MEDUSA©: An Innovative Software Ecosystem to Accelerate BCI and Cognitive Neuroscience Experimentation

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MEDUSA www.medusabci.com

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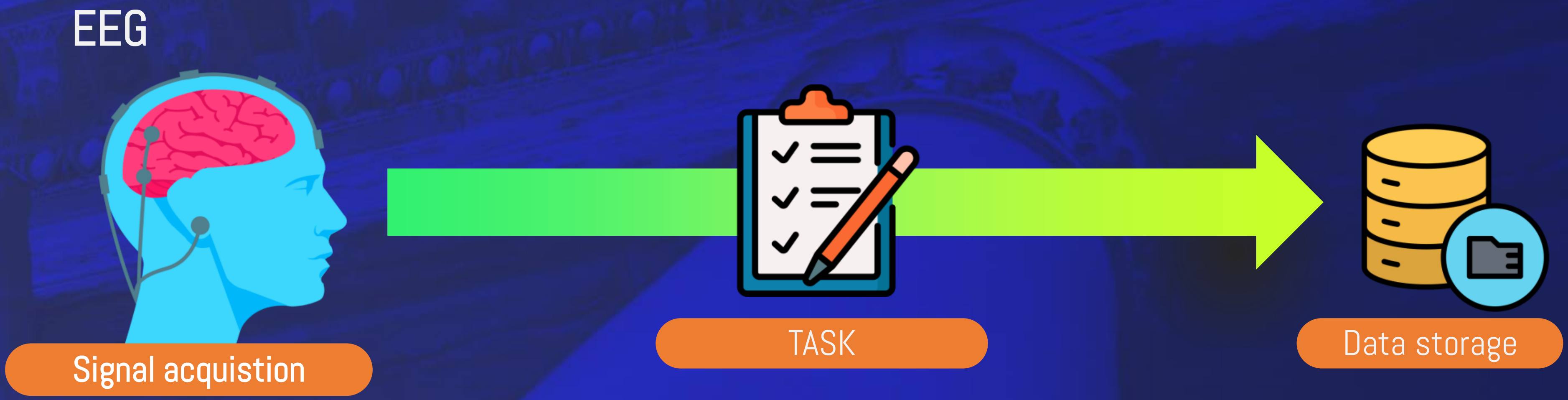
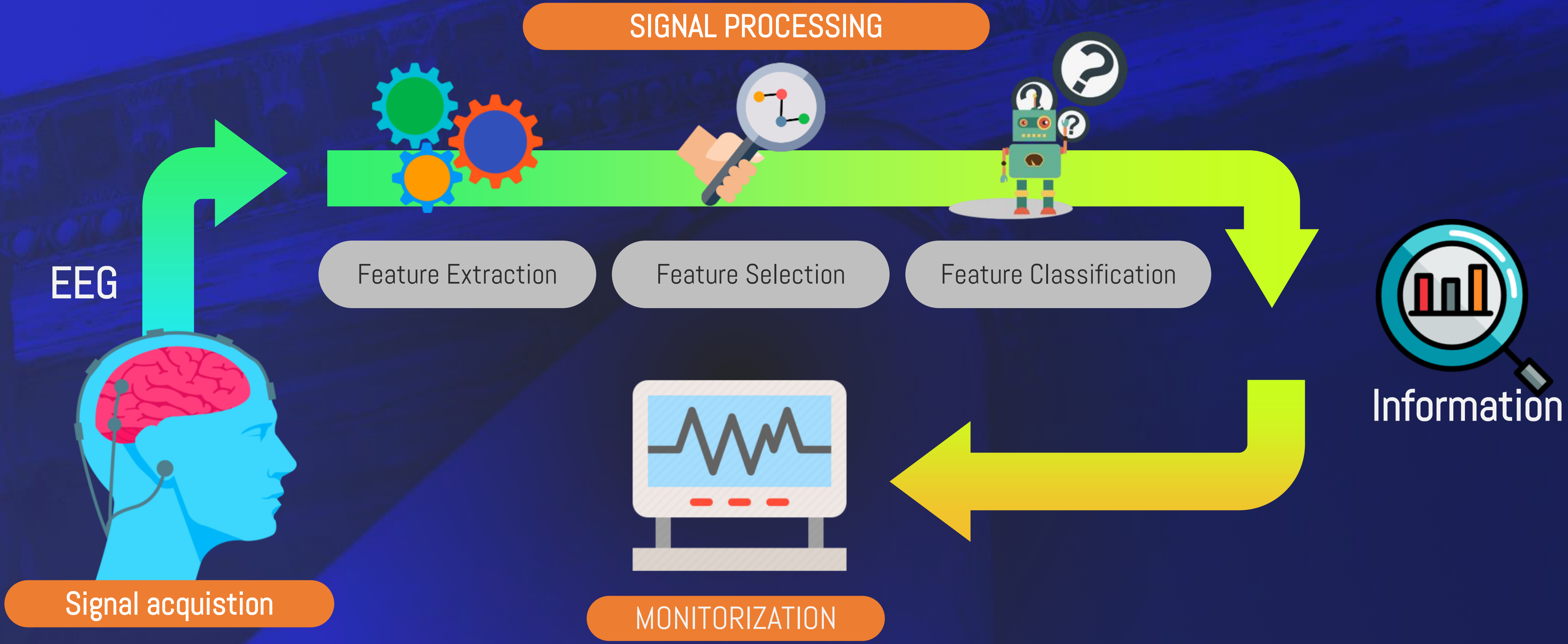
BCI experiments

BCI experiments
Recording experiments

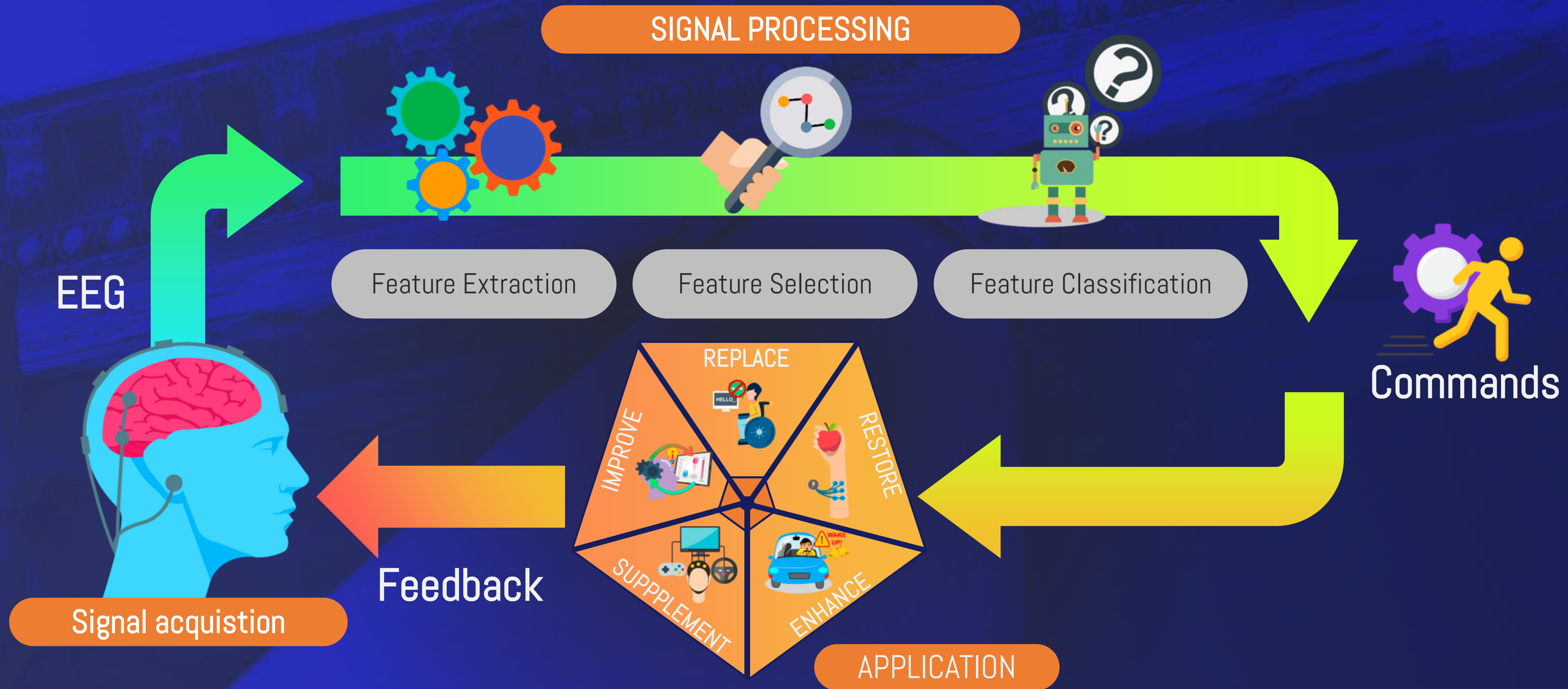


BCI experiments

Passive BCIs



BCI experiments
Active BCIs



BCI experiments

Development of a BCI experiment

Data acquisition → Signal processing → Application

Data acquisition

- Real-time acquisition of data streams
- Synchronization between streams
- Real-time visualization

Signal processing

- Basic functions: frequency and spatial filters
- Advanced functions: artifact rejection, neural decoding
- Real-time application

Application

- High-performance graphical applications
- Challenges of game engines: integration with signal processing, synchronization

BCI software

BCI software

What is a BCI platform?

- Software designed to facilitate BCI experimentation
  - Built-in signal acquisition tools
  - Real-time analysis functions
  - Ready-to-use BCI experiments
- Advantages of using a BCI platform:
  - Accelerates experiment implementation
  - Reduces development costs
  - Improves results
  - Enables the participation of non-technical researchers

BCI software

BCI software platforms

- Signal analysis toolboxes:
  - EEGLAB
  - BrainStorm
  - MNE
- Open-source BCI platforms:
  - Most known: BCI2000, OpenVibe
  - No longer mantained: BF++, xBCI, Pyff
  - New approaches: Timeflux, Dareplane

BCI software

Current challenges

Limitations

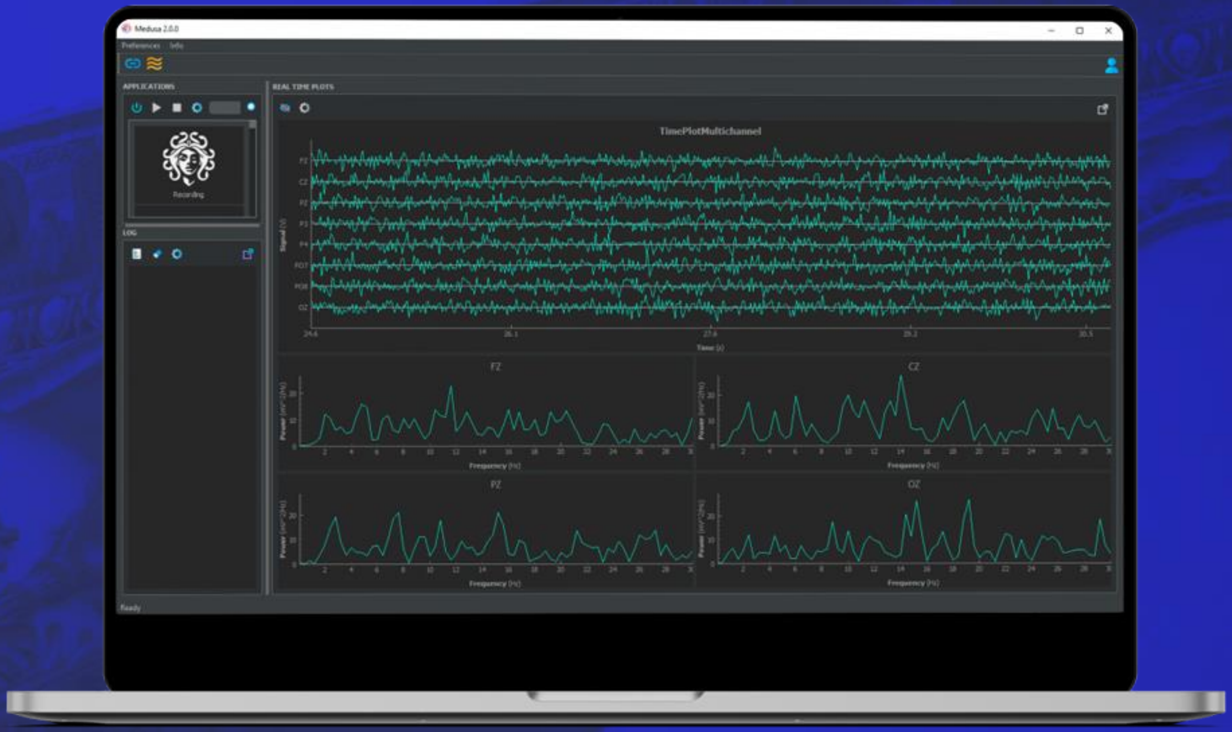
- Limited compatibility with hardware
- Complex implementations
- Fail to keep up with the latest developments
- Lack specific tools for community contributions
- Difficult to use

