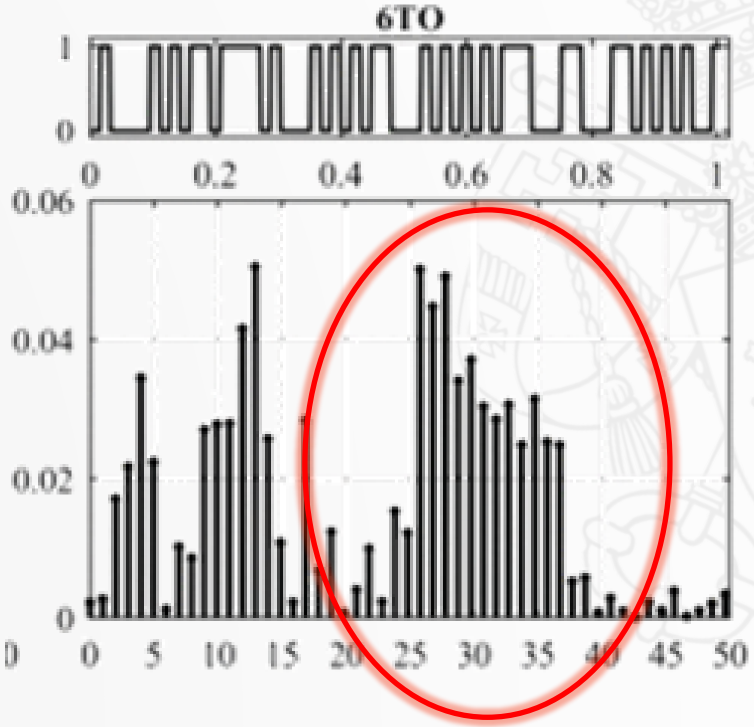
Keywords: brain computer interface, coded visually evoked response, EEG, stimulus design, BCI speller

Supplementary material for this article is available online

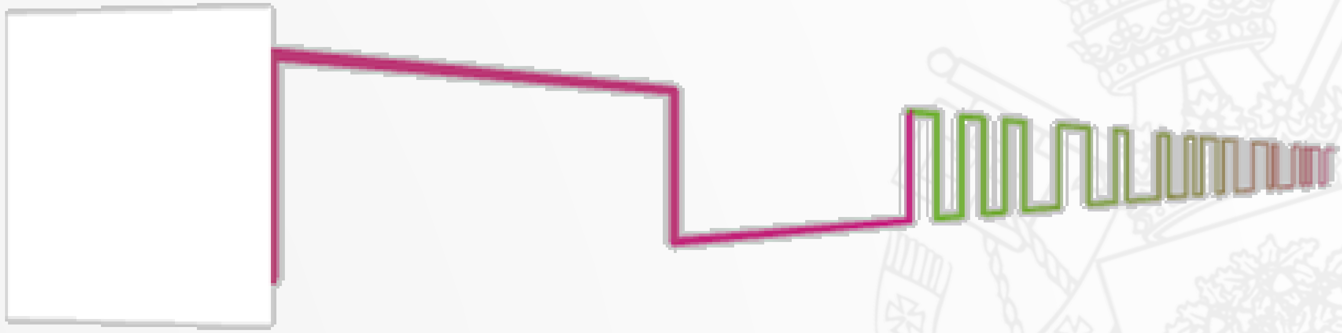




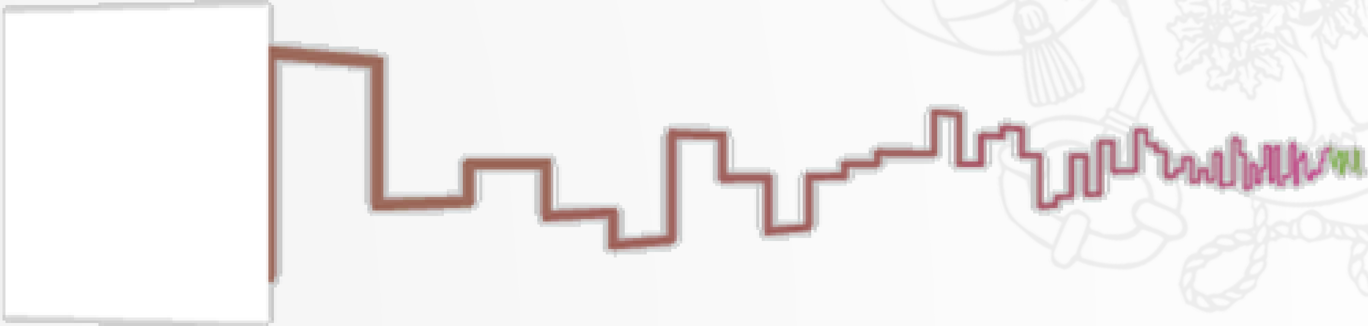
Introduction

- **Addressing user convenience in c-VEP-based BCIs**
  3. Non-binary codes
     - I.e., codes with more levels than just 0 and 1
     - We can encode them with different shades of gray and colors to reduce amplitude depth
     - Demonstrated to be more comfortable than binary codes → Martínez-Cagigal et al., 2023

Binary (base 2)

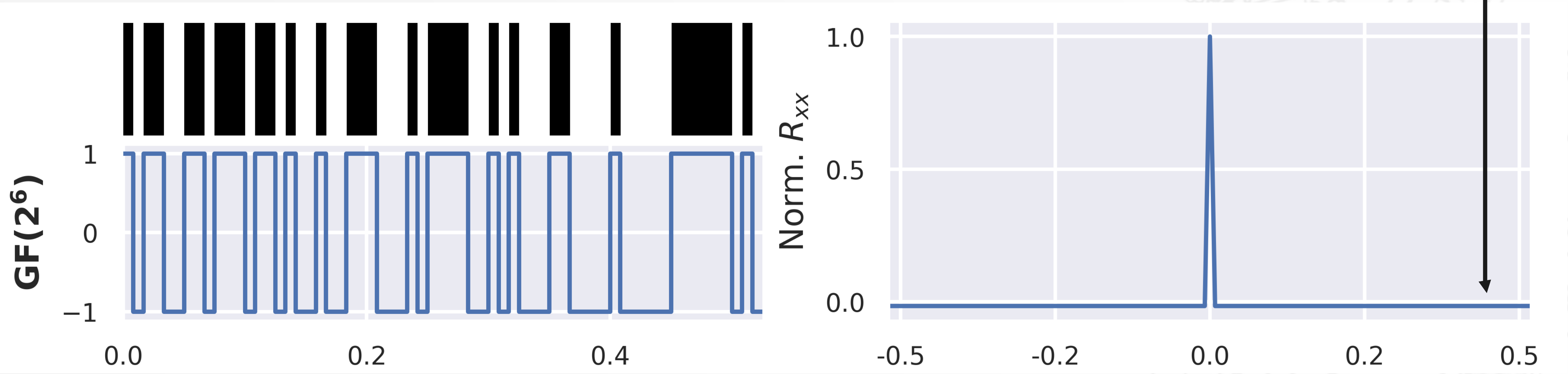


11-ary (base 11)



