

MEDUSA[®]: An Innovative Software Ecosystem to Accelerate BCI and Cognitive Neuroscience Experimentation

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2. BCI Software
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4. MEDUSA© Platform
5. Website
6. What now?
7. Practical Workshop



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BCI experiments



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BCI experiments

Recording experiments

EEG



Signal acquisition



TASK



Data storage



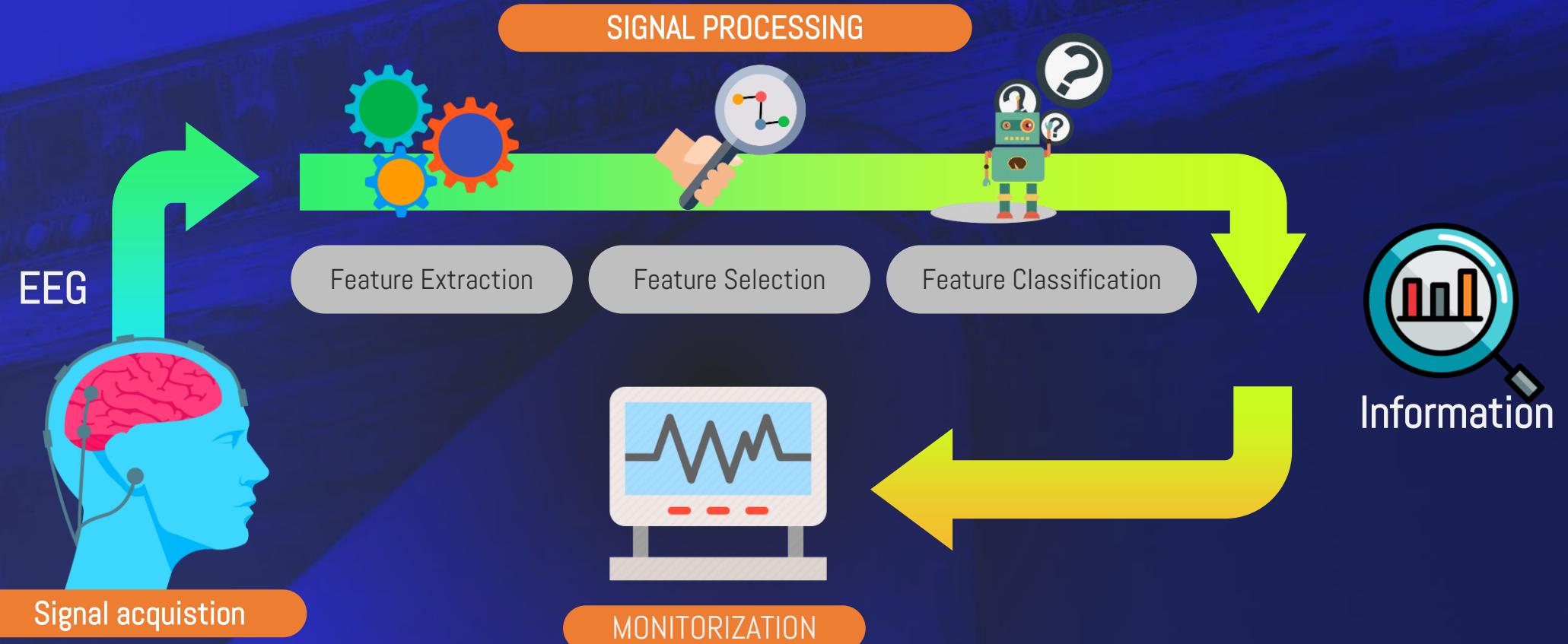
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BCI experiments

Passive BCIs



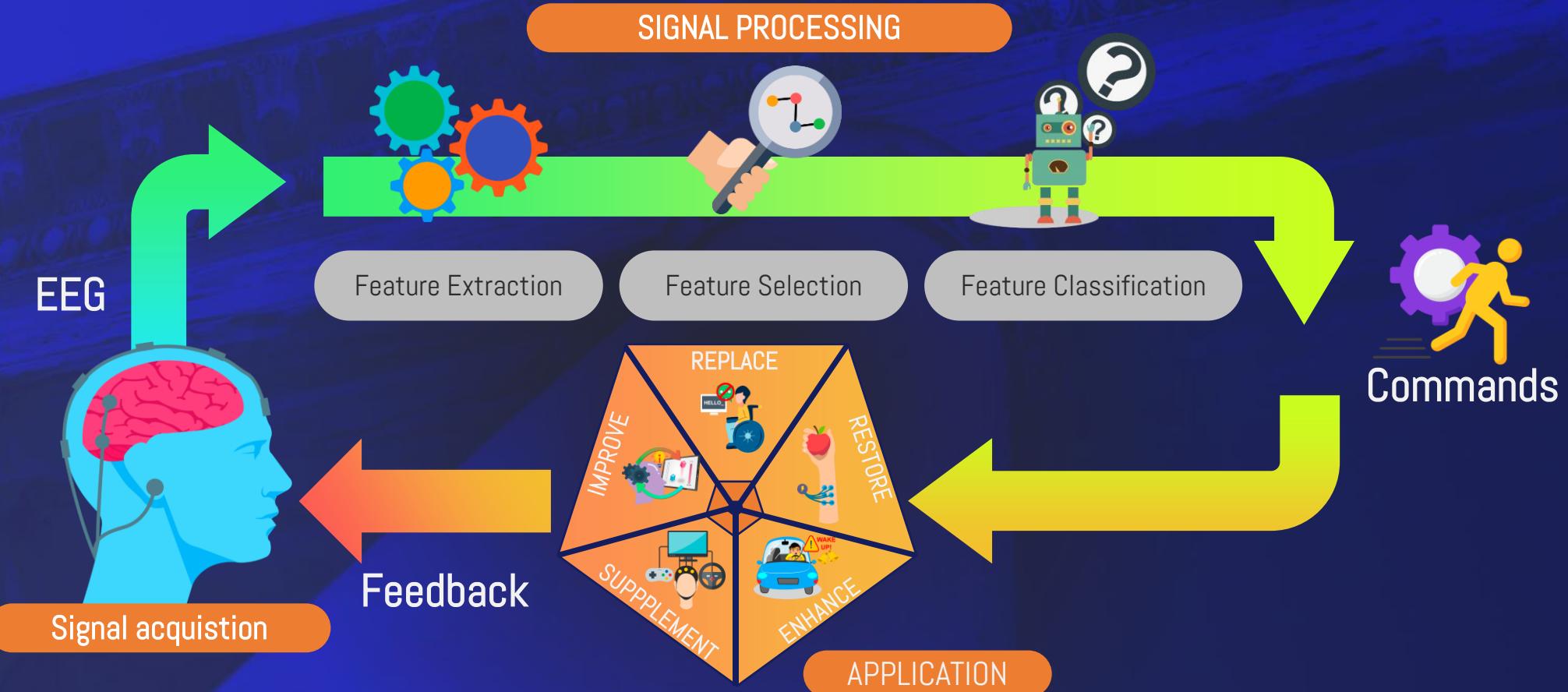
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BCI experiments

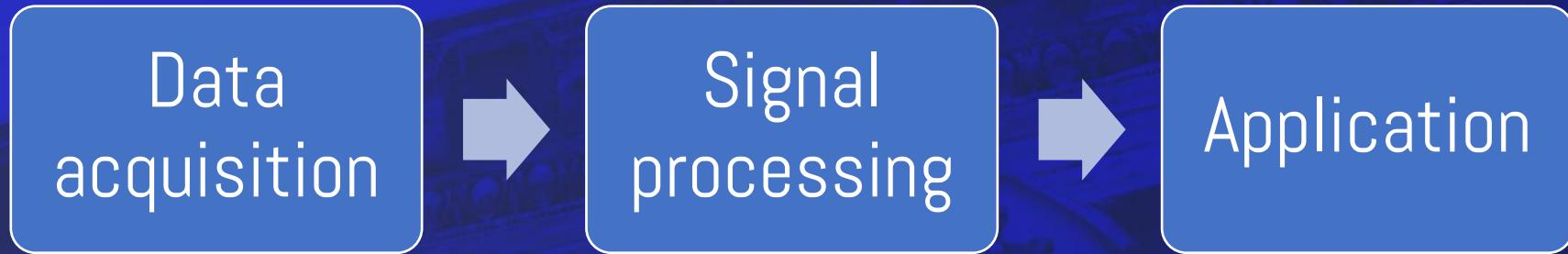
Active BCIs





BCI experiments

Development of a BCI experiment



- Real-time acquisition of data streams
- Synchronization between streams
- Real-time visualization
- Basic functions: frequency and spatial filters
- Advanced functions: artifact rejection, neural decoding
- Real-time application
- High-performance graphical applications
- Challenges of game engines: integration with signal processing, synchronization



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The background of the slide features a photograph of a classical building's facade. The image is heavily tinted with a dark blue color. The facade includes detailed carvings on the columns and a decorative frieze above the entablature.