Consequences

- Repetitive experiments with the same databases
- Limited development of novel ideas
- Barrier to interdisciplinary collaboration, especially non-technical researchers
- Lack of reproducibility of results

BCI software

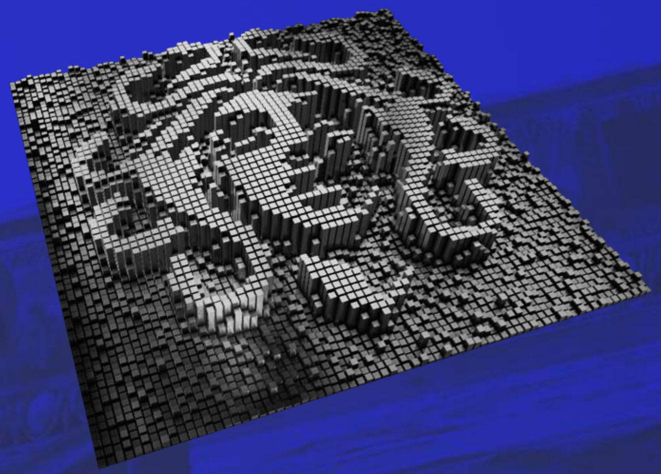
MEDUSA© ecosystem

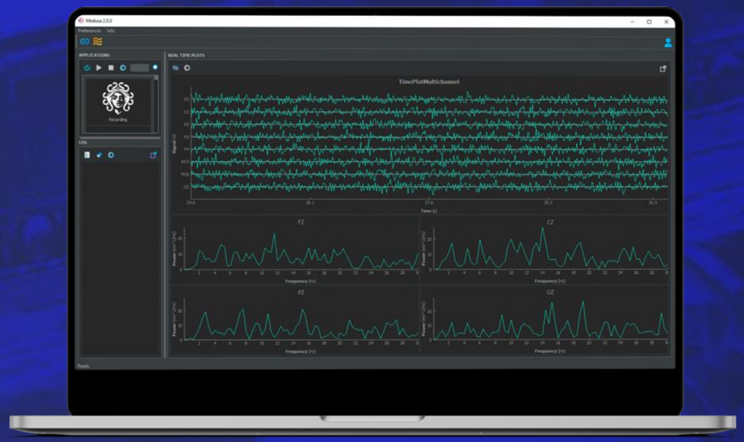


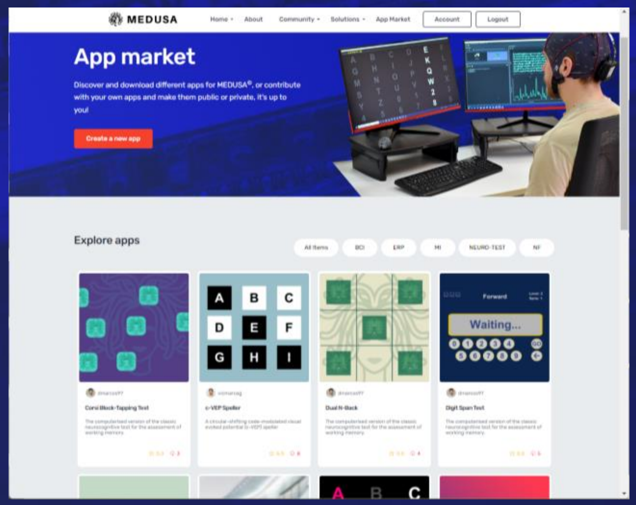
- Open-source
- Broad hardware compatibility through LSL
- Modular, scalable and flexible design
- Python-based signal processing
- Unity-based graphical user interface
- Comprehensive suite of BCI experiments
- Specific tools to develop and share applications through the app market

BCI software

MEDUSA© ecosystem







MEDUSA© Kernel

An independent PyPI package containing all the necessary functions to record and process biosignals, especially EEG

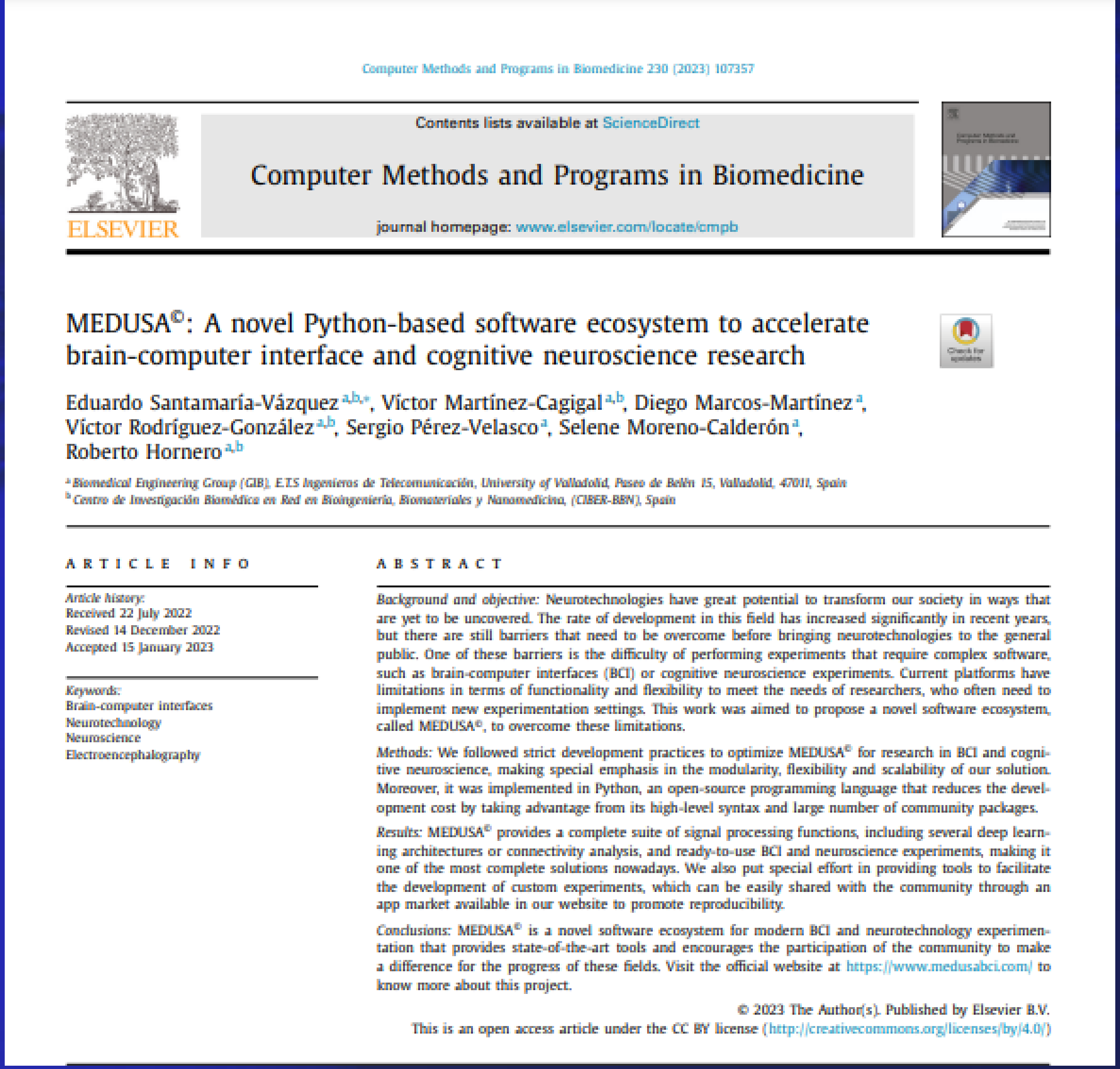
MEDUSA© Platform

A BCI platform that provides real-time visualization of biosignals and implements functions to perform real-time BCI experiments.

Website

Discover and download different apps for MEDUSA in the market, create your own apps and browse the documentation.

Eduardo Santamaría-Vázquez, Víctor Martínez-Cagigal, Diego Marcos-Martínez, Víctor Rodríguez-González, Sergio Pérez-Velasco, Selene Moreno-Calderón, Roberto Hornero, **MEDUSA©: A novel Python-based software ecosystem to accelerate brain-computer interface and cognitive neuroscience research**. Computer Methods and Programs in Biomedicine, 2023,
DOI: doi.org/10.1016/j.cmpb.2023.107357


Computer Methods and Programs in Biomedicine 230 (2023) 107357

Contents lists available at ScienceDirect

Computer Methods and Programs in Biomedicine

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

MEDUSA©: A novel Python-based software ecosystem to accelerate brain-computer interface and cognitive neuroscience research

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ARTICLE INFO

Article history:
Received 22 July 2022
Revised 14 December 2022
Accepted 15 January 2023

Keywords:
Brain-computer interfaces
Neurotechnology
Neuroscience
Electroencephalography

ABSTRACT

Background and objective: Neurotechnologies have great potential to transform our society in ways that are yet to be uncovered. The rate of development in this field has increased significantly in recent years, but there are still barriers that need to be overcome before bringing neurotechnologies to the general public. One of these barriers is the difficulty of performing experiments that require complex software, such as brain-computer interfaces (BCI) or cognitive neuroscience experiments. Current platforms have limitations in terms of functionality and flexibility to meet the needs of researchers, who often need to implement new experimentation settings. This work was aimed to propose a novel software ecosystem, called MEDUSA©, to overcome these limitations.

Methods: We followed strict development practices to optimize MEDUSA© for research in BCI and cognitive neuroscience, making special emphasis in the modularity, flexibility and scalability of our solution. Moreover, it was implemented in Python, an open-source programming language that reduces the development cost by taking advantage from its high-level syntax and large number of community packages.

Results: MEDUSA© provides a complete suite of signal processing functions, including several deep learning architectures or connectivity analysis, and ready-to-use BCI and neuroscience experiments, making it one of the most complete solutions nowadays. We also put special effort in providing tools to facilitate the development of custom experiments, which can be easily shared with the community through an app market available in our website to promote reproducibility.

Conclusions: MEDUSA© is a novel software ecosystem for modern BCI and neurotechnology experimentation that provides state-of-the-art tools and encourages the participation of the community to make a difference for the progress of these fields. Visit the official website at https://www.medusabci.com/ to know more about this project.