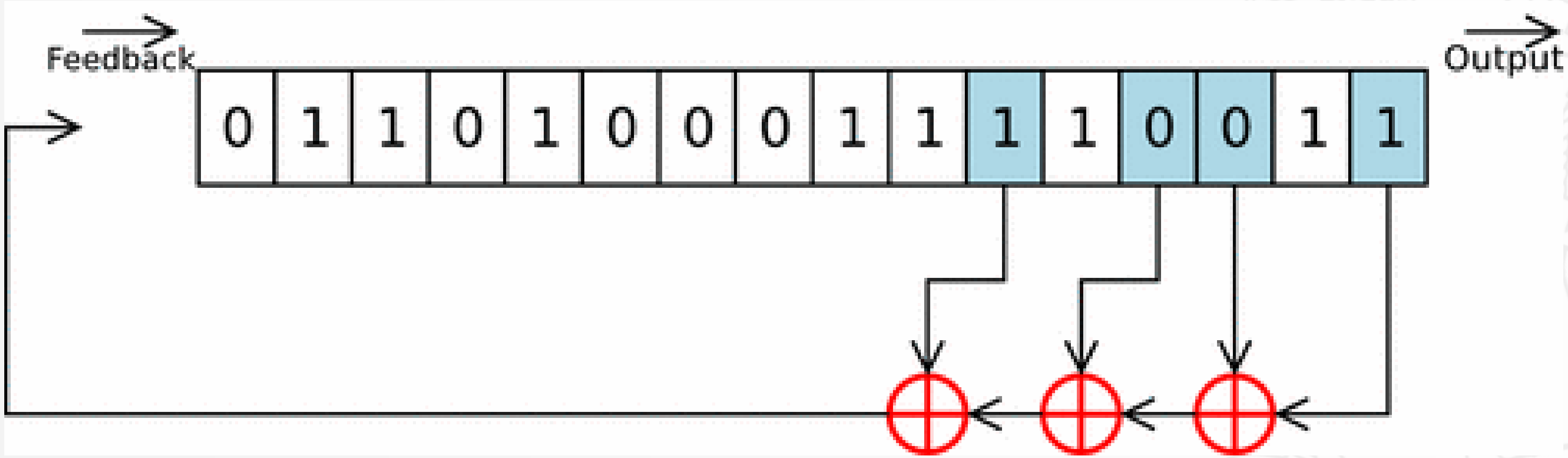
Maximal-length Sequences

- **What are maximal-length sequences (m-sequences)?**
  - Pseudorandom periodic time series
  - With optimal autocorrelation profiles
    - For binary codes, -1/N for any shift different than 0



Maximal-length Sequences

- **Linear Feedback Shift Registers (LFSR)**
  - Shift registers that compute new values using a linear function of the immediate previous state
  - The code is generated by appending the output to the initial position of the state



Maximal-Length Sequences

- **Generation of *p*-ary m-sequences**
  - The length of the output code depends on:

$$L = p^r - 1$$

Length

Base

Polynomial order

  - Notation:

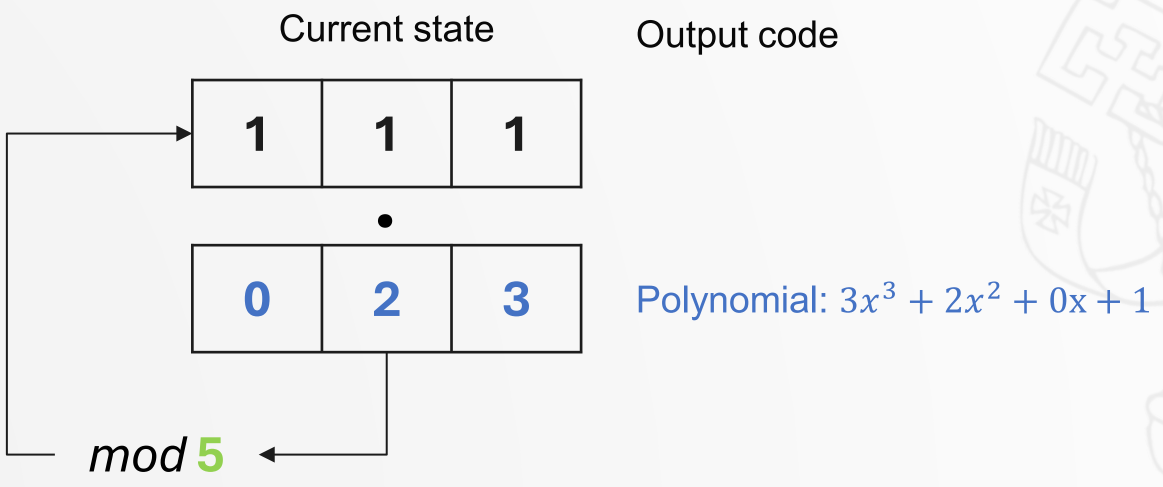
$$\mathrm{GF}(p^r) \longrightarrow \text{For } \mathrm{GF}(2^6),\ L = 63 \text{ bits}$$

  - Requirement: using primitive polynomials over Galois Field $\mathrm{GF}(p^r)$
    1. Only bases where p is prime are allowed (e.g., 2, 3, 5, 7, 11...)
    2. The codes are fixed in length (i.e., $L = p^r - 1$)