BCI software



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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



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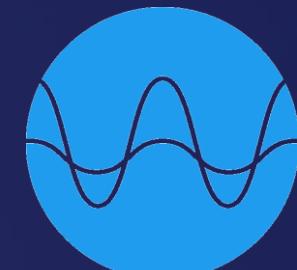
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BCI software

BCI software platforms

- Signal analysis toolboxes:
 - EEGLAB
 - BrainStorm
 - MNE
- Open-source BCI platforms:
 - Most known: BCI2000, OpenVibe
 - No longer maintained: 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

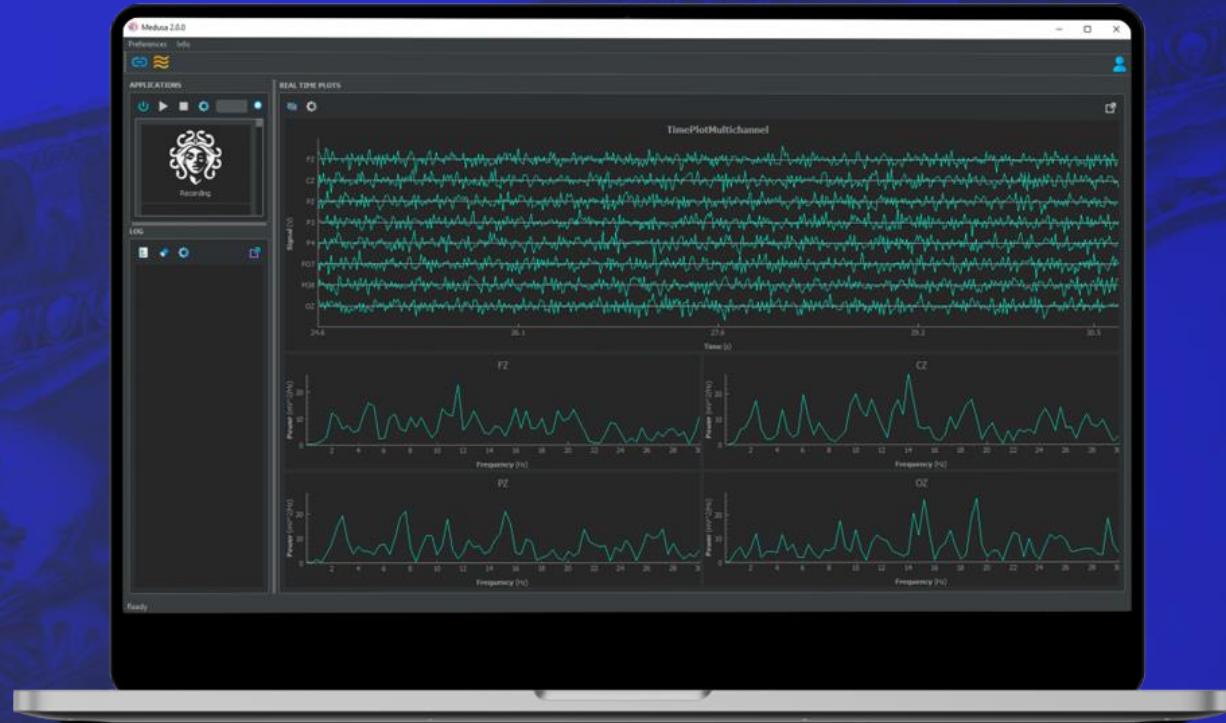
- Repetitive experiments with the same databases
- Limited development of novel ideas
- Barrier to interdisciplinary collaboration, especially non-technical researchers
- Lack of reproducibility of results





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



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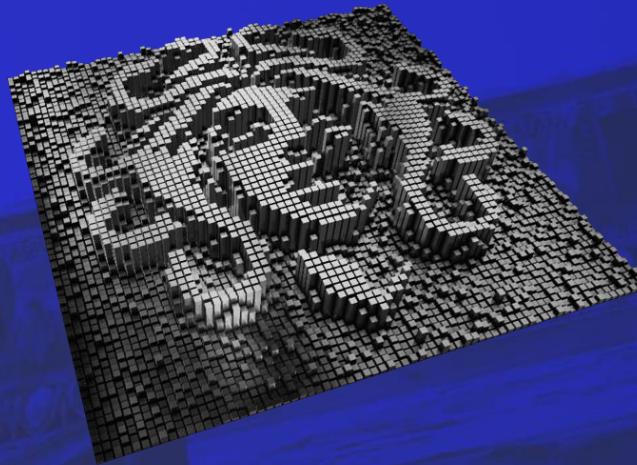
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BCI software

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.

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

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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.

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MEDUSA© Kernel



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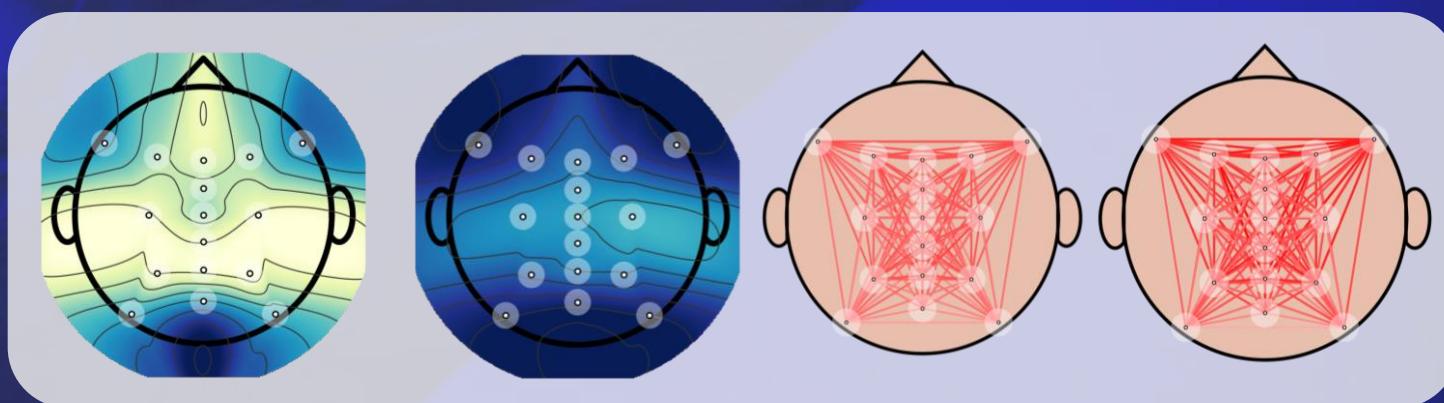
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MEDUSA© Kernel