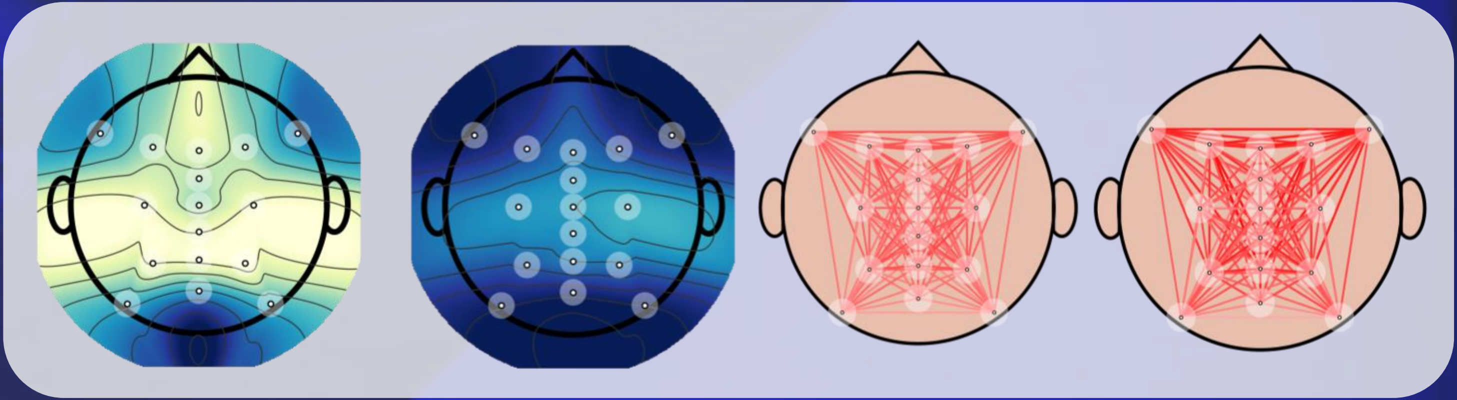
MEDUSA www.medusabci.com

MEDUSA© Kernel

MEDUSA© Kernel

EEG analysis

- Basic functions: Frequency and spatial filtering, transforms
- Local activation metrics: Spectral analysis, entropies, complexity
- Connectivity & network metrics: AEC, IAC, PLV, PLI, wPLI
- Pattern recognition models: Bindings for sklearn, EEG-Inception, EEGSym
- Visualization



SciPy

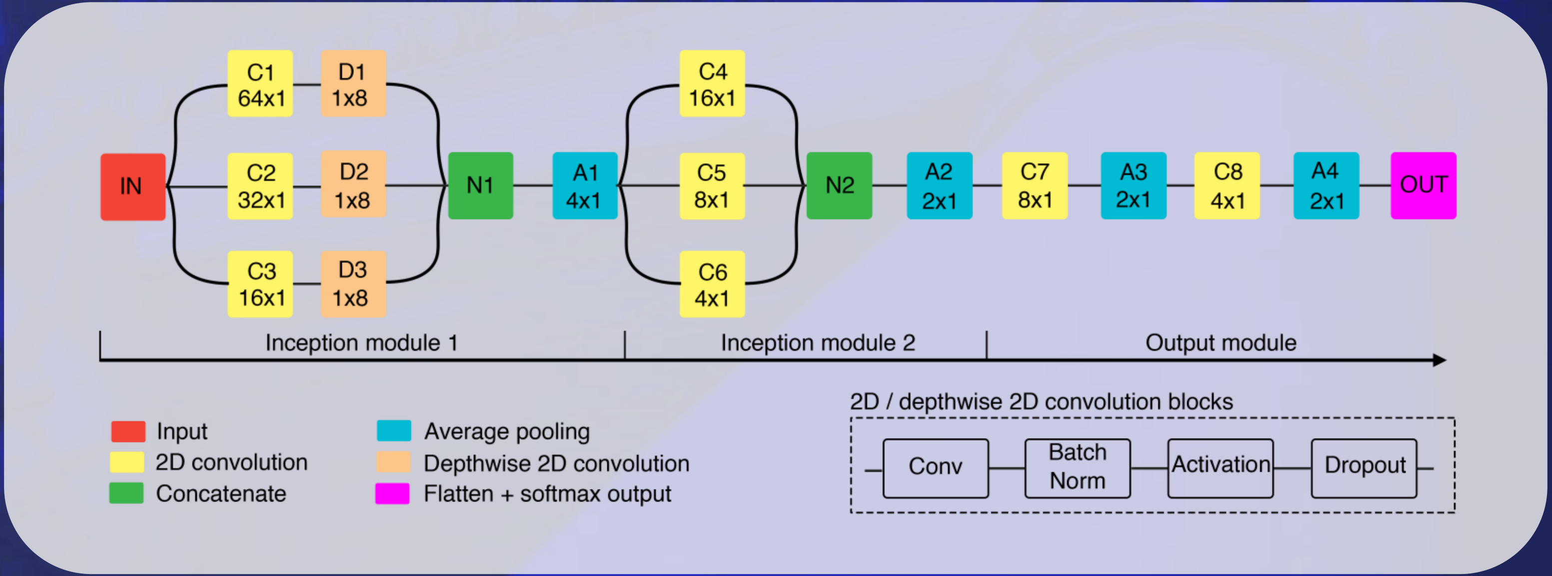
NumPy

matplotlib

MEDUSA© Kernel

EEG decoding

- High-level BCI models: Neurofeedback, motor imagery, ERP-based spellers, c-VEP-based spellers



MEDUSA© Platform

MEDUSA© Platform

Main functionalities

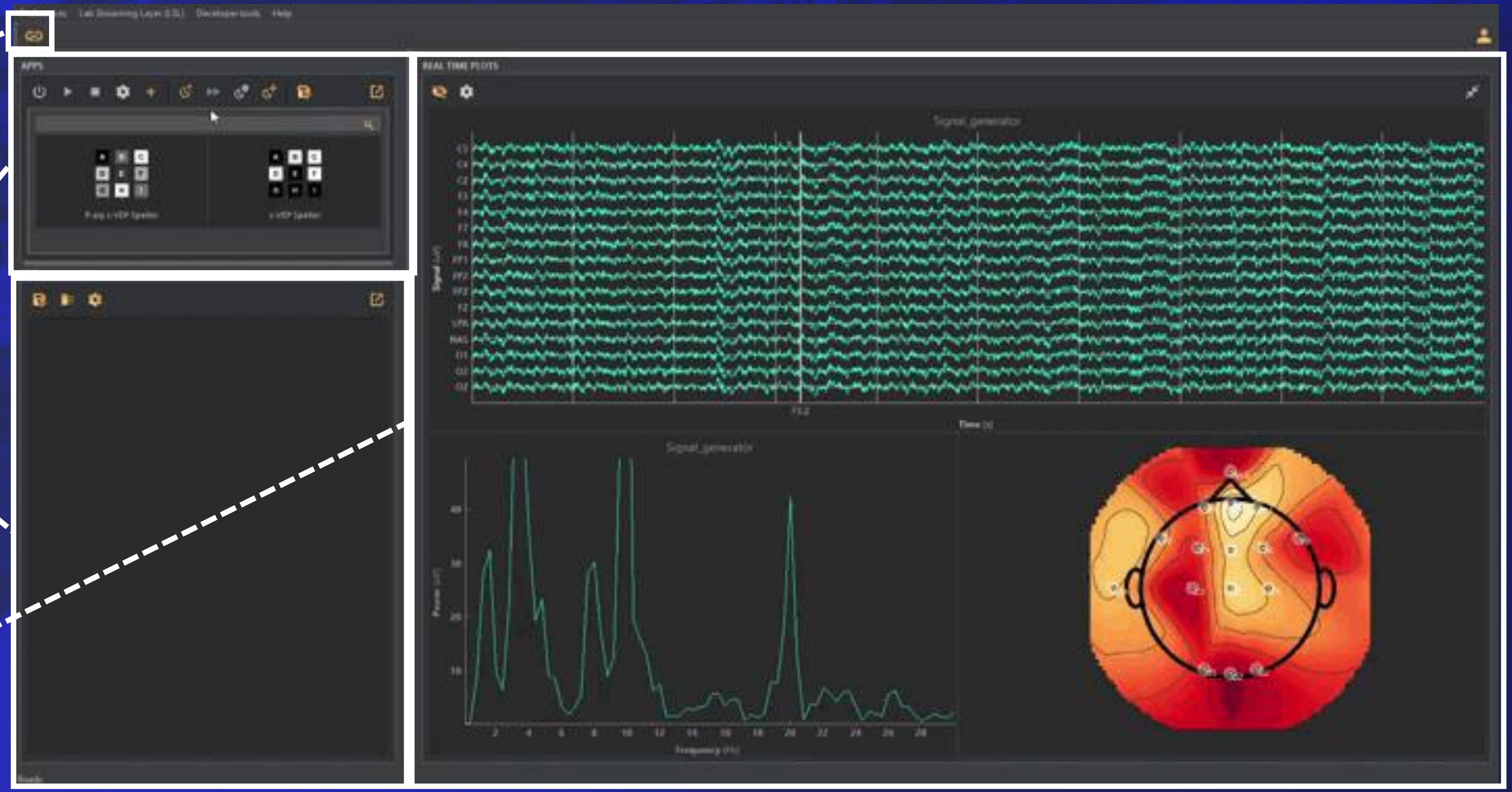
- Signal acquisition
  - Lab-streaming layer (LSL)
  - Compatible with any data stream
  - Multimodal acquisition
- Real-time charts
  - Temporal, spectral and topoplots
  - Pre-processing
- Applications
  - Apps to perform experiments
  - Developer tools: tutorials, templates

Documentation: docs.medusabci.com/platform

MEDUSA© Platform

Main functionalities

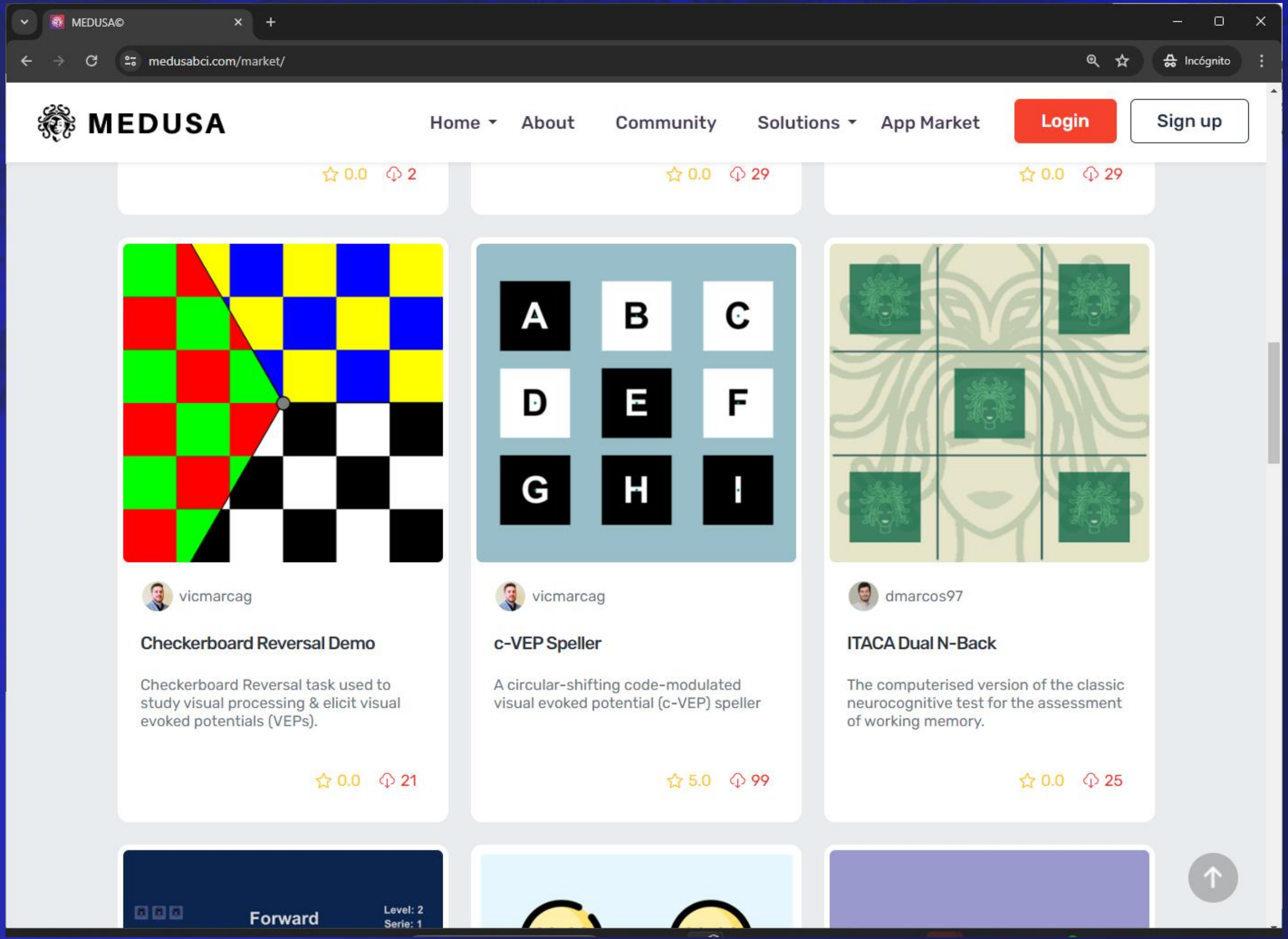
- LSL configuration
- Apps panel
- Log panel
- Plots panel