Maximal-Length Sequences

- **Generation of *p*-ary m-sequences**
  - Each bit is calculated by:
    1. Applying matrix product between the current state and the polynomial
    2. Then applying the modulo p operation
  - Example for base 5 → $\mathrm{GF}(5^3)$

Base	Order	Length	Polynomial
5	3	124 bits	$3x^3 + 2x^2 + 1$



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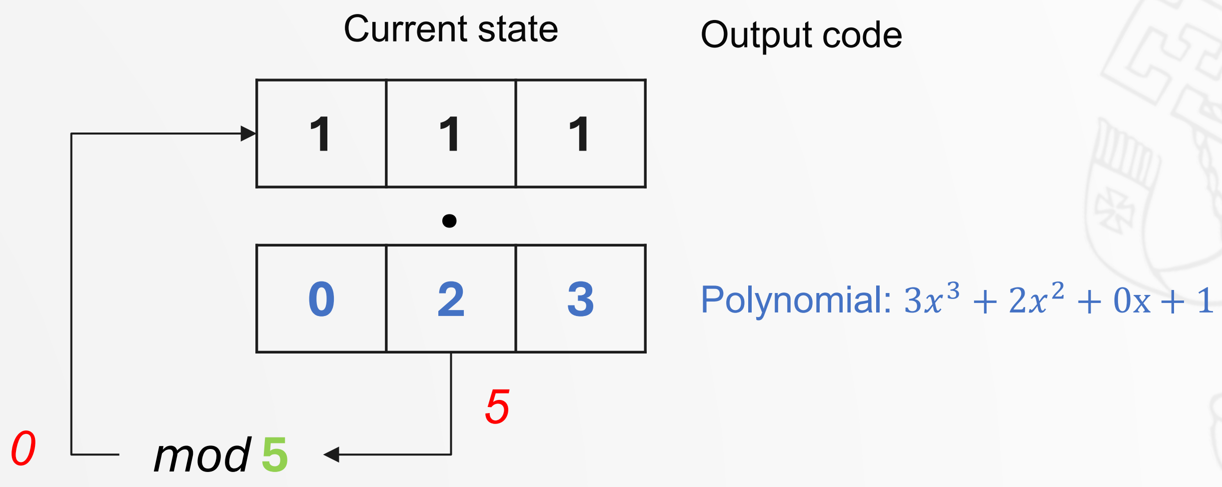

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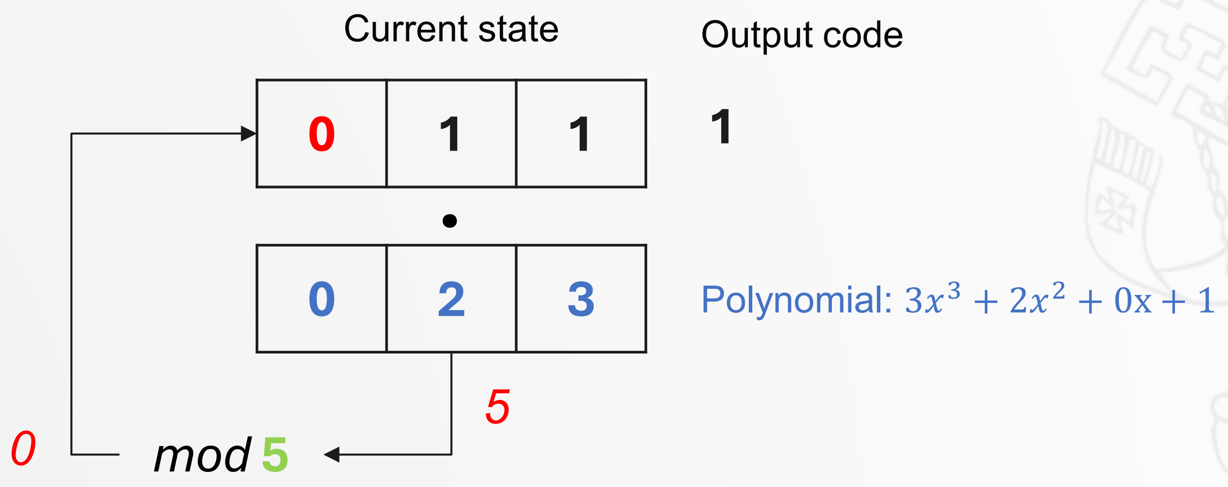

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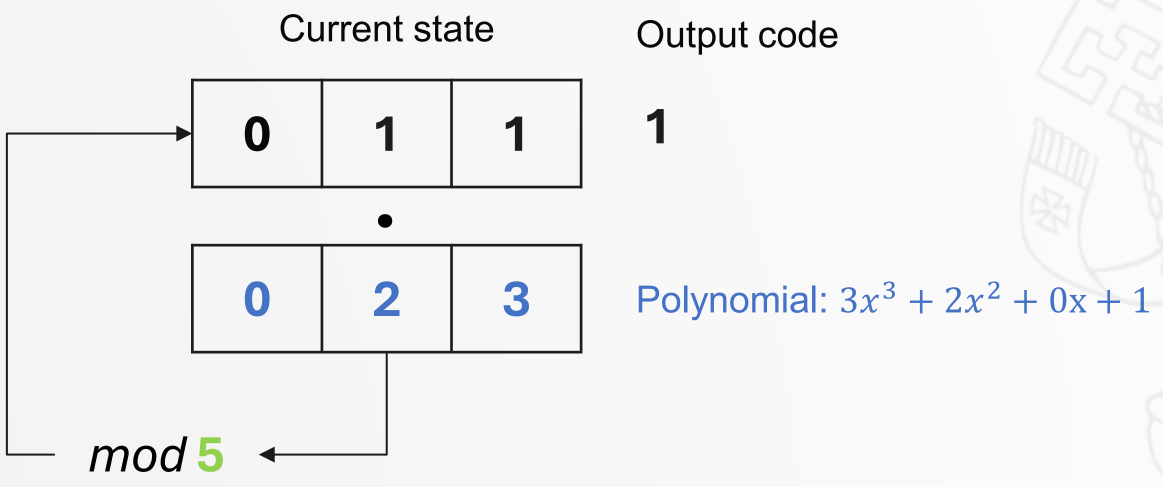