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

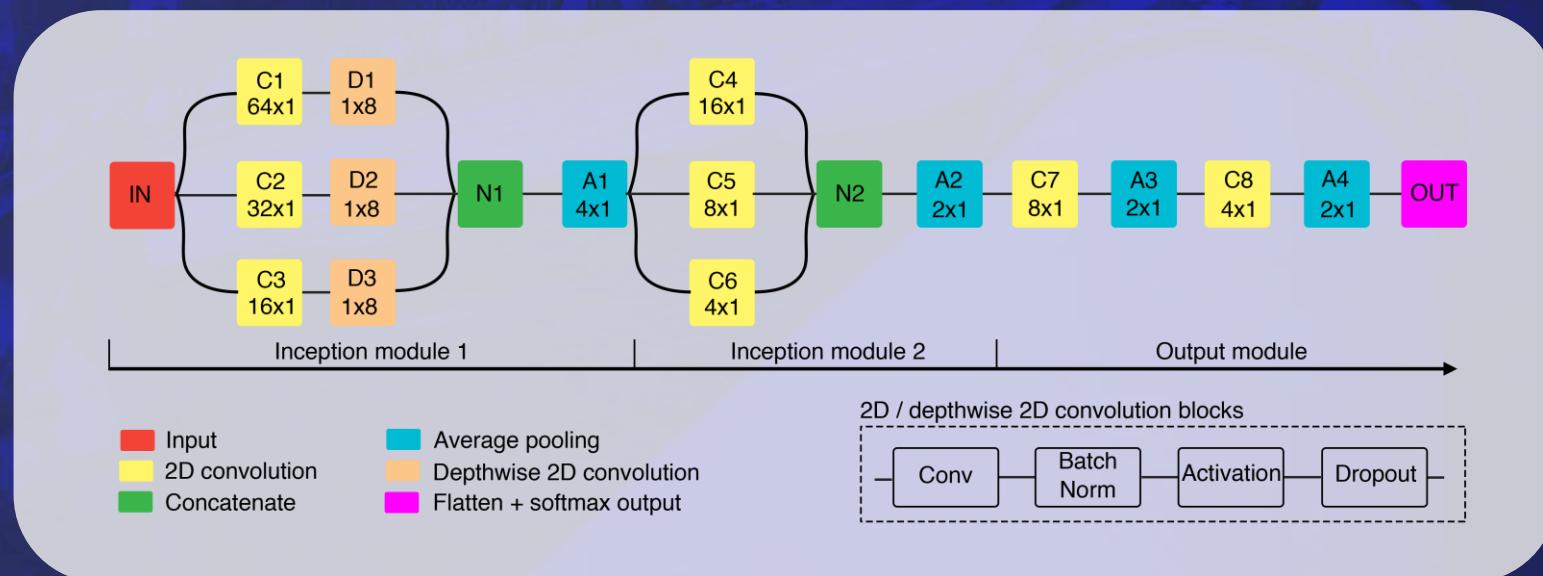




MEDUSA© Kernel

EEG decoding

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

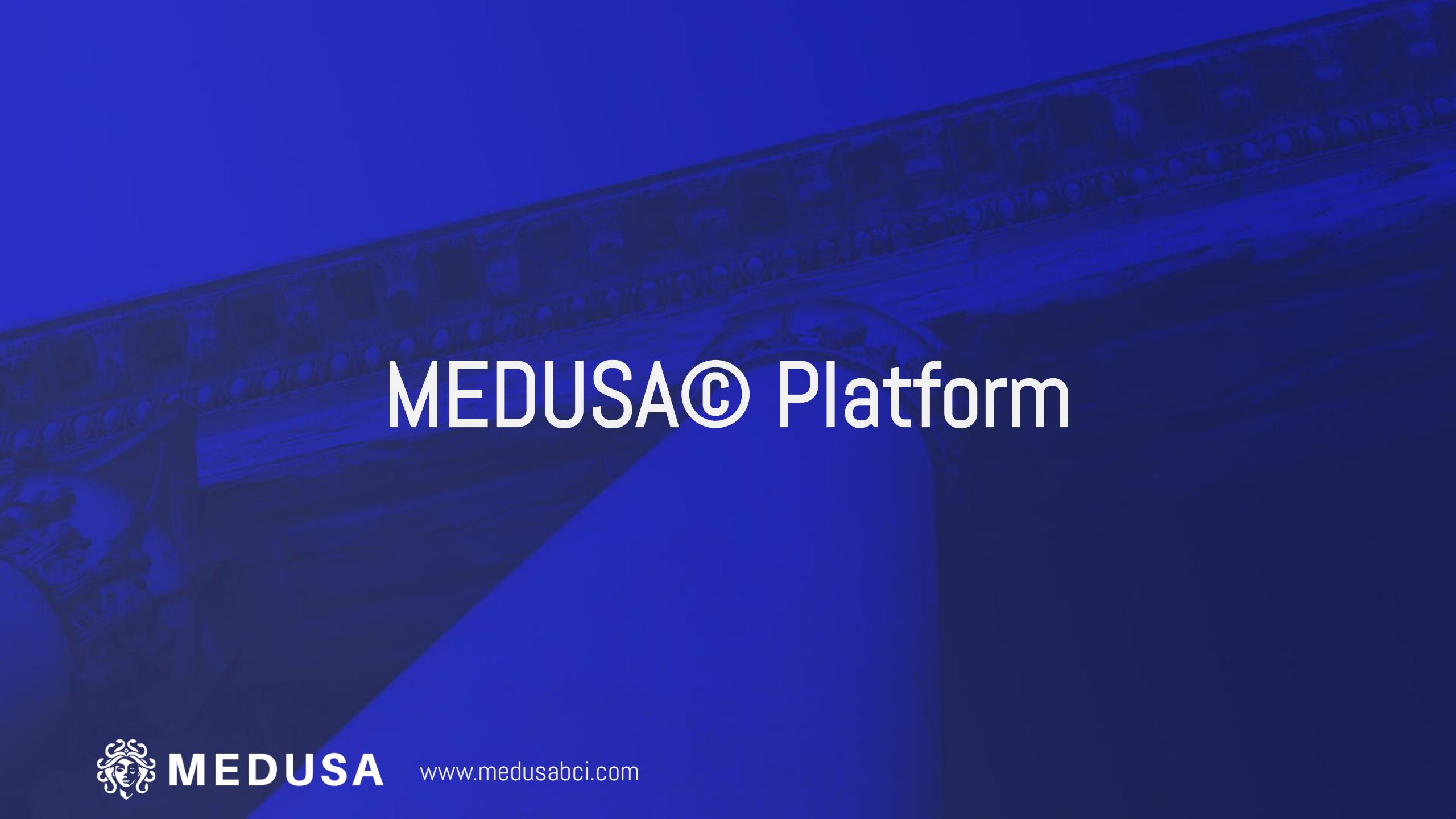


TensorFlow



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The background features a classical architectural facade with detailed stonework, columns, and a pediment, all set against a dark blue gradient.

MEDUSA© Platform



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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



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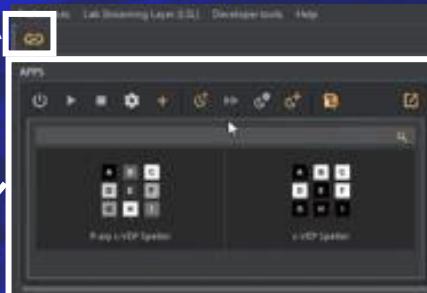
www.medusabci.com



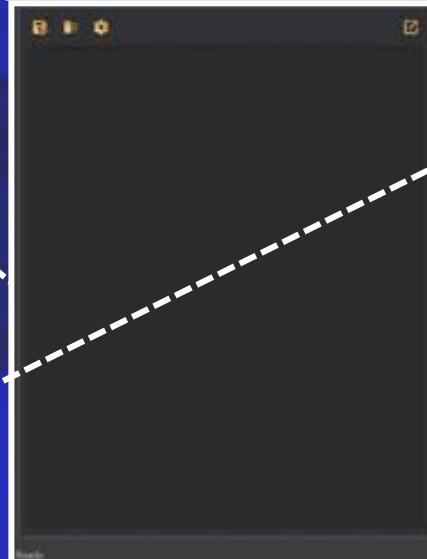
MEDUSA© Platform

Main functionalities

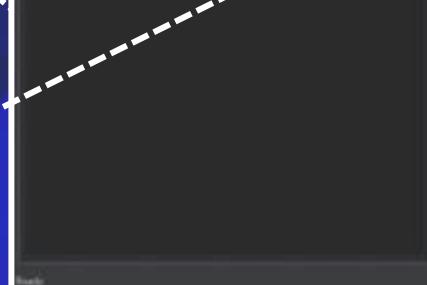
LSL configuration



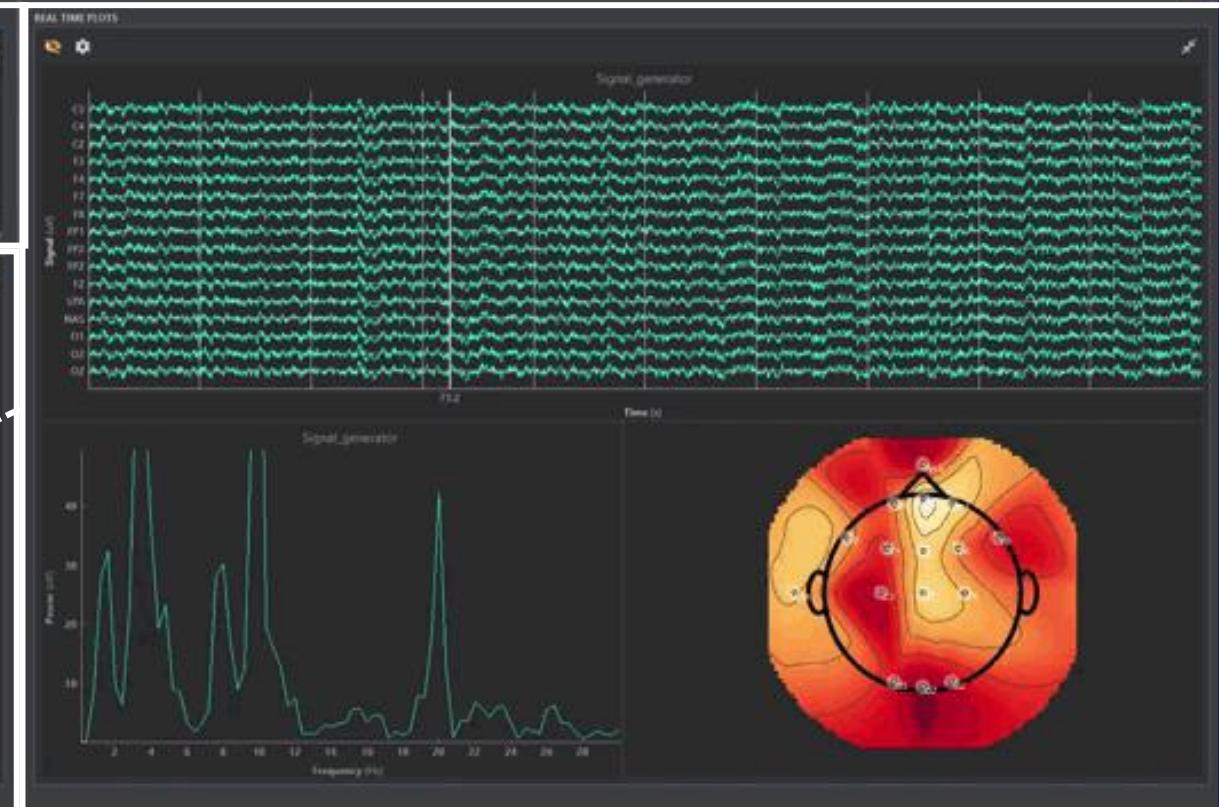
Apps panel



Log panel



Plots panel



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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

The screenshot shows the MEDUSA App Market page. At the top, there is a navigation bar with links for Home, About, Community, Solutions, App Market, Login, and Sign up. Below the navigation bar, there are three app cards displayed in a grid.