MEDUSA© Platform

Web & app marketplace

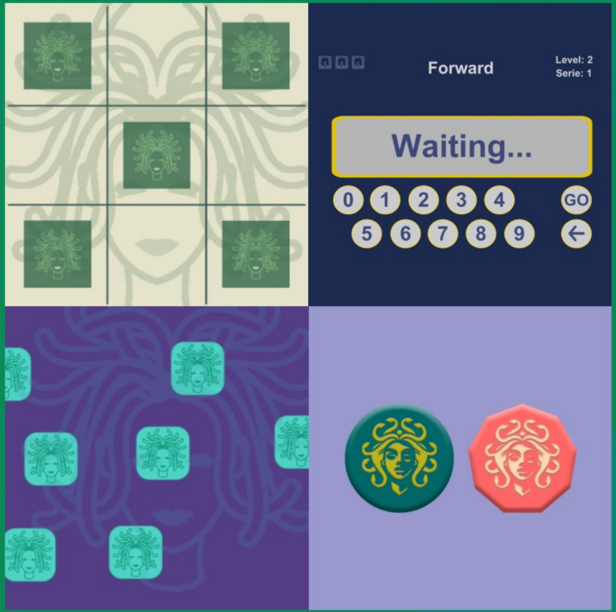
- Website: medusabci.com
  - Repositories on github
  - Community on discord
- App market
  - Collection of built-in apps
  - Upload and share your own apps
  - Apps are installed in your user directory within MEDUSA© Platform



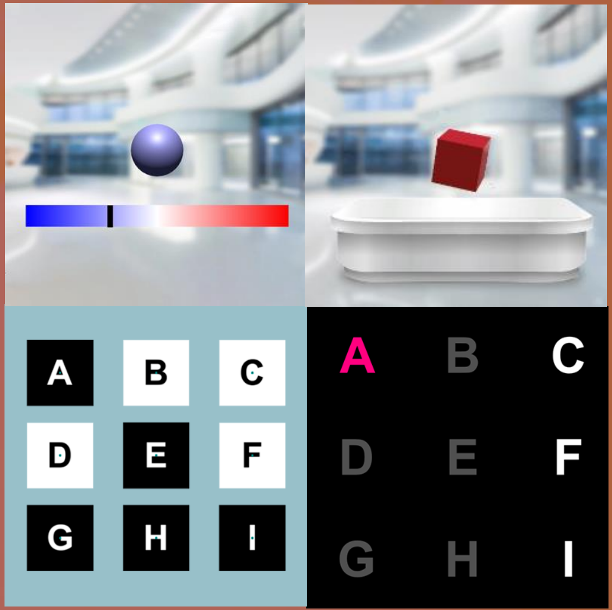
MEDUSA© Platform

Built-in open-source applications

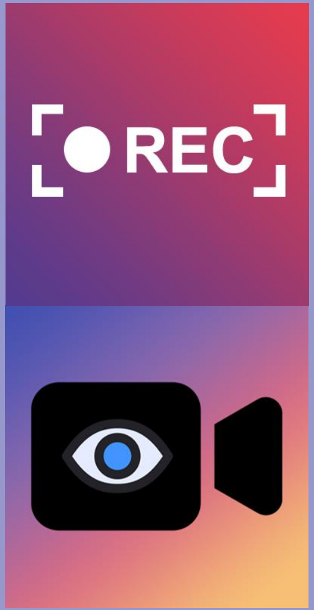
Cognitive Psychology Tests



State-of-the-art BCI paradigms



Other apps...



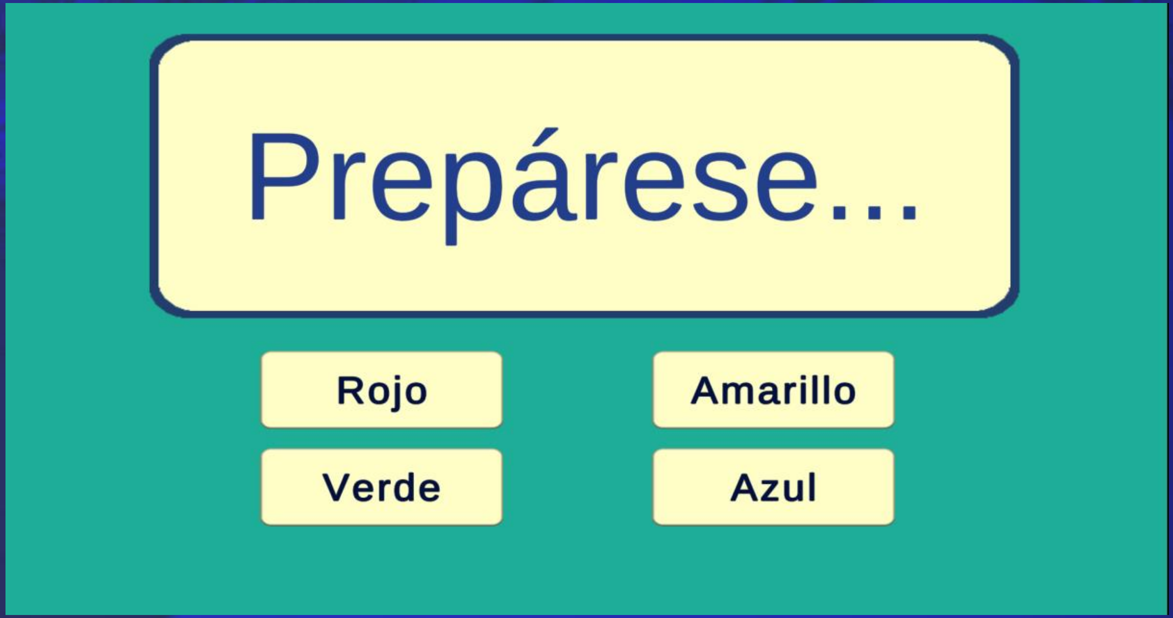
MEDUSA© Platform

Built-in cognitive psychology tests

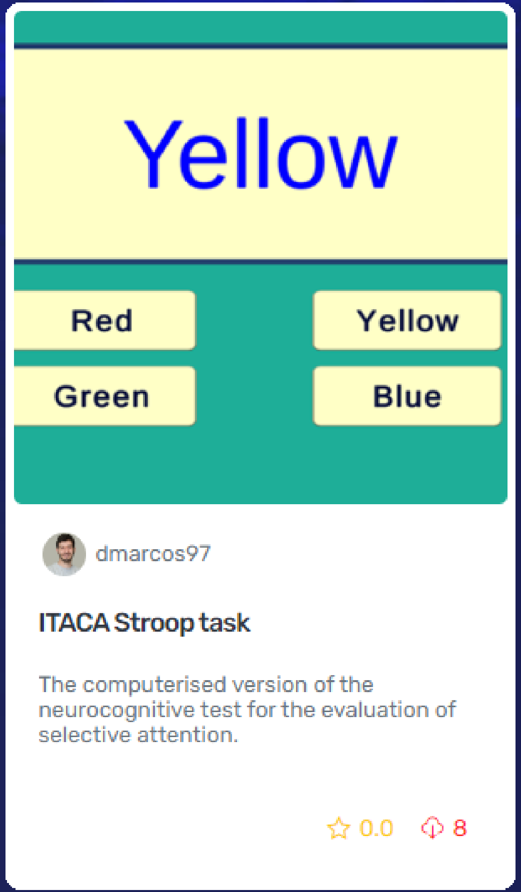
MEDUSA© Platform

Built-in cognitive psychology tests

- Stroop task
  - Delay in reaction time between congruent/incongruent stimuli
  - Selective attention, cognitive flexibility and processing speed



medusabci.com/market/stroop



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Built-in cognitive psychology tests

- Corsi Block-Tapping Test
  - Visuo-spatial short-term working memory
  - Mimicking a sequence of flashes after is displayed
    - Increasing level: average of 5-6 spans for healthy subjects

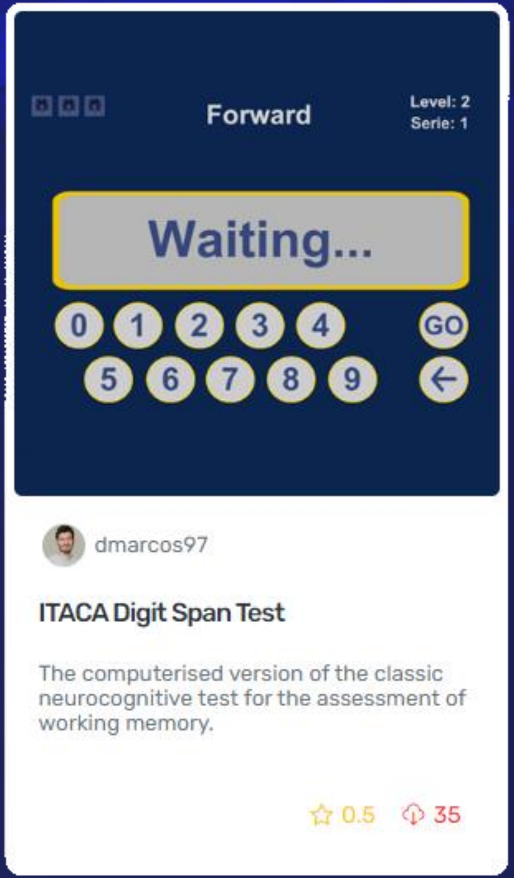
medusabci.com/market/corsi

MEDUSA© Platform

Built-in cognitive psychology tests

- Digit Span Test
  - Short-term working memory
  - Mimicking a sequence of numbers after is displayed
    - Increasing level: average of 5-9 spans for healthy subjects

medusabci.com/market/dspan



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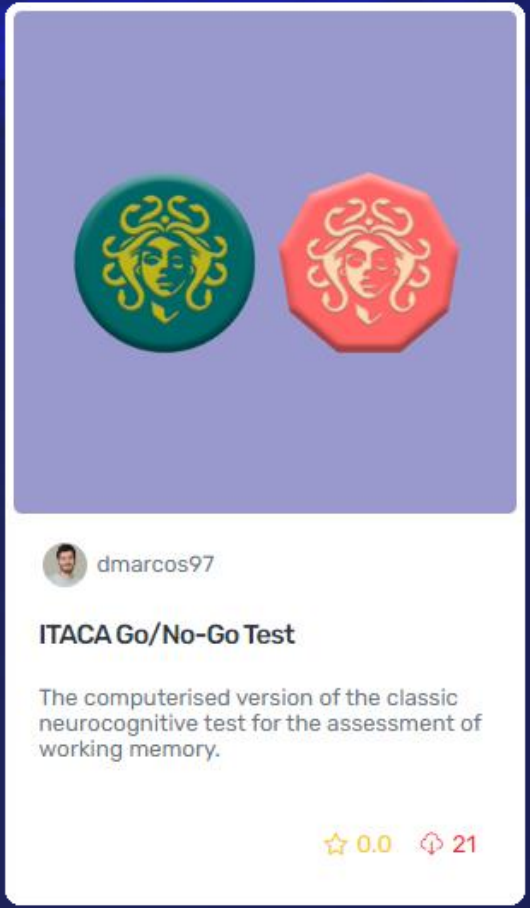
Built-in cognitive psychology tests

- Go/No-Go Task
  - Response inhibition (capacity not to respond)
  - Press the spacebar whenever the “Go” stimulus is presented and inhibit in case of a “No-Go” stimulus