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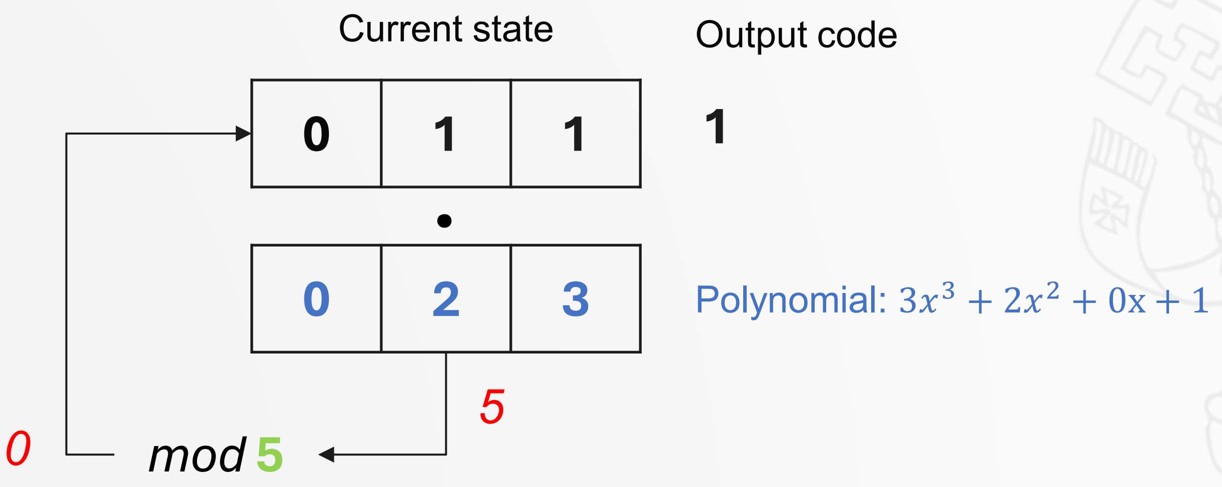

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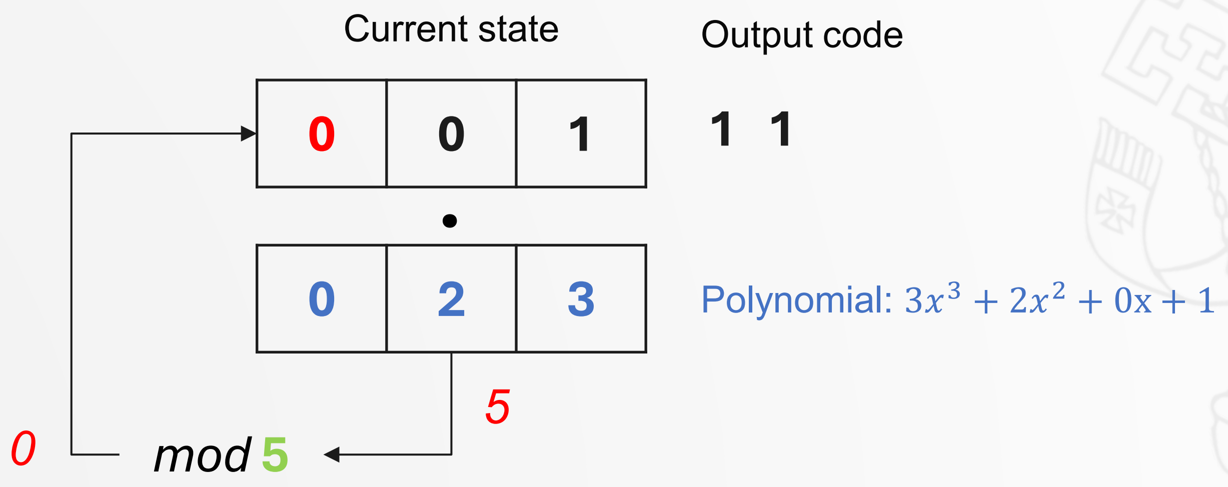

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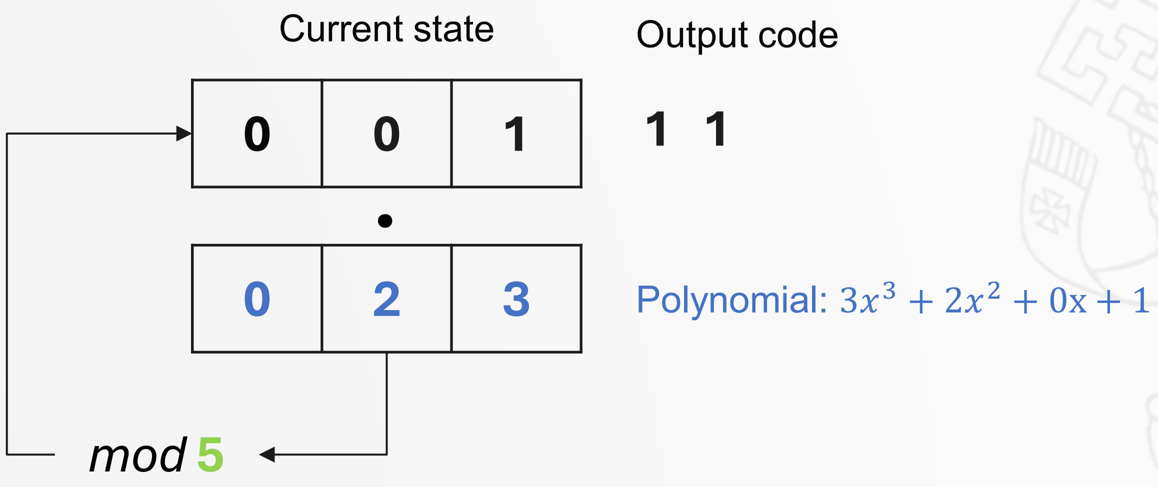