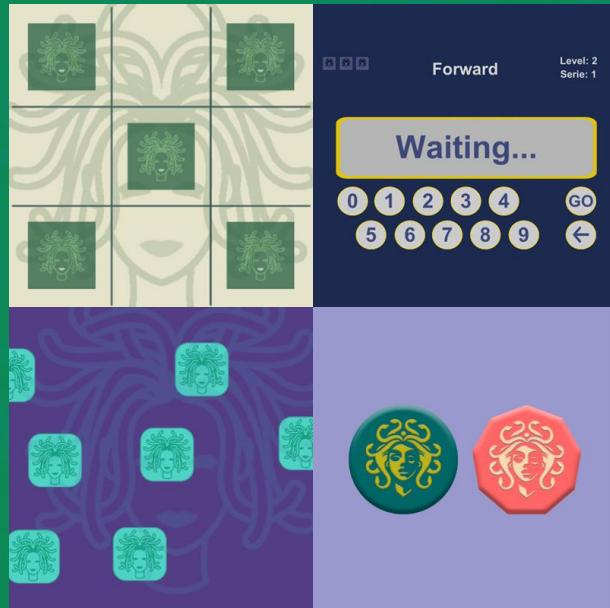
- Checkerboard Reversal Demo**: Developed by vicmarcag. It features a 4x4 grid of colored squares (red, green, yellow, blue) and a small circular cursor. Description: "Checkerboard Reversal task used to study visual processing & elicit visual evoked potentials (VEPs)." Rating: 0.0 stars, 2 reviews.
- c-VEP Speller**: Developed by vicmarcag. It features a 3x3 grid of letters (A-I). Description: "A circular-shifting code-modulated visual evoked potential (c-VEP) speller." Rating: 5.0 stars, 99 reviews.
- ITACA Dual N-Back**: Developed by dmarcos97. It features a 4x4 grid with a repeating pattern of Medusa faces. Description: "The computerised version of the classic neurocognitive test for the assessment of working memory." Rating: 0.0 stars, 25 reviews.



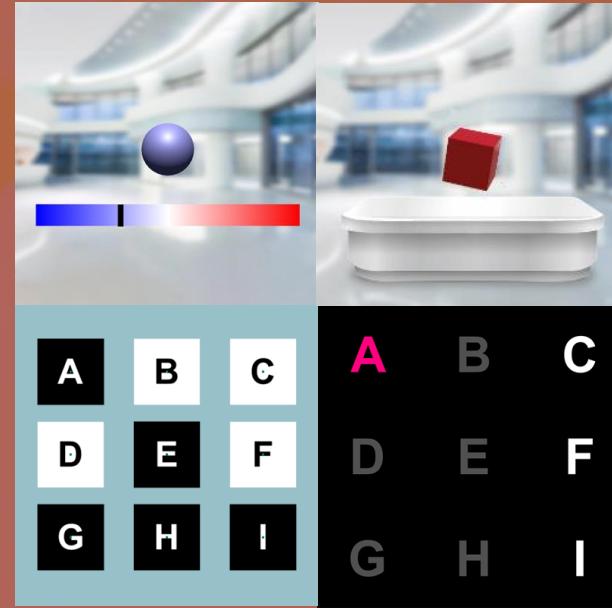
MEDUSA® Platform

Built-in open-source applications

Cognitive Psychology
Tests



State-of-the-art BCI
paradigms



Other apps...



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MEDUSA© Platform

Built-in cognitive psychology tests



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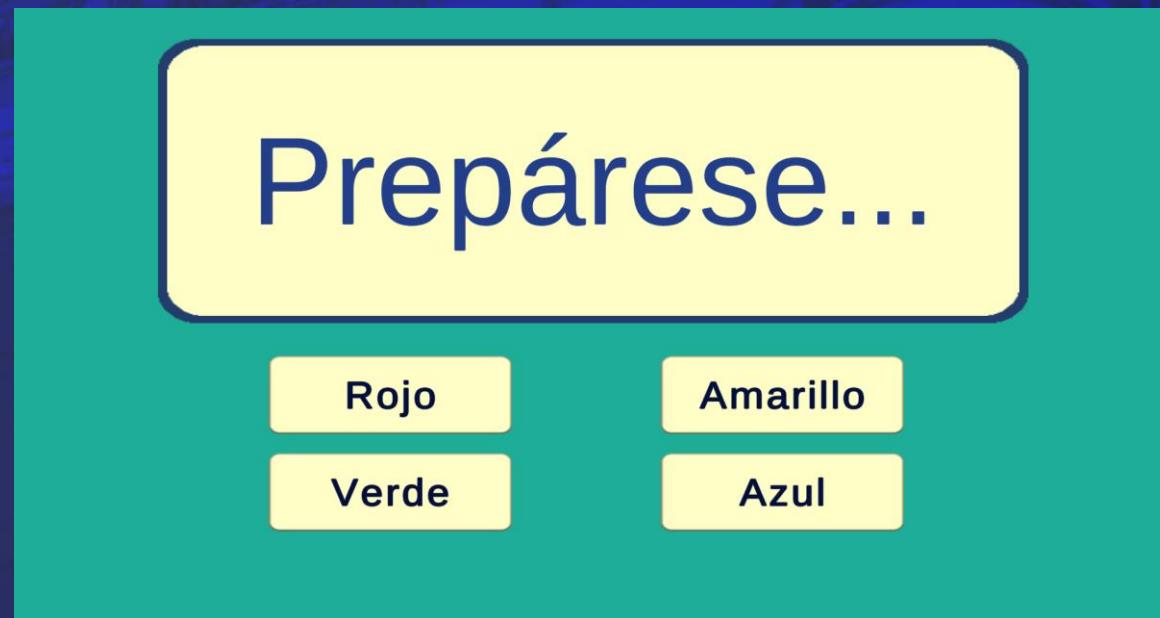
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Built-in cognitive psychology tests

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



medusabci.com/market/stroop

The screenshot shows a digital interface for the ITACA Stroop task. At the top, the word "Yellow" is displayed in large blue letters. Below it, there are two columns of color names: "Red" and "Green" on the left, and "Yellow" and "Blue" on the right. A user profile for "dmarcos97" is shown, along with the text "ITACA Stroop task" and a description: "The computerised version of the neurocognitive test for the evaluation of selective attention." At the bottom, there are rating icons for stars and reviews.

Yellow

Red
Green

Yellow
Blue

dmarcos97

ITACA Stroop task

The computerised version of the neurocognitive test for the evaluation of selective attention.

★ 0.0 ⚡ 8



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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

dmarcos97

ITACA Corsi Block-Tapping Test

The computerised version of the classic neurocognitive test for the assessment of working memory.

☆ 0.0 29



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MEDUSA® Platform

Built-in cognitive psychology tests

- **Digit Span Test**

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

Forward

Level: 5
Serie: 1

1

0 1 2 3 4 GO
5 6 7 8 9 ←

medusabci.com/market/dspan

Forward

Level: 2
Serie: 1

Waiting...

0 1 2 3 4 GO
5 6 7 8 9 ←

dmarcos97

ITACA Digit Span Test

The computerised version of the classic neurocognitive test for the assessment of working memory.

★ 0.5 ⚡ 35



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MEDUSA® Platform

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

The screenshot shows a product listing for the "ITACA Go/No-Go Test". At the top, there are two circular icons: a green one on the left and a red one on the right, both featuring the Medusa logo. Below the icons, the user name "dmarcos97" is displayed next to a small profile picture. The test name "ITACA Go/No-Go Test" is centered above a brief description: "The computerised version of the classic neurocognitive test for the assessment of working memory." At the bottom of the listing, there is a rating section showing "0.0" stars and "21" reviews.

dmarcos97

ITACA Go/No-Go Test

The computerised version of the classic neurocognitive test for the assessment of working memory.

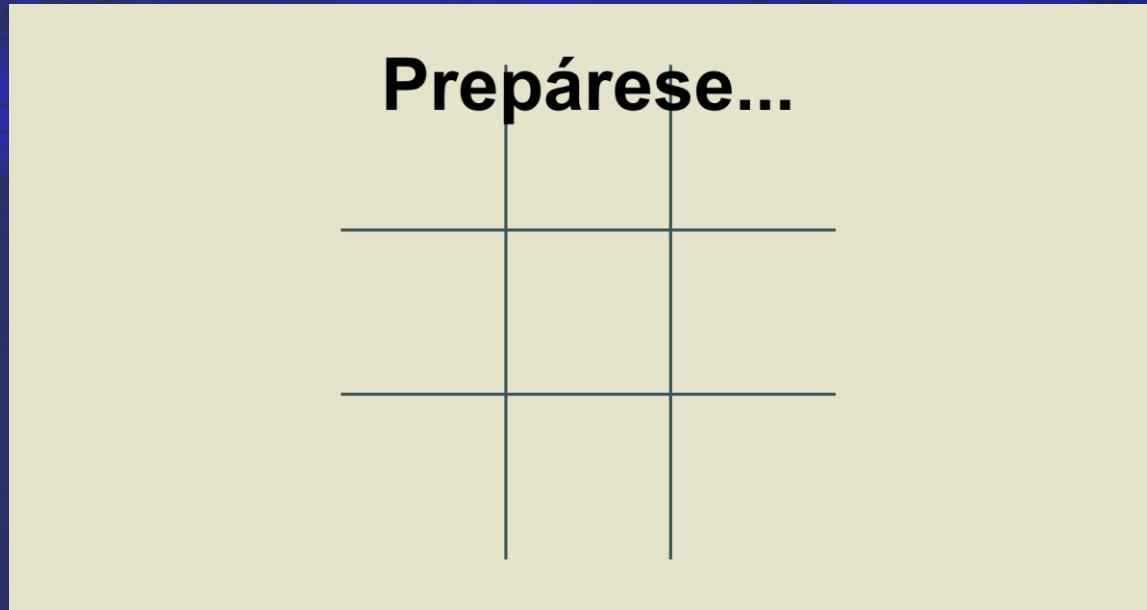
0.0 21



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



medusabci.com/market/dnbck

The screenshot shows a product page for 'ITACA Dual N-Back'. At the top is a 3x3 grid of green squares, each containing a stylized Medusa head. Below the grid is a user profile picture of a man and the name 'dmarcos97'. The product title 'ITACA Dual N-Back' is centered. A descriptive text below it reads: 'The computerised version of the classic neurocognitive test for the assessment of working memory.' At the bottom right are two small icons: a yellow star with '0.0' next to it and a blue diamond with '25' next to it.

dmarcos97

ITACA Dual N-Back

The computerised version of the classic neurocognitive test for the assessment of working memory.