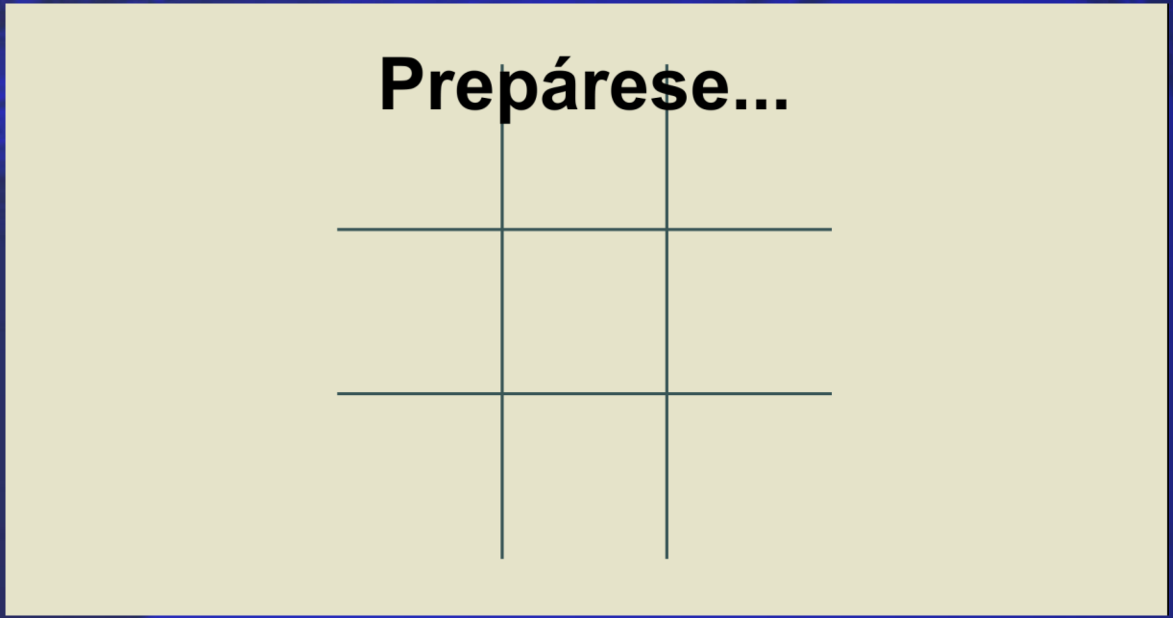
medusabci.com/market/gonogo



MEDUSA© Platform

Built-in cognitive psychology tests

- Dual N-Back
  - Working memory
  - Users must indicate when a stimulus matches the stimulus presented N-times before



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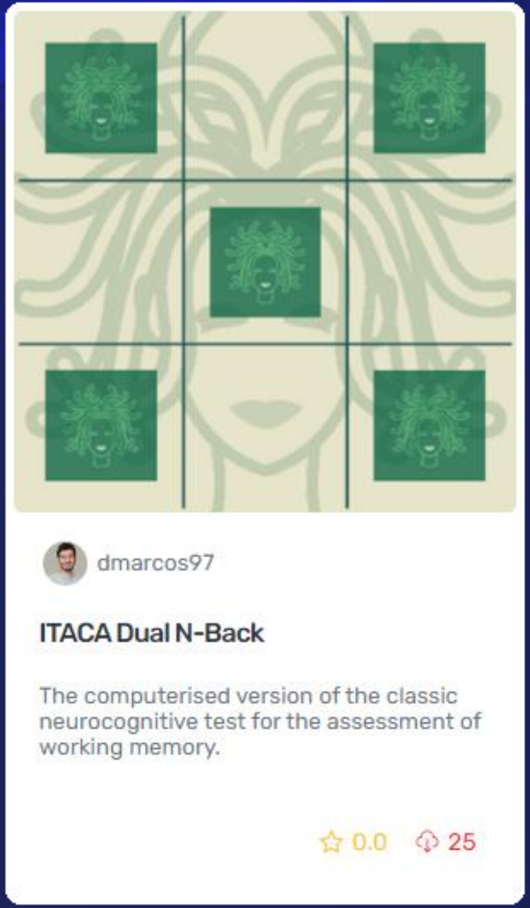

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Built-in BCI paradigms

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Non-invasive BCI control signals

Control Signals

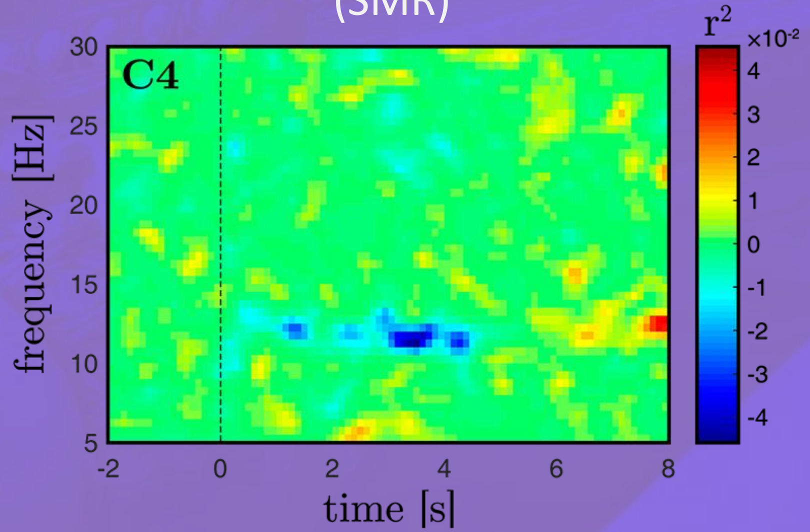
Self-regulated

"Endogenous"

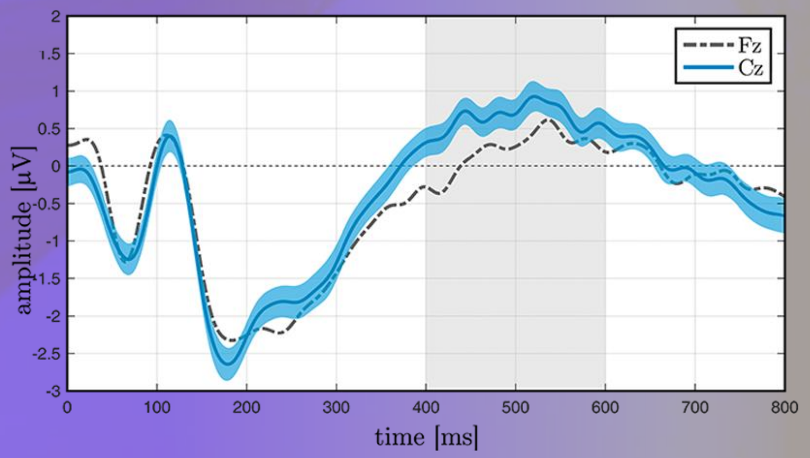
Natural responses

"Exogenous"

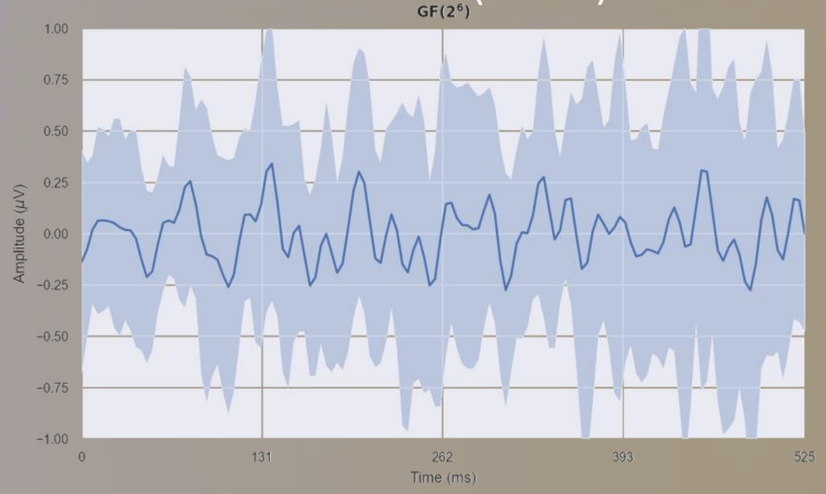
Sensorimotor Rhythms (SMR)



P300 evoked potentials



Code-modulated Visual Evoked Potentials (c-VEP)



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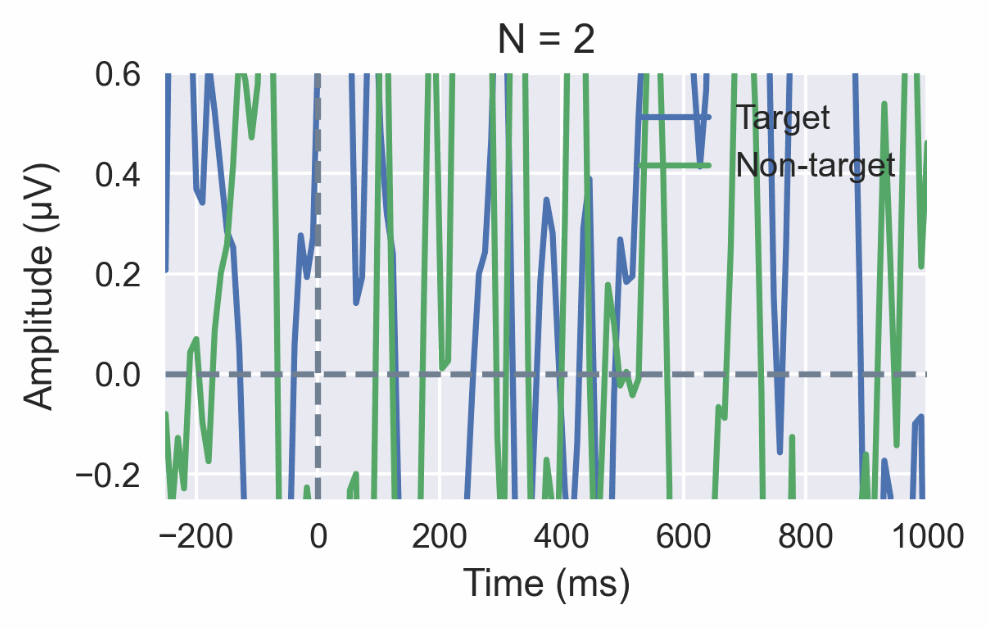
P300 evoked potentials

Endogenous/Exogenous

- P300 evoked potentials
  - Positive deflections in response to infrequent stimuli
  - Approx. 300 ms after the onset
  - At centro-parietal scalp positions
  - Elicited by oddball paradigms



P300!

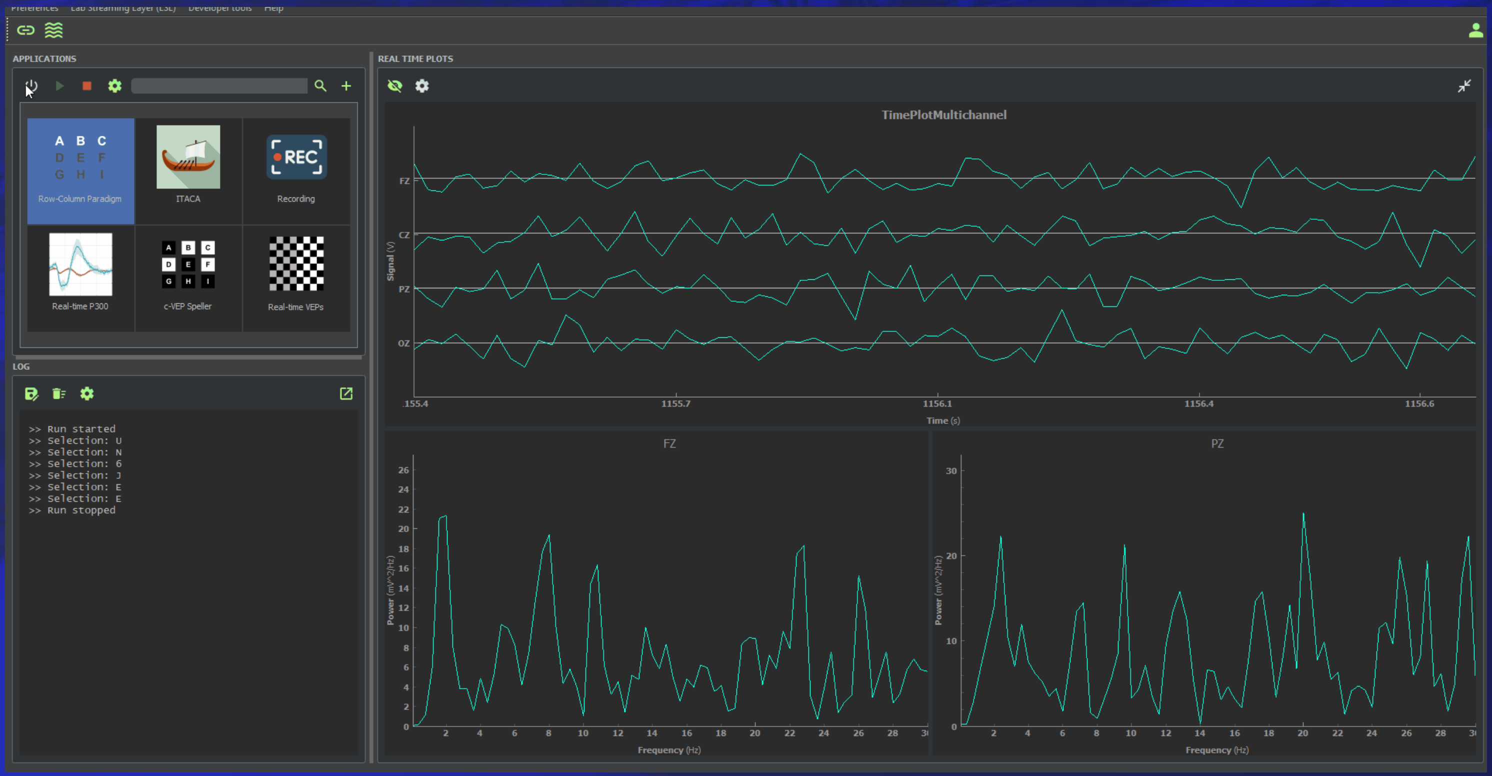
P300!