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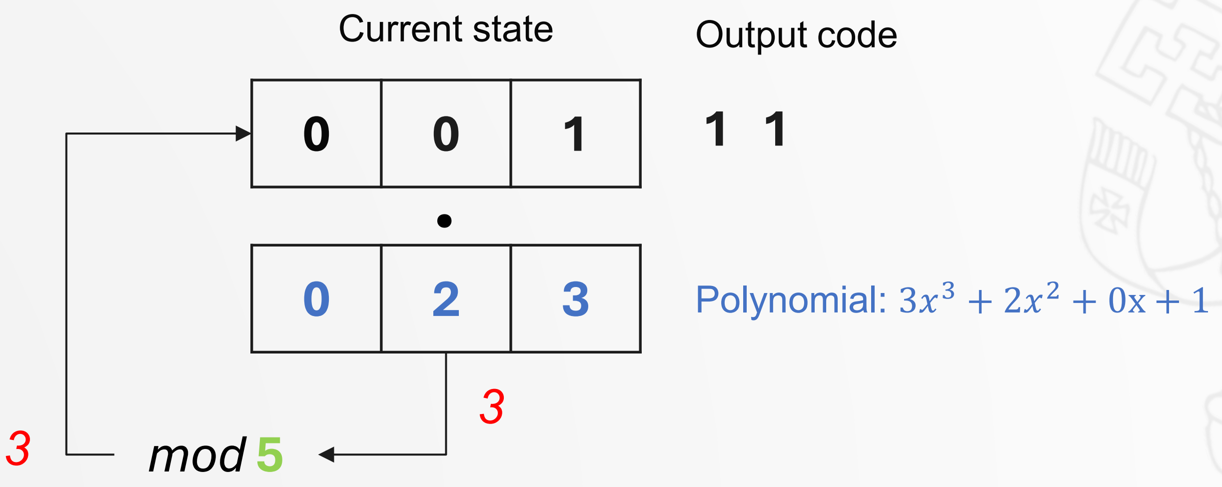