☆ 0.0 ♦ 25

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Built-in BCI paradigms



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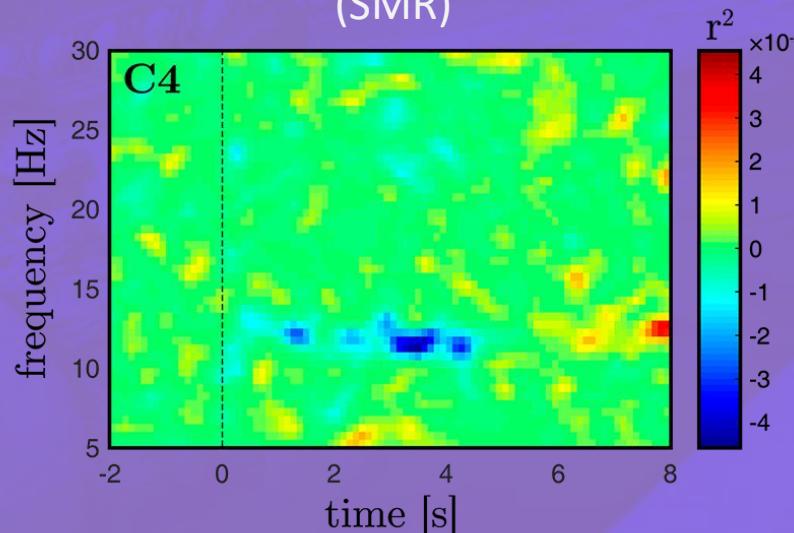
Non-invasive BCI control signals

Control Signals

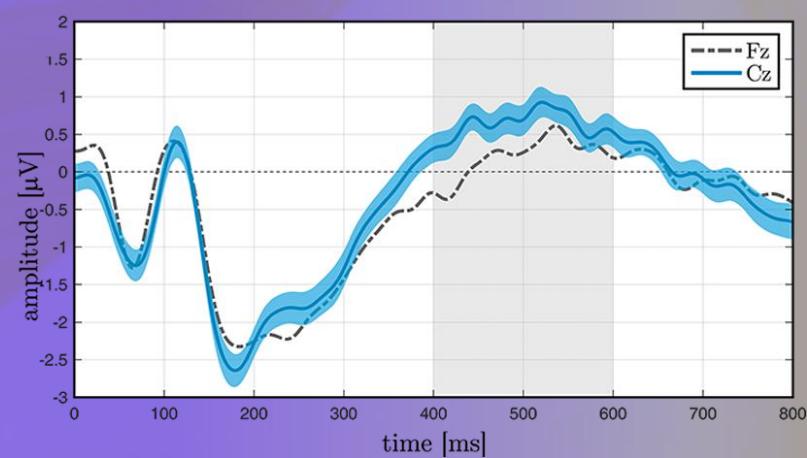
Self-regulated

"Endogenous"

Sensorimotor Rhythms
(SMR)



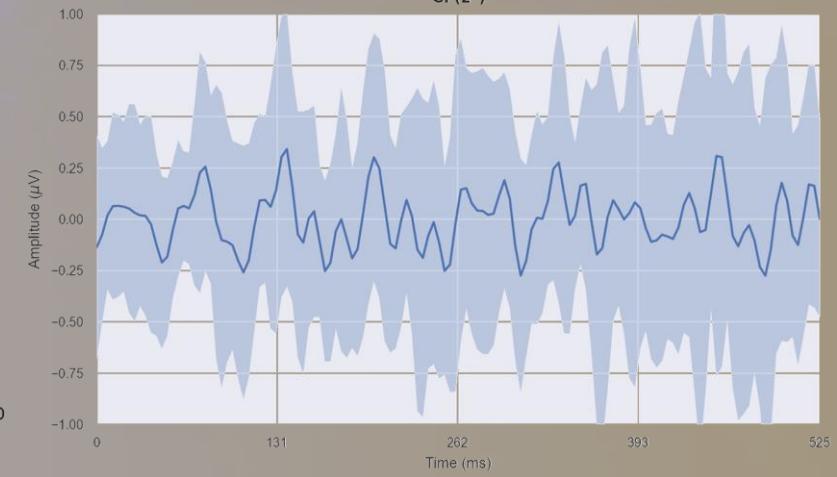
P300 evoked potentials



Natural responses

"Exogenous"

Code-modulated Visual Evoked
Potentials (c-VEP)



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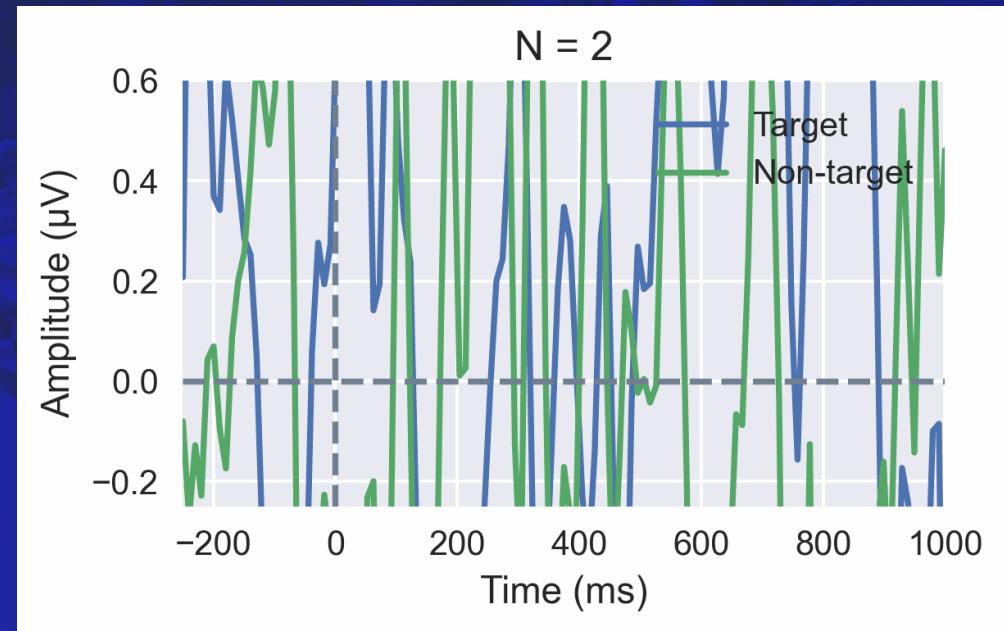


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P300 evoked potentials

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



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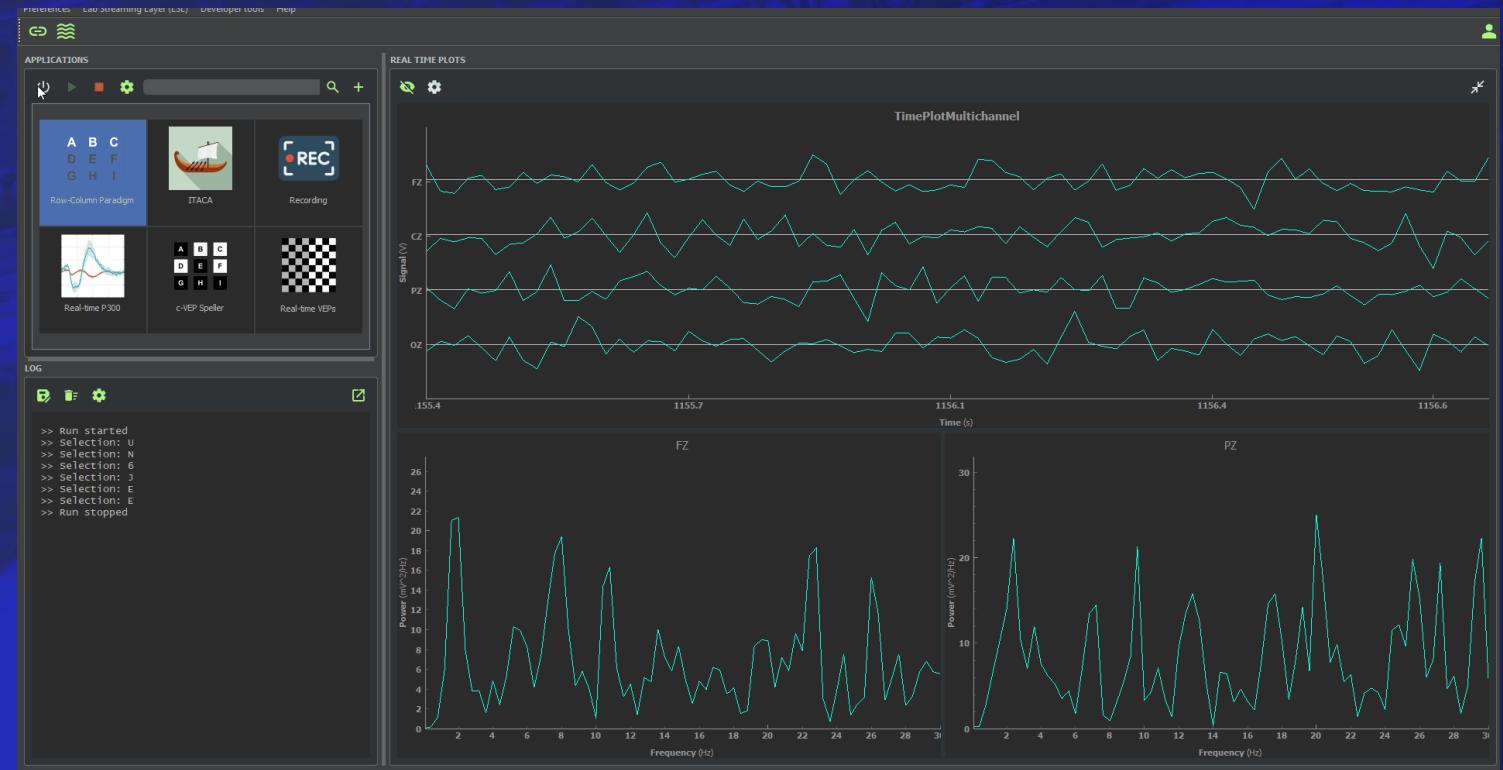