Endogenous/Exogenous

MEDUSA© Platform

P300 evoked potentials

- Row-col paradigm (RCP)
  - Rows and columns flash randomly
  - Only one row and one column will elicit a P300 potential
  - Target command is decoded by determining most probable row and column



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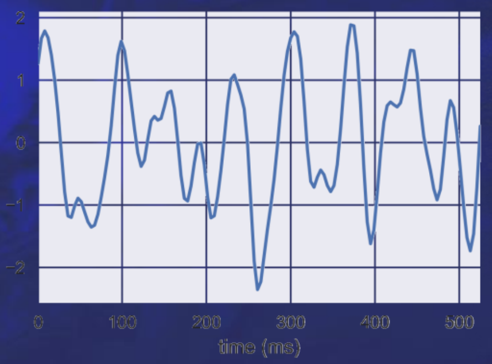
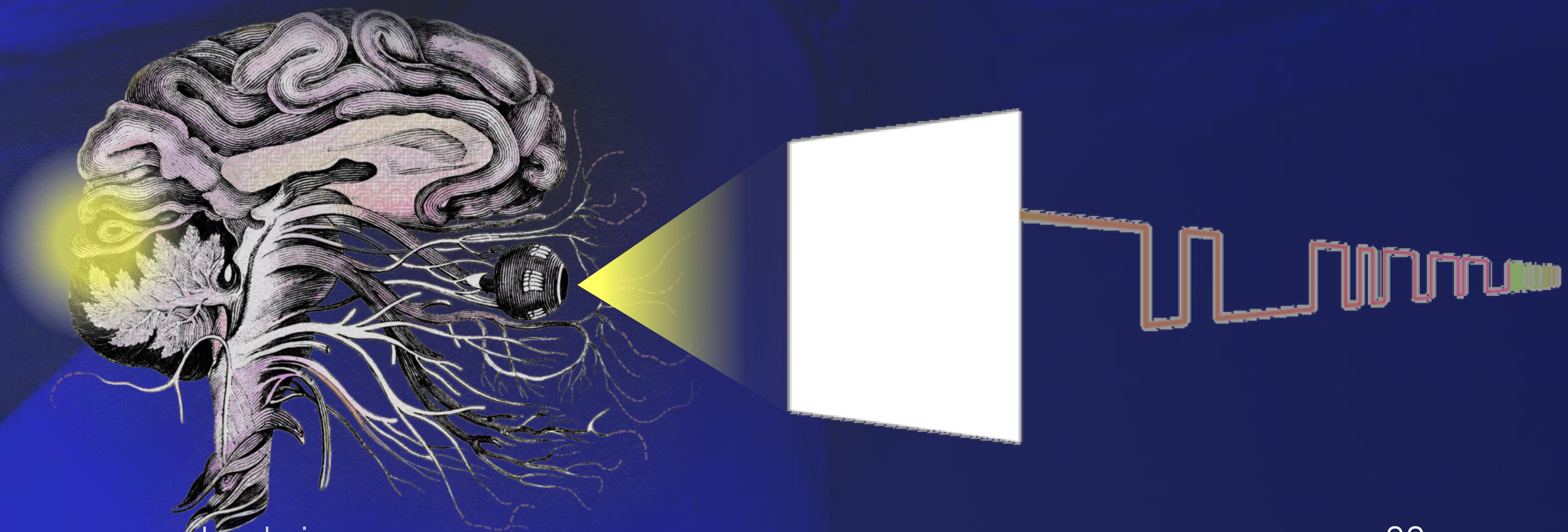
Code-modulated visual evoked potentials

Exogenous

- **Code-modulated visual evoked potentials (c-VEP)**
  - Visual evoked potentials to pseudorandom flickering codes
  - Code is shown at a fixed rate (e.g., 120 Hz)
  - Mainly generated over occipital cortex



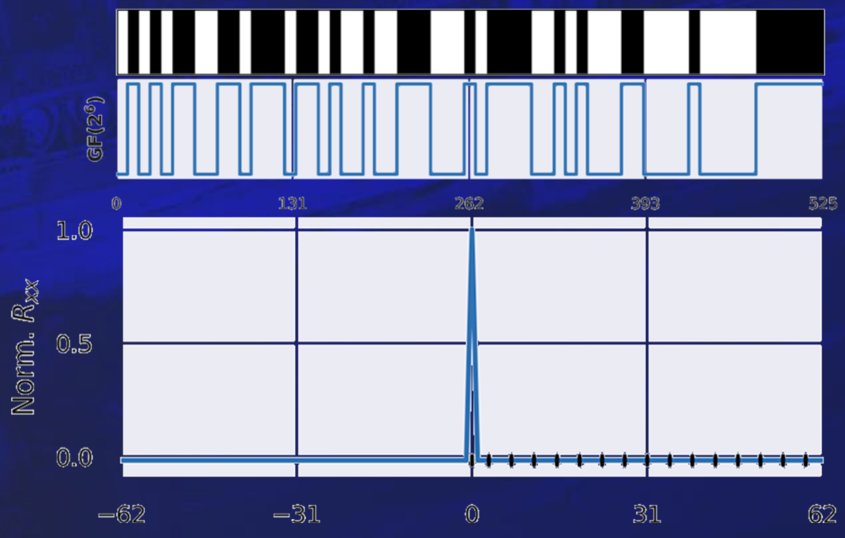


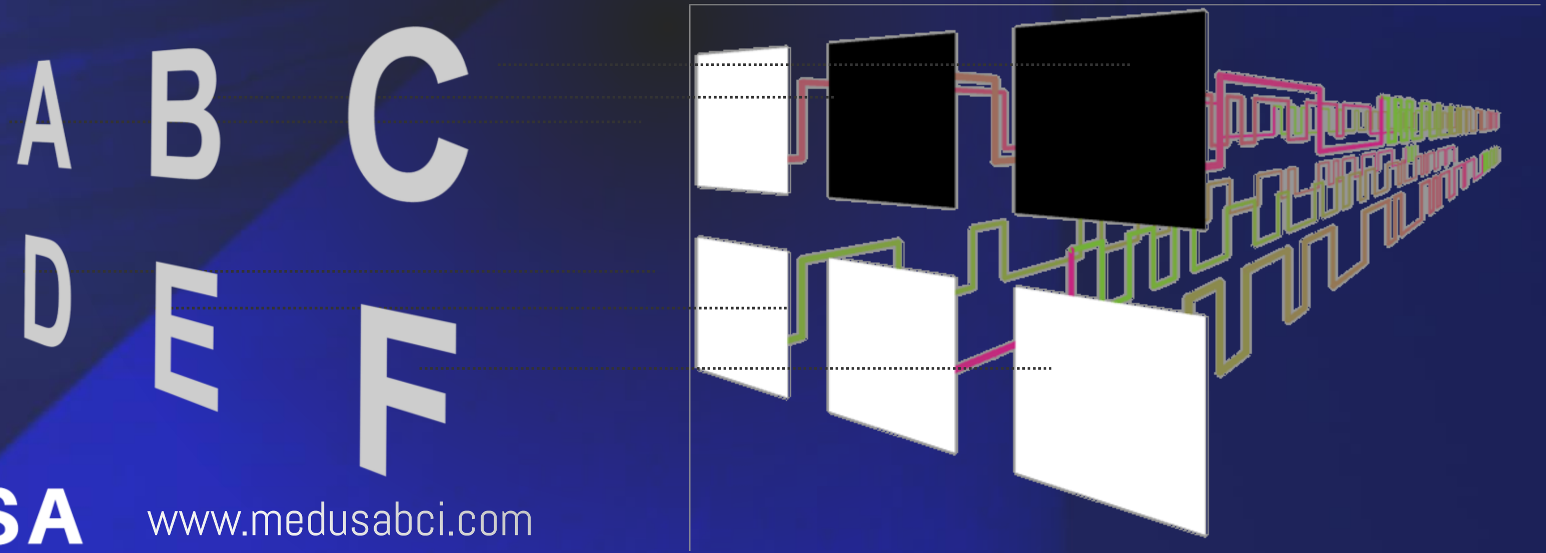
MEDUSA© Platform

Code-modulated visual evoked potentials

Exogenous

- **Circular shifting paradigm**
  - Encoding commands with shifted versions of the code
  - Codes with flat autocorrelation (e.g., m-sequences)
    1. VEP in response to the original code is used as template
    2. Online VEP is compared with shifted templates
    3. Selected command: yields highest correlation



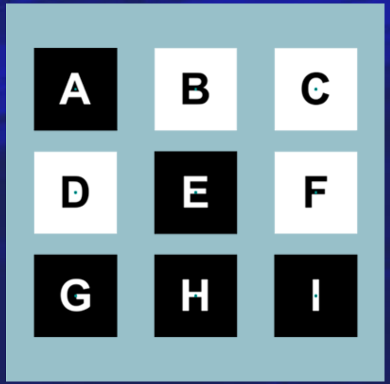


MEDUSA© Platform

Code-modulated visual evoked potentials

Exogenous

c-VEP Speller



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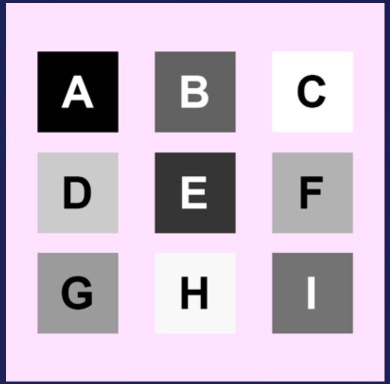
P-ary c-VEP Speller