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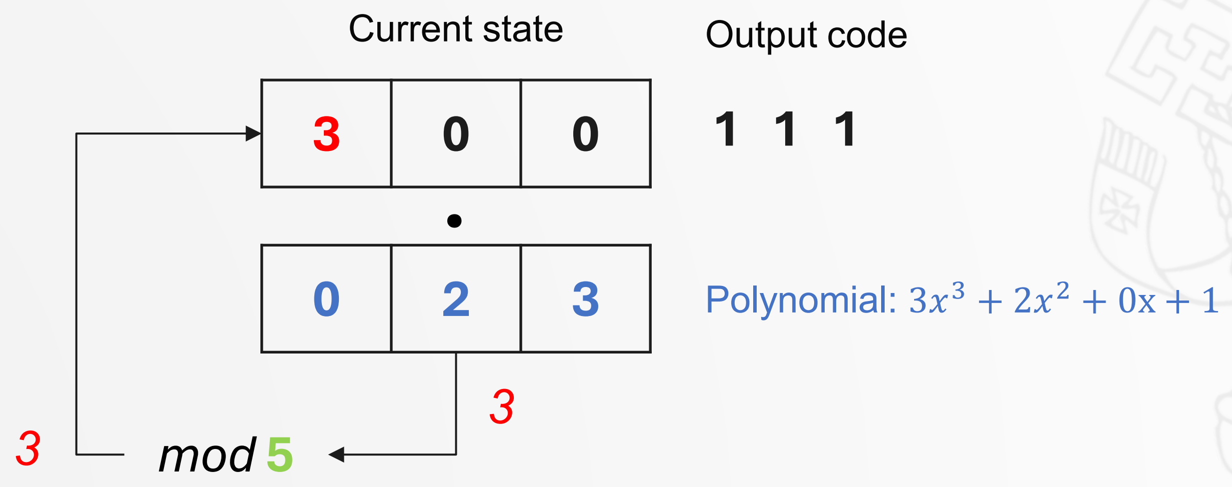
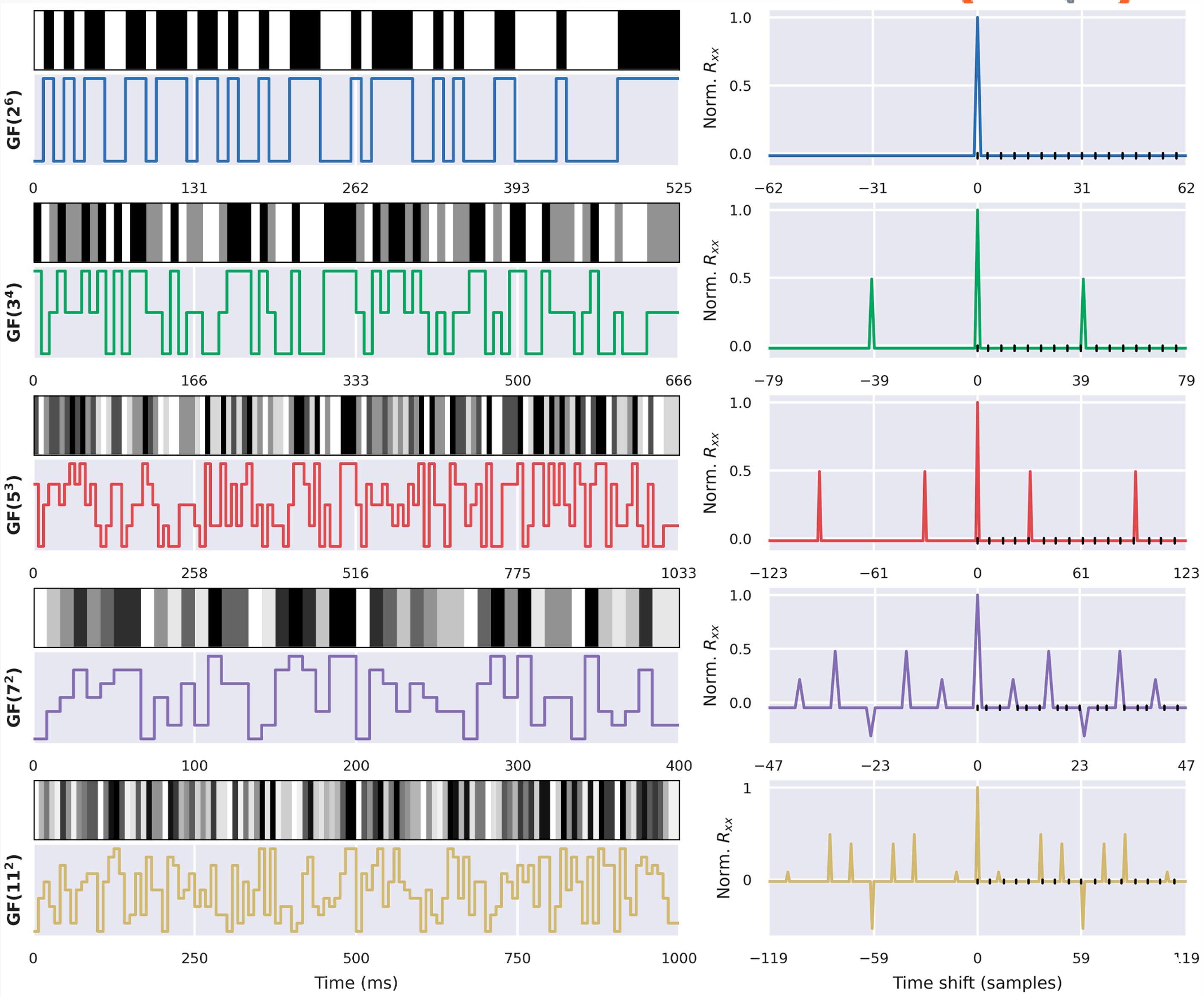
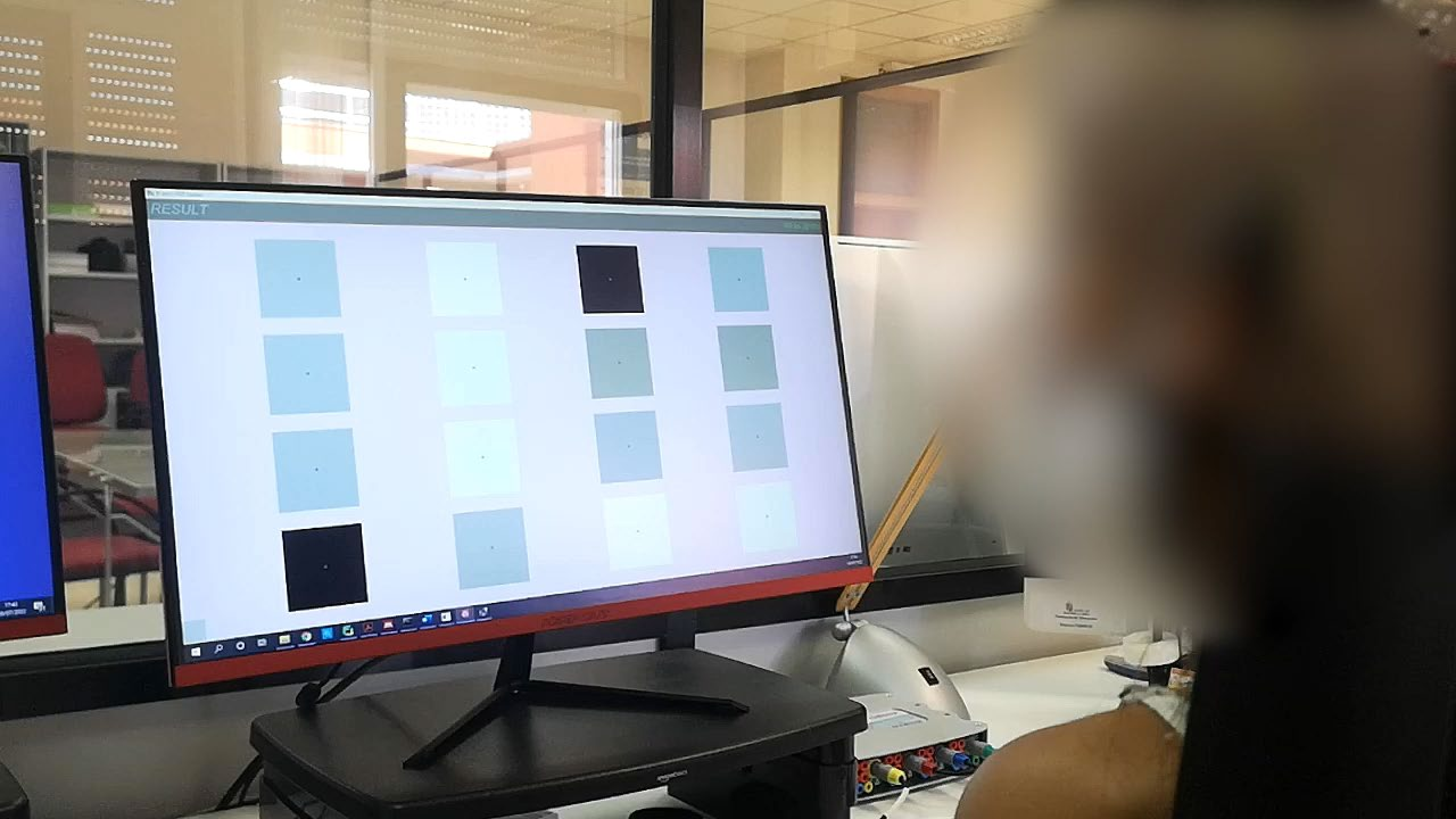


Correlation local maxima



Generation details of the p-ary m-sequences.

	Base	Order	Length (bits)	Polynomial	Duration (s/cycle) 120 Hz	Duration (s/cycle) 60 Hz
GF(2^6)	2	6	63	$x^6 + x^5 + 1$	0.525	1.050
GF(3^4)	3	4	80	$x^4 + 2x^3 + 1$	0.667	1.333
GF(5^3)	5	3	124	$3x^3 + 2x^2 + 1$	1.033	2.067
GF(7^2)	7	2	48	$4x^2 + 1$	0.408	0.800
GF(11^2)	11	2	120	$3x^2 + x + 1$	1.000	2.000


RESULT

Evidence of benefits of non-binary codes

Expert Systems With Applications 232 (2023) 120815

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journal homepage: www.elsevier.com/locate/eswa