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P300 evoked potentials

Endogenous/Exogenous

- 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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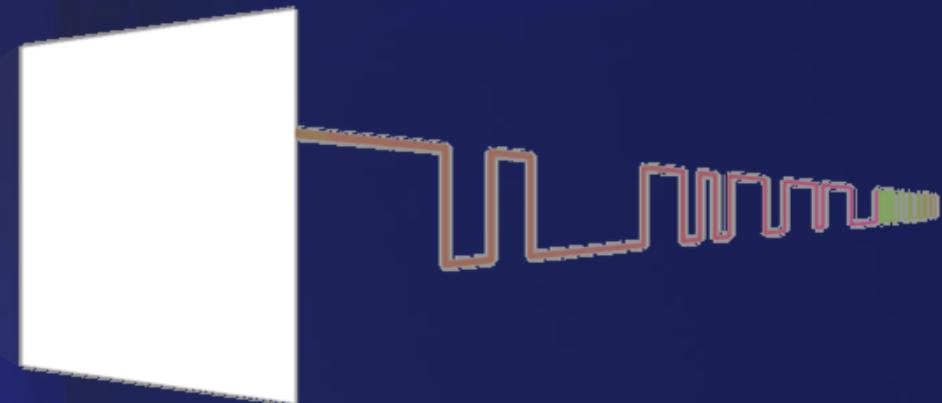
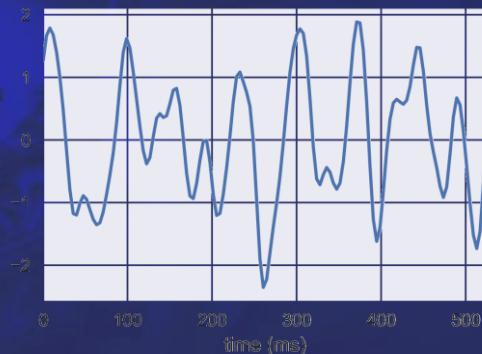


MEDUSA® Platform

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



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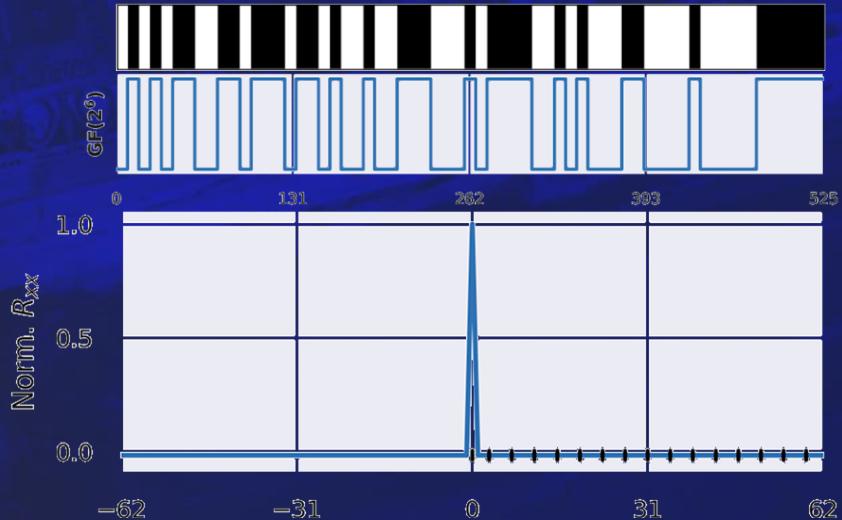
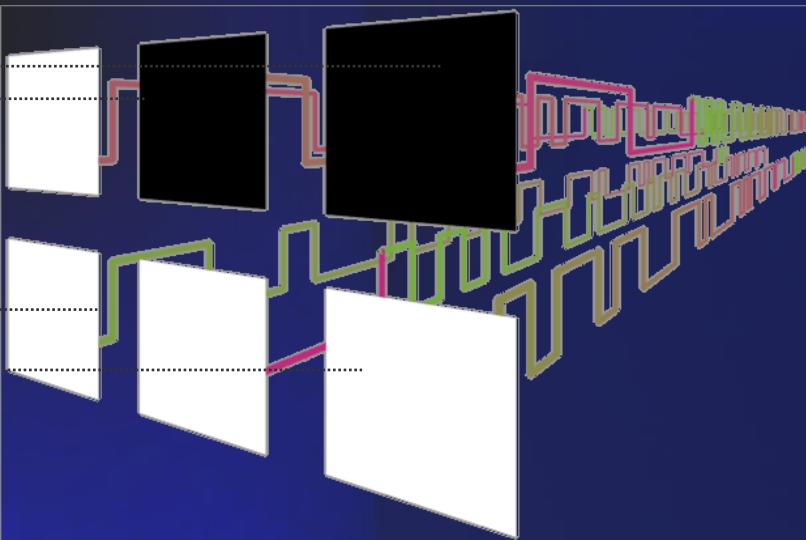
Code-modulated visual evoked potentials

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

A B C
D E F



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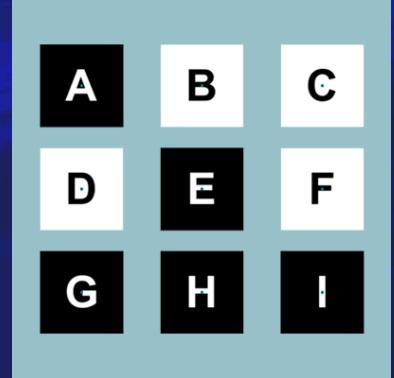
MEDUSA® Platform