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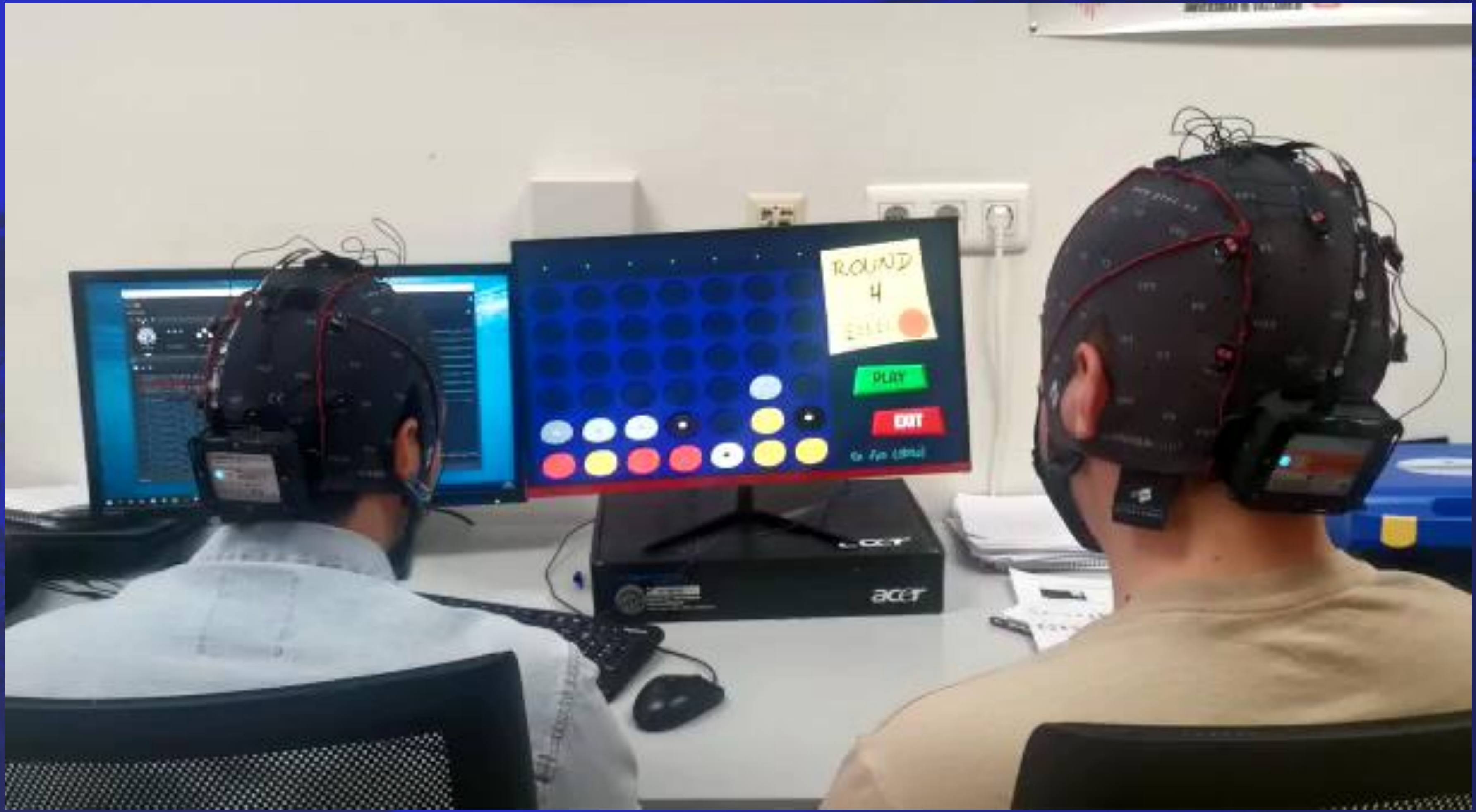
MEDUSA© Platform

Code-modulated visual evoked potentials

Exogenous



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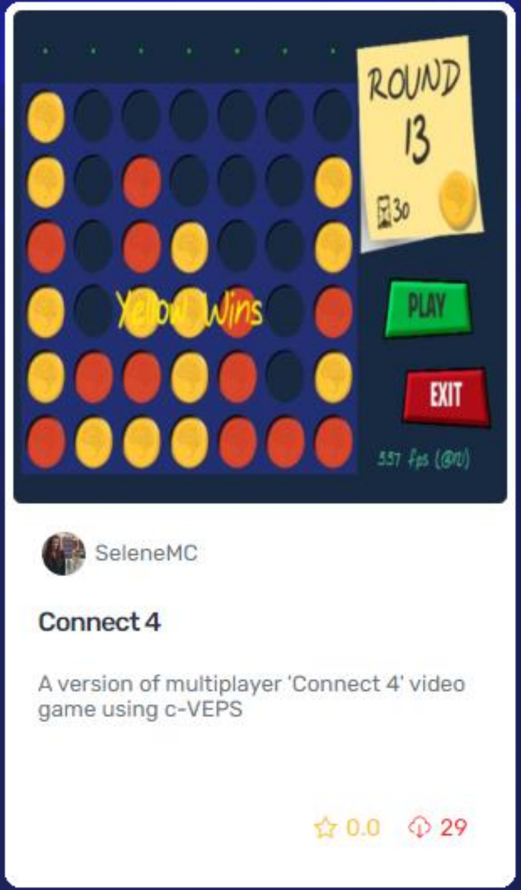
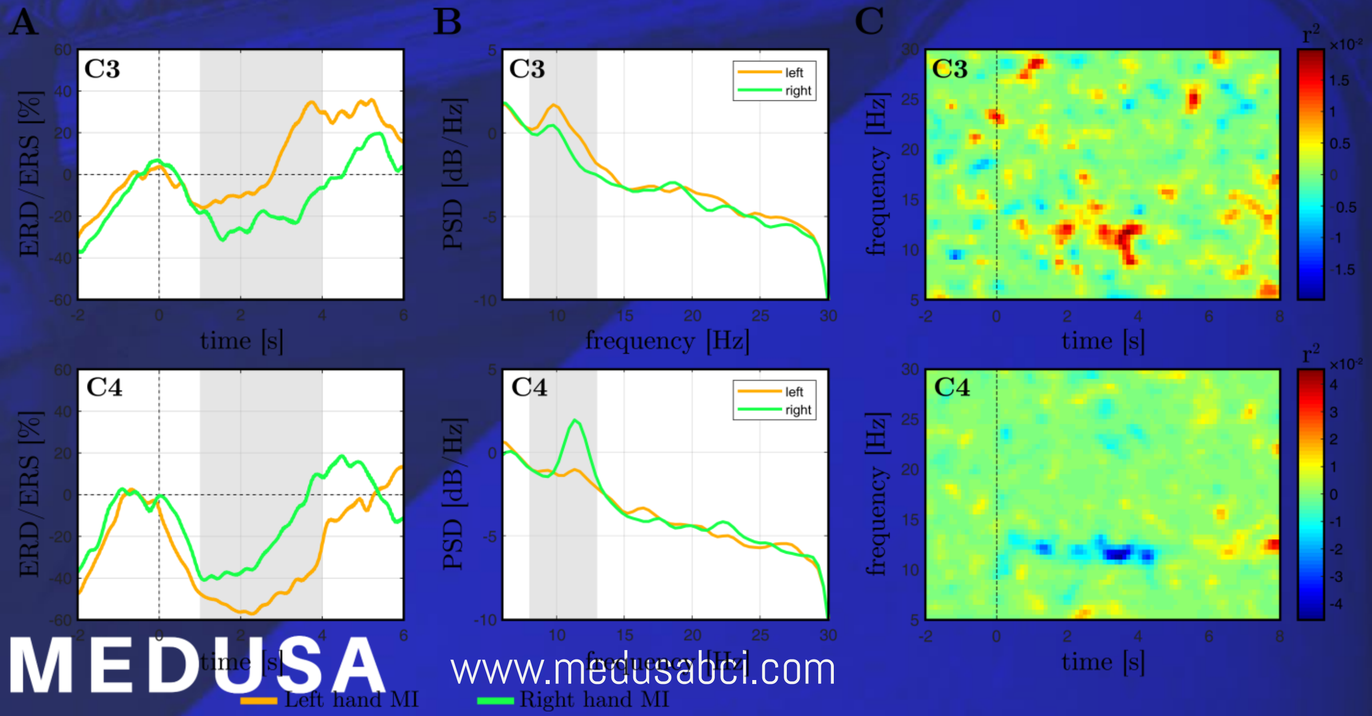


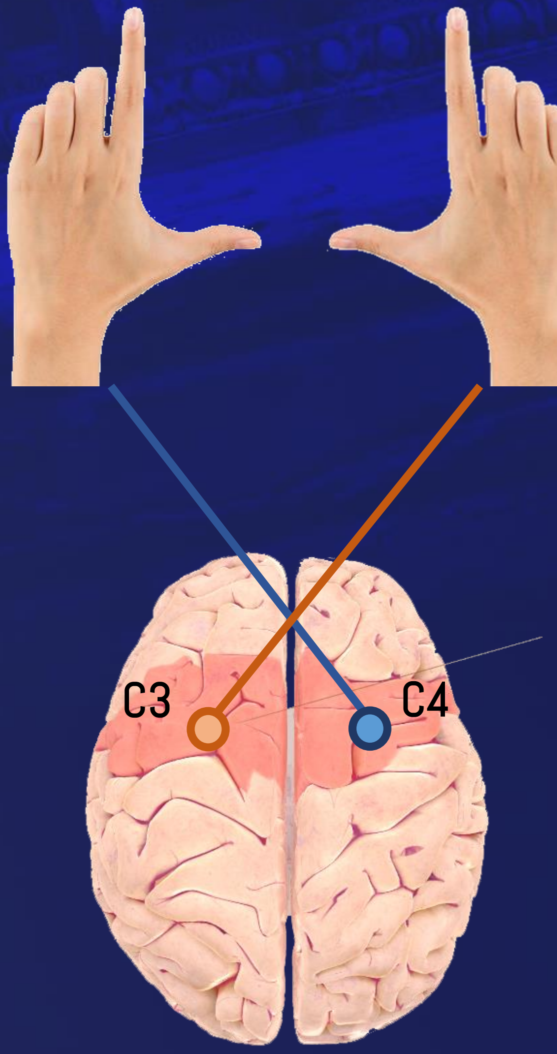
MEDUSA© Platform

Motor imagery via sensorimotor rhythms

Endogenous

- SensoriMotor Rhythms (SMR)
  - Self-generated neural oscillations before, during and after movement execution or imagination over S1 & M1
  - Desynchronization at α, followed by synchronization at β





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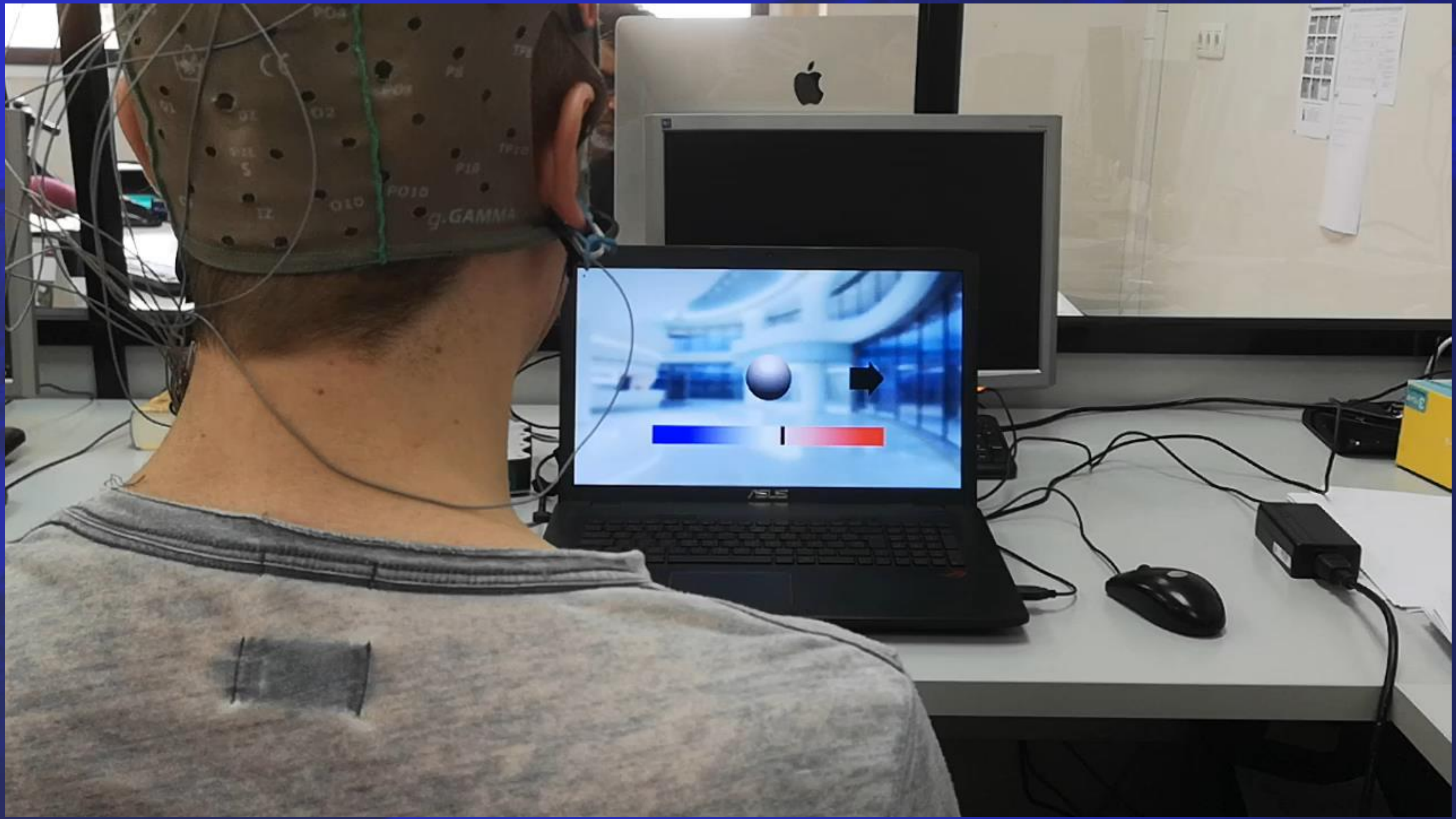
Motor imagery via sensorimotor rhythms