ELSEVIER

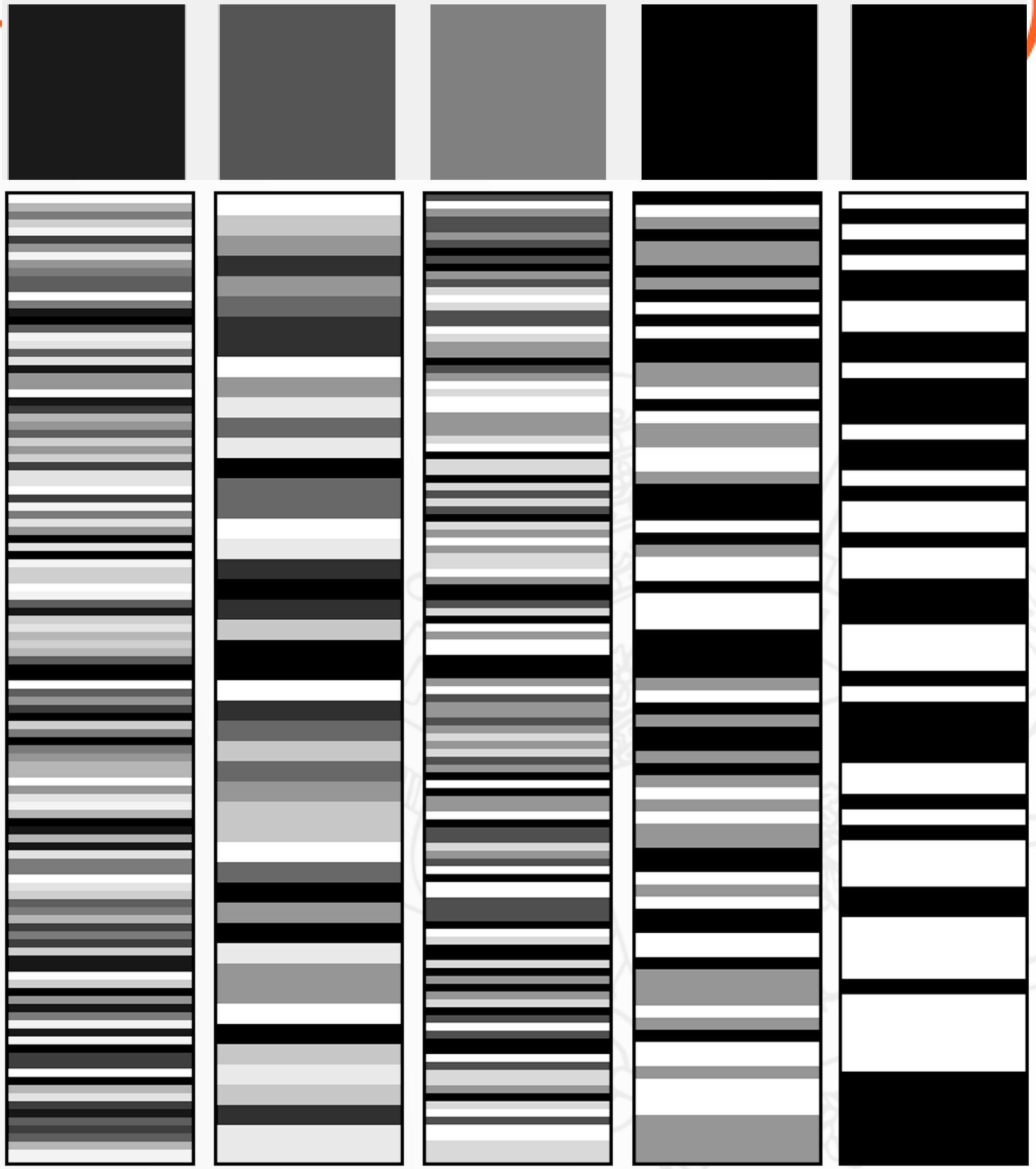
Non-binary m-sequences for more comfortable brain–computer interfaces based on c-VEPs

Víctor Martínez-Cagigal [a,b,*], Eduardo Santamaría-Vázquez [a,b], Sergio Pérez-Velasco [a,b], Diego Marcos-Martínez [a,b], Selene Moreno-Calderón [a], Roberto Hornero [a,b]

SCAN ME

Evidence of benefits of non-binary codes

- **Our study**
  - Five different *p*-ary m-sequences (bases 2, 3, 5, 7 and 11)
  - Reference signal processing (📖 Martínez-Cagigal et al., 2021)
  - Equipment
    - g.USBamp with 16 active channels
    - MEDUSA© software (www.medusabci.com)
  - Experimental protocol
    - 15 healthy subjects (28.80 ± 5.02 years)
    - Calibration: 300 cycles for each sequence
    - Online: 32 trials (10 cycles/trial)
    - Command matrix of 4×4 dimensions



Evidence of benefits of non-binary codes

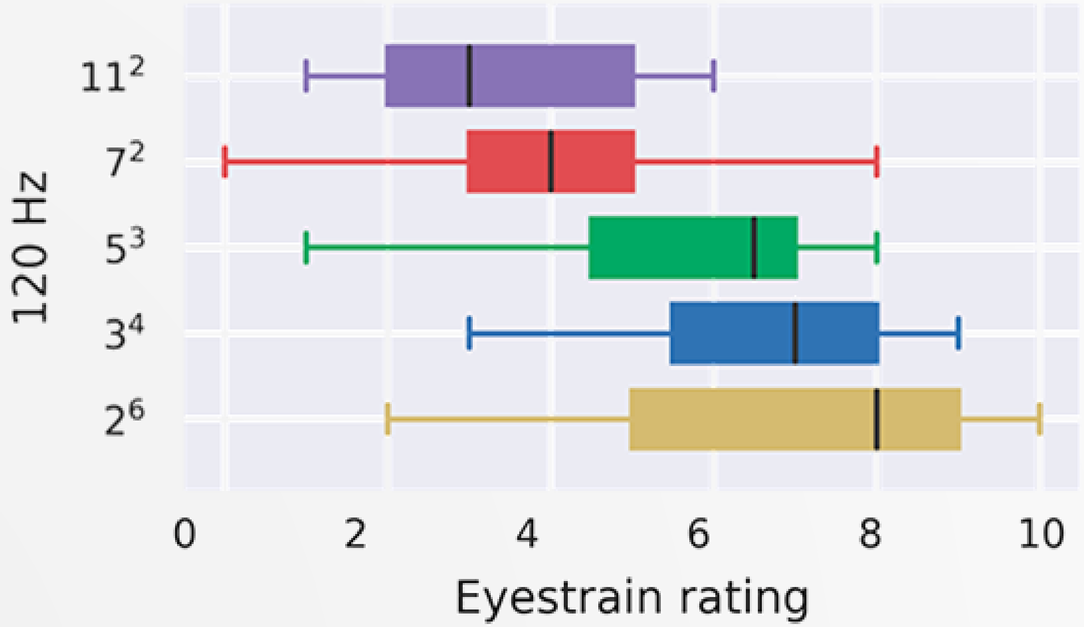
- **Performance analysis**
  - Users were able to reach more than 98% grand-averaged accuracy with 10 cycles using all the proposed p-ary m-sequences