Code-modulated visual evoked potentials

Exogenous

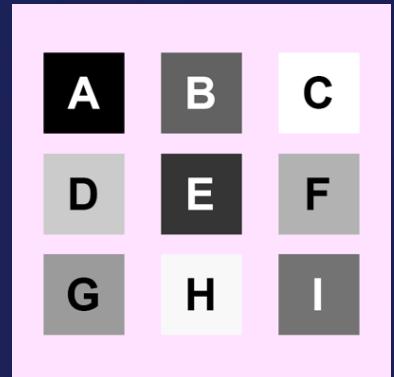


c-VEP Speller



medusabci.com/market/cvep_speller

P-ary c-VEP Speller



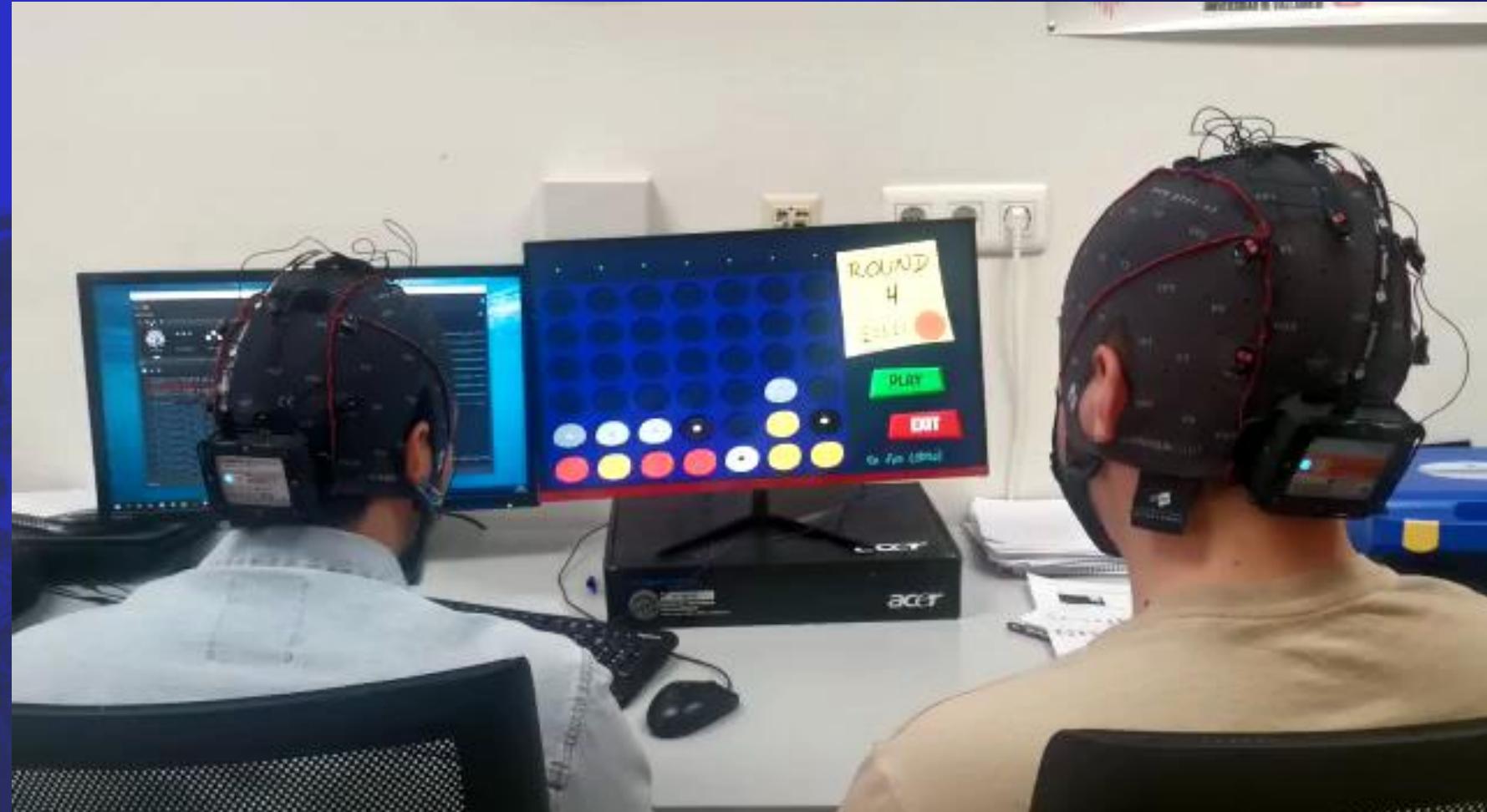
medusabci.com/market/pary_cvep



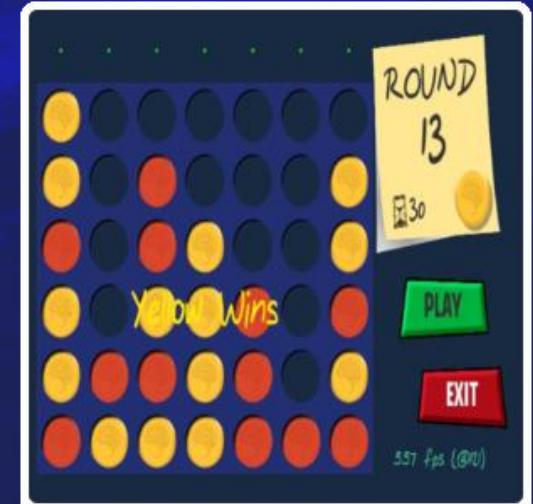
MEDUSA® Platform

Code-modulated visual evoked potentials

Exogenous



medusabci.com/market/connect4



SeleneMC

Connect 4

A version of multiplayer 'Connect 4' video game using c-VEPS

★ 0.0 ⚡ 29



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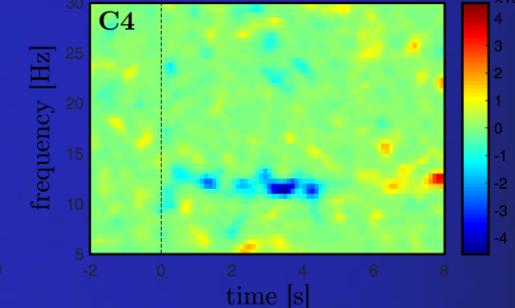
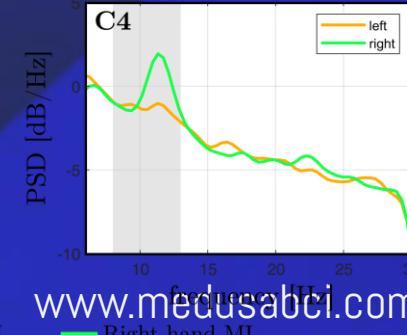
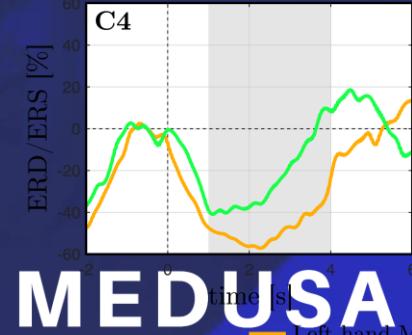
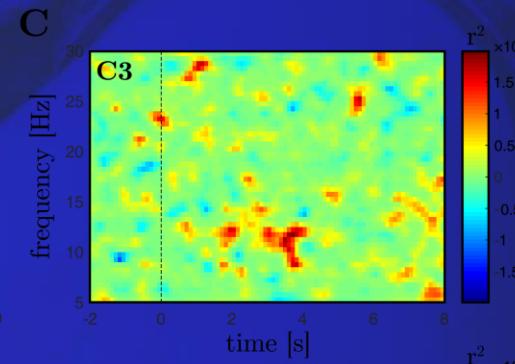
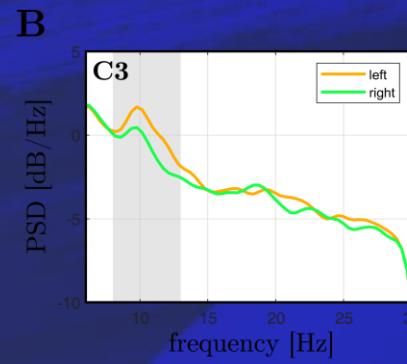
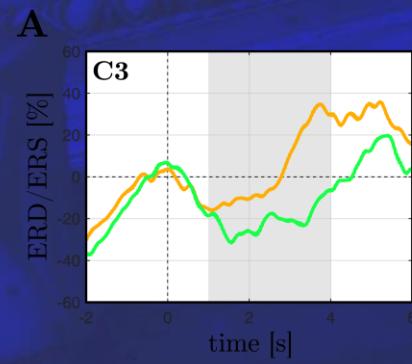


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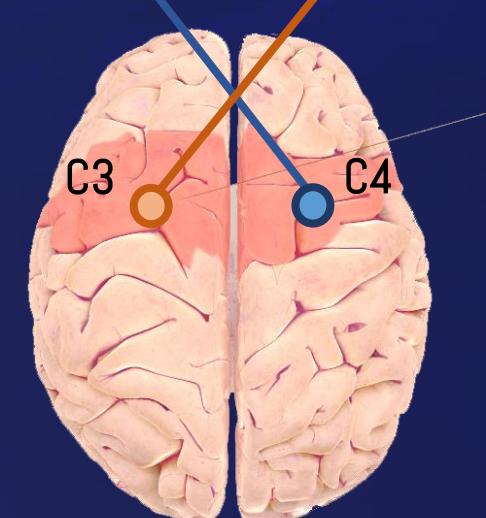
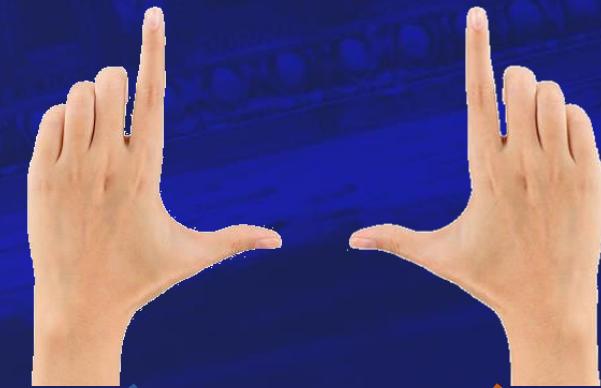
Motor imagery via sensorimotor rhythms