Endogenous



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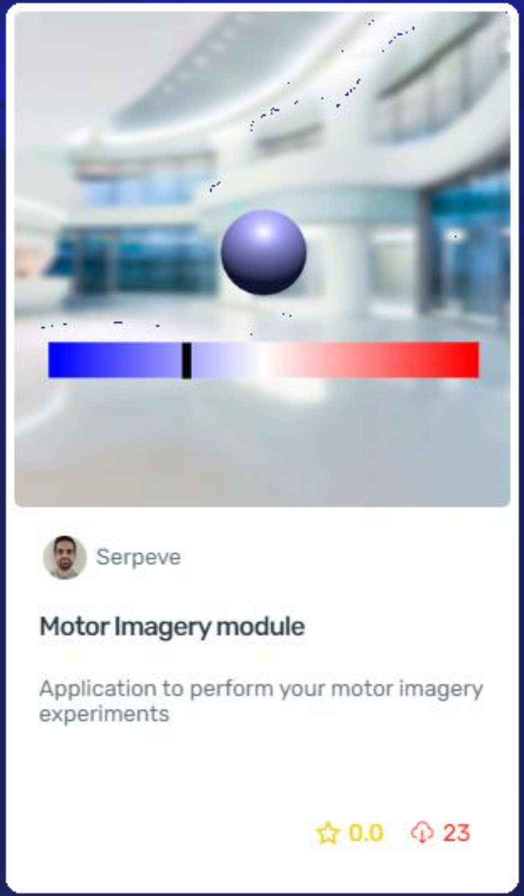


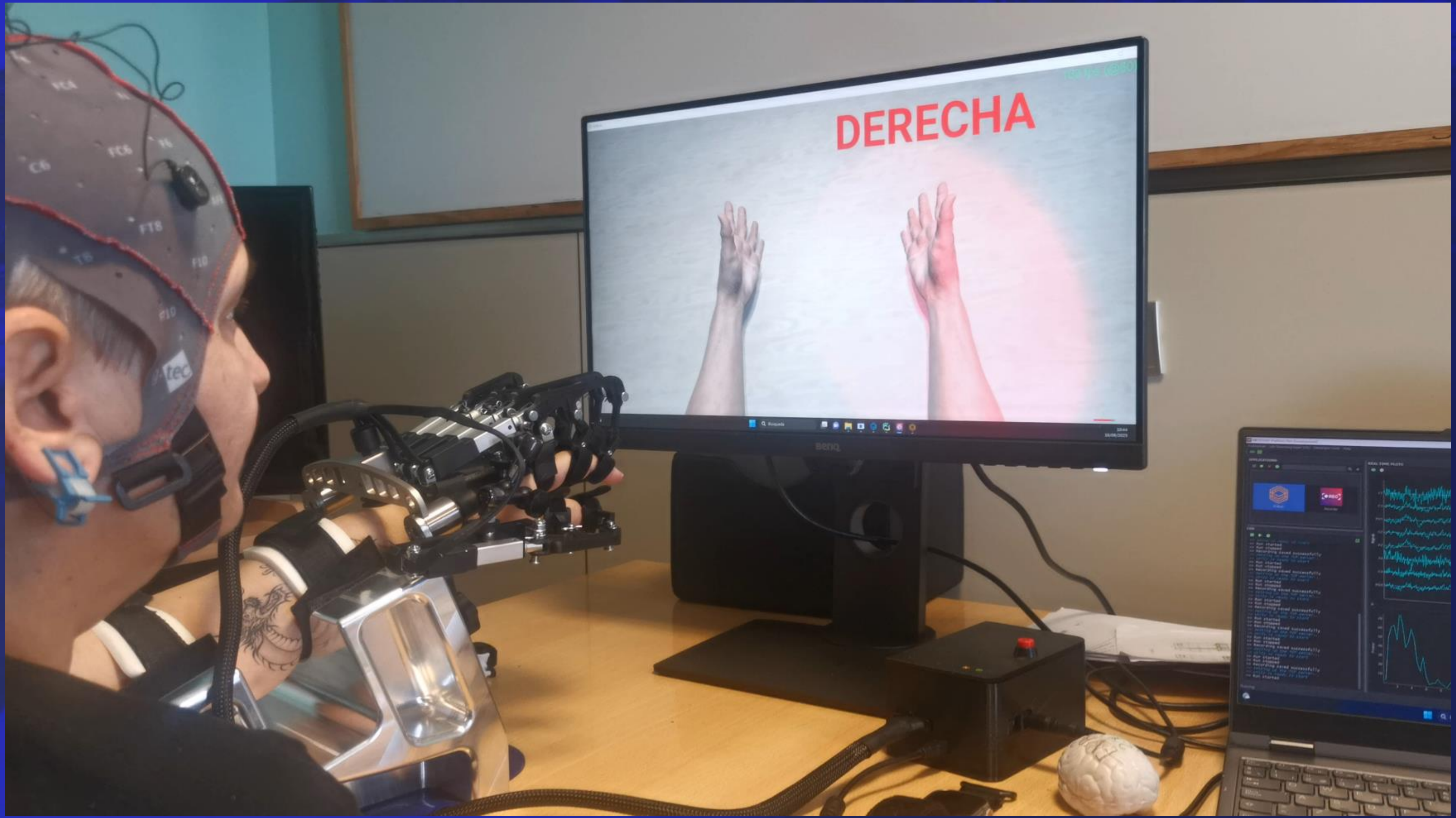
(in maintenance)

MEDUSA© Platform

Motor imagery via sensorimotor rhythms

Endogenous

- **Neurorehab.**
  - Private app
  - Stroke patients and synch with a haptic robot
  - M3Rob project



https://gib.tel.uva.es/m3rob

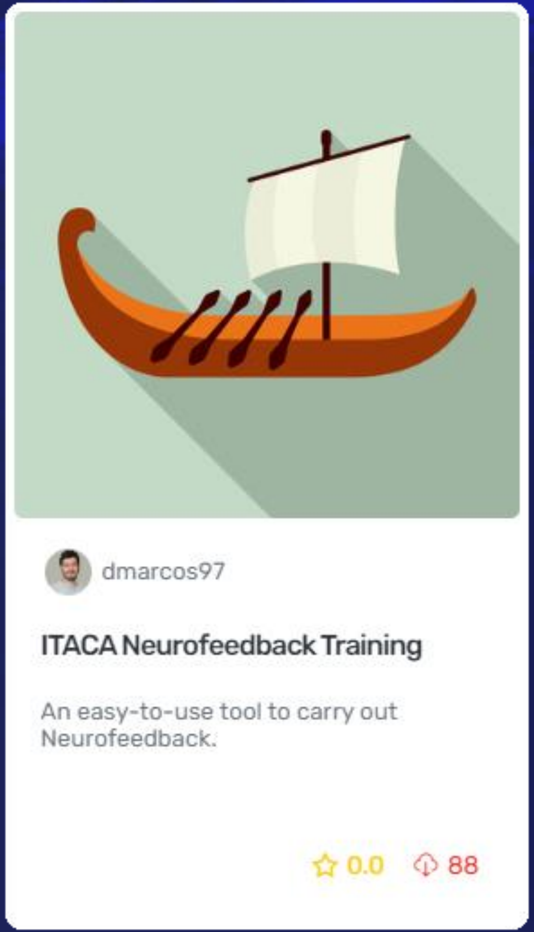
MEDUSA© Platform

Neurofeedback

Endogenous

medusabci.com/market/itaca

- Neurofeedback (NF)
  - Self-regulated activity over custom frequencies or locations
  - Band power and connectivity measures
  - Simple and attractive visual feedback to motivate subjects



MEDUSA© Platform

Neurofeedback

Endogenous

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dmarcos97

ITACA Neurofeedback Training

An easy-to-use tool to carry out Neurofeedback.

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Website

What now?

A look into the future of MEDUSA©

- Grow the community
- Keep implementing new functionalities and experiments
- Expand the scope: application to other fields
- Achieve sustainability to continue our purpose:
    - Customized app development
    - Commercialization of applications
    - Partners & Investors

Dr. Eduardo Santamaría-Vázquez

Dr. Víctor Martínez-Cagigal

Dr. Roberto Hornero

Diego Marcos-Martínez

Víctor Rodríguez-González

Sergio Pérez-Velasco

Selene Moreno-Calderón

Scientific production

Publications using MEDUSA©

1. Eduardo Santamaría-Vázquez, Víctor Martínez-Cagigal, Diego Marcos-Martínez, Víctor Rodríguez-González, Sergio Pérez-Velasco, Selene Moreno-Calderón, Roberto Hornero, MEDUSA©: A novel Python-based software ecosystem to accelerate brain-computer interface and cognitive neuroscience research, Computer Methods and Programs in Biomedicine, vol. 230, pp. 107357, Marzo, 2023, DOI: 10.1016/j.cmpb.2023.107357
2. Diego Marcos-Martínez, Víctor Martínez-Cagigal, Eduardo Santamaría-Vázquez, Sergio Pérez-Velasco, Roberto Hornero, Neurofeedback Training Based on Motor Imagery Strategies Increases EEG Complexity in Elderly Population, Entropy, vol. 23 (12), pp. 1574, Noviembre, 2021, DOI: 10.3390/e23121574
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Questions?

Practical Workshop

Module 1: Configure MEDUSA© Platform

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Task 1.1: Stream a fake EEG with the signal generator

Module 1: Configure MEDUSA© Platform

Task 1.2: Connect MEDUSA© platform to the LSL signal

Module 1: Configure MEDUSA© Platform

Task 1.3: Configure plots panel

Module 2: Learn to work with apps

Module 2: Learn to work with apps

Task 2.1: Install an app: “Recorder”

Module 2: Learn to work with apps

Task 2.2: Experiment with the “Recorder”

Module 3: Advanced functions for experimentation

Module 3: Advanced functions for experimentation

Task 3.1: Select a study

Module 3: Advanced functions for experimentation

Task 3.2: Create a session

Module 4: ERP-based paradigms

Module 4: ERP-based paradigms

Task 4.1: Configure the “RCP Speller” app

Module 4: ERP-based paradigms

Task 4.2: Run the paradigm: calibration and test modes

Module 4: ERP-based paradigms

Task 4.3: [Google Colab] Processing ERP signals

Module 5: c-VEP-based paradigms

Module 5: c-VEP-based paradigms

Task 5.1: Configure the “c-VEP Speller” app

Module 5: c-VEP-based paradigms

Task 5.2: Run the paradigm: calibration and online modes

Module 5: c-VEP-based paradigms

Task 5.3: [Google Colab] Processing c-VEP signals

Module 5: c-VEP-based paradigms

Task 5.4: Other apps: “P-ary c-VEP Speller”, “c-VEP Keyboard”

Module 6: MI-based paradigms

Task 6.1: Configure the “Motor Imagery” app

Module 6: MI-based paradigms

Task 6.2: Run the paradigm: calibration and feedback mode

Module 6: MI-based paradigms

Task 6.3: [Google Colab] Processing Motor Imagery signals

MEDUSA©: An Innovative Software Ecosystem to Accelerate BCI and Cognitive Neuroscience Experimentation

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