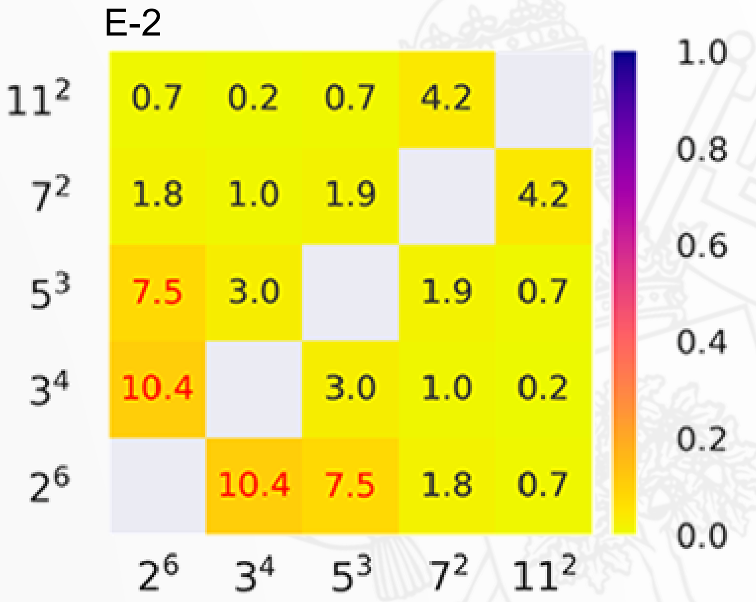
Grand-averaged online results across users.

	No. cycles	1	2	3	4	5	6	7	8	9	10	Mean ± STD
GF(2^6)	Accuracy (%)	65.43	90.43	96.68	98.05	**99.41**	**99.41**	**99.61**	**99.61**	**99.41**	**99.61**	94.77 ± 10.14
	ITR (bpm)	208.06	188.03	141.04	108.91	90.14	75.11	64.65	56.57	50.08	45.25	102.78 ± 55.19
	Duration (s)	0.53	1.05	1.58	2.10	2.62	3.15	3.68	4.20	4.73	5.25	2.89 ± 1.51
GF(3^4)	Accuracy (%)	75.78	92.77	97.27	97.66	98.44	98.83	99.02	99.02	99.02	99.22	95.70 ± 6.89
	ITR (bpm)	216.59	154.70	113.27	85.68	69.67	58.54	50.31	44.02	39.13	35.36	86.73 ± 55.97
	Duration (s)	0.67	1.33	2.00	2.67	3.33	4.00	4.67	5.33	6.00	6.67	3.67 ± 1.91
GF(5^3)	Accuracy (%)	83.20	94.14	**98.05**	**98.83**	99.02	99.22	99.41	99.41	99.22	99.22	96.97 ± 4.83
	ITR (bpm)	163.72	103.05	74.01	56.54	45.47	38.02	32.76	28.66	25.39	22.85	59.05 ± 42.20
	Duration (s)	1.03	2.07	3.10	4.13	5.17	6.20	7.23	8.27	9.30	10.33	5.68 ± 2.97
GF(7^2)	Accuracy (%)	49.80	82.23	93.36	95.90	97.27	97.46	98.05	97.66	98.24	98.05	90.80 ± 14.42
	ITR (bpm)	168.14	205.30	174.38	137.45	113.43	95.18	82.46	71.65	64.31	57.72	117.00 ± 49.15
	Duration (s)	0.40	0.80	1.20	1.60	2.00	2.40	2.80	3.20	3.60	4.00	2.20 ± 1.15
GF(11^2)	Accuracy (%)	**86.72**	**97.46**	**98.05**	98.63	98.83	98.63	98.63	98.63	98.63	98.44	**97.27** ± 3.54
	ITR (bpm)	179.64	113.79	76.79	58.36	46.93	38.99	33.42	29.24	25.99	23.33	62.65 ± 47.10
	Duration (s)	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	5.50 ± 2.87

Evidence of benefits of non-binary codes

- **Eyestrain analysis**
  - The higher the base (i.e., number of levels), the less eyestrain users perceive
    - E.g., GF(7^2) and GF(11^2) are significantly less fatiguing than binary GF(2^6)

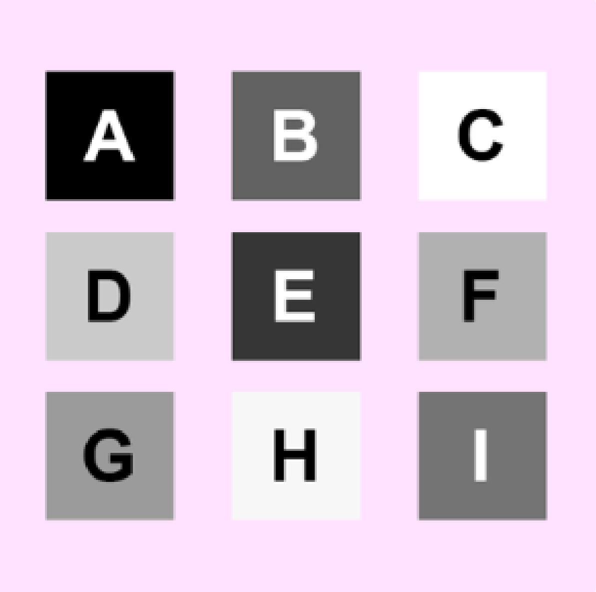




Black: significant differences (p-value < 0.05)
Red: no differences (p-value > 0.05)

Open-source software for non-binary codes

www.medusabci.com



vicmarcag

P-ary c-VEP Speller

A circular-shifting c-VEP speller that supports non-binary m-sequences

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Any questions?

9th Graz Brain-Computer Interface Conference

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GRAZ BCI

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