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



www.medusabci.com
— Left hand MI
— Right hand MI



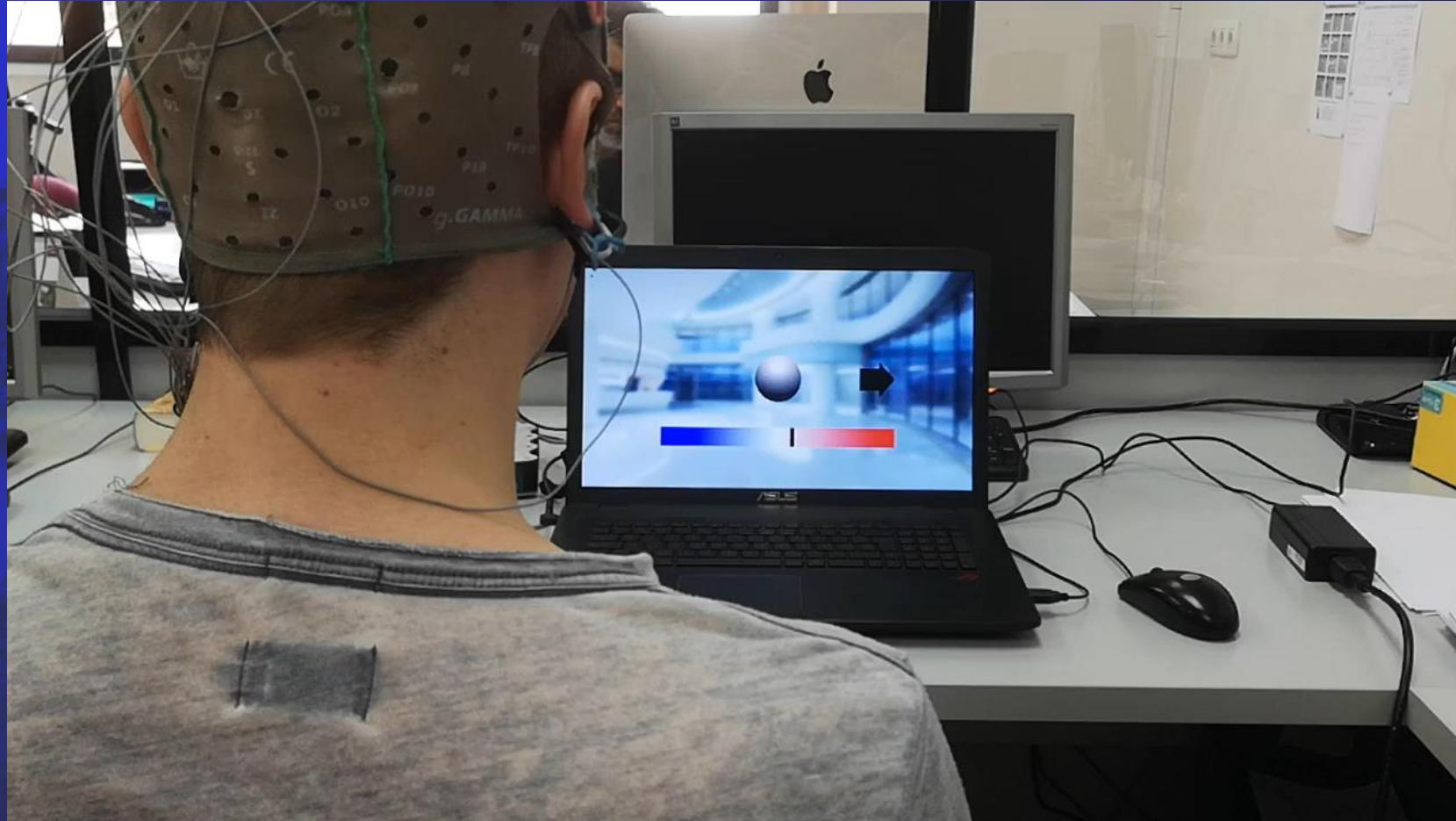
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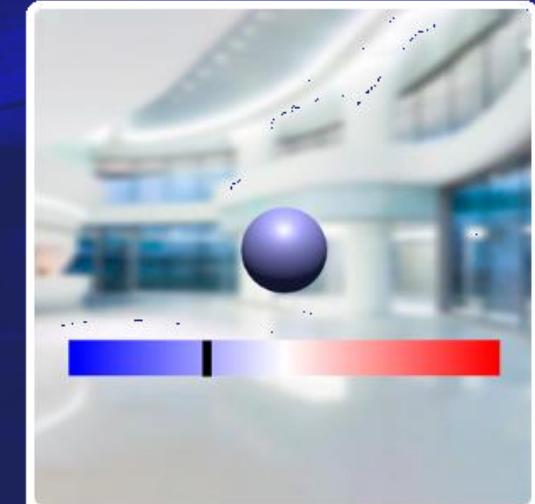
MEDUSA® Platform

Motor imagery via sensorimotor rhythms

Endogenous



medusabci.com/market/mi



Serpeve

Motor Imagery module

Application to perform your motor imagery experiments

★ 0.0 ⚡ 23

(in maintenance)



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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>



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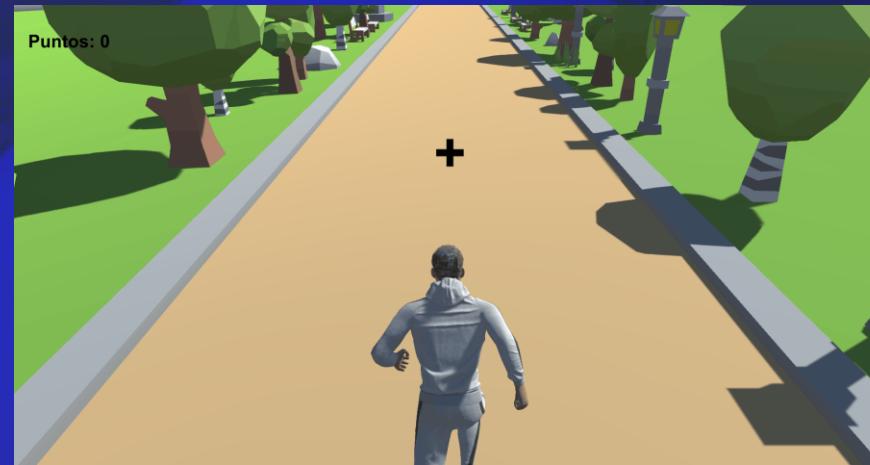
MEDUSA® Platform

Neurofeedback

Endogenous

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



dmarcos97

ITACA Neurofeedback Training

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

★ 0.0 ⚡ 88



MEDUSA® Platform

Neurofeedback



Endogenous

medusabci.com/market/itaca

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ITACA Neurofeedback Training

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

★ 0.0 88



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The background features a photograph of a classical building's facade, likely made of stone, with detailed carvings on the cornices and columns. The lighting suggests it might be at dusk or dawn.

Website



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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



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Dr. Eduardo Santamaría-
Vázquez



Dr. Víctor Martínez-
Cagigal



Dr. Roberto Hornero



Diego Marcos-Martínez



Víctor Rodríguez-González



Sergio Pérez-Velasco



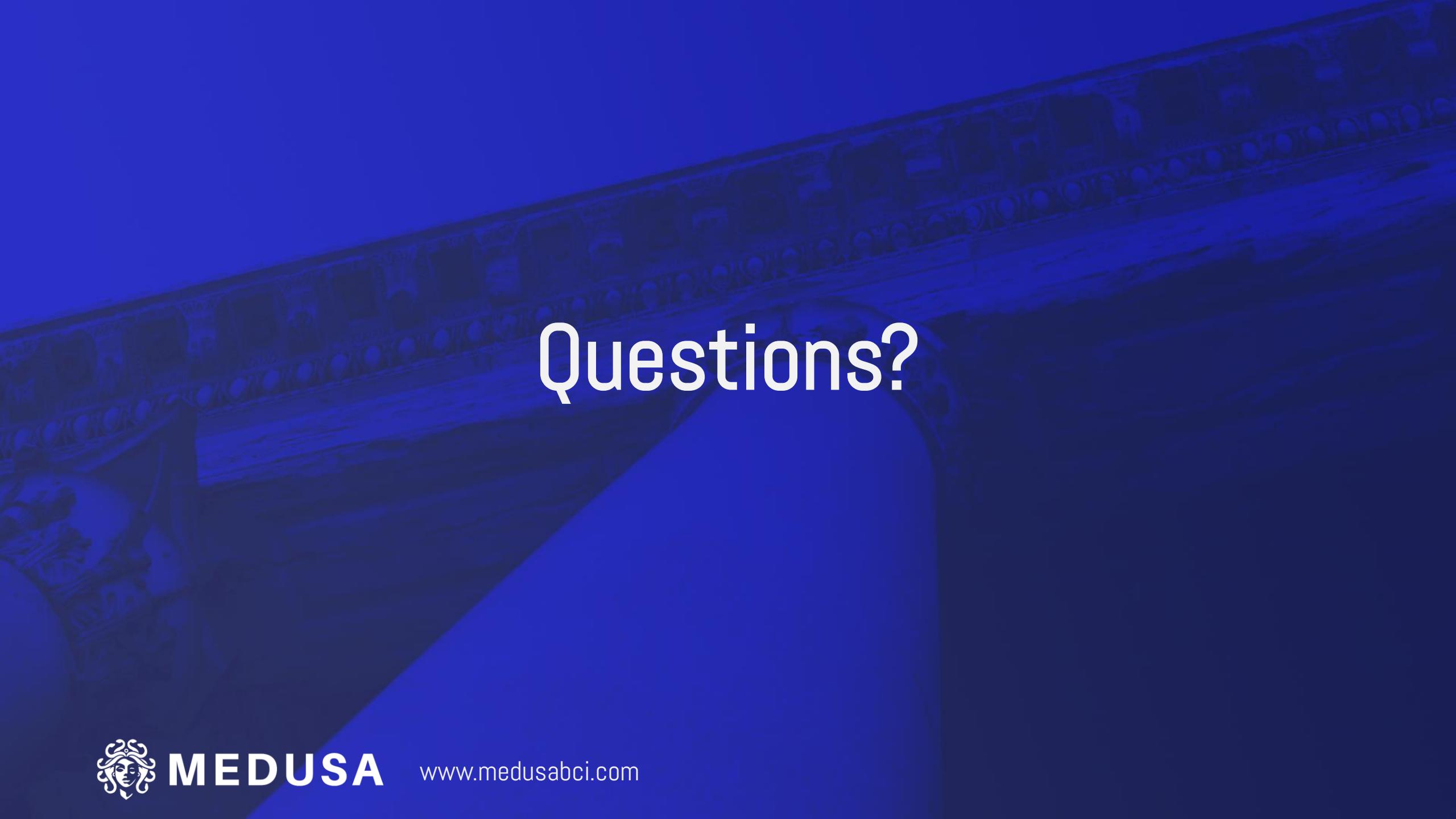
Selene Moreno-Calderón



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
3. Sergio Pérez-Velasco, Eduardo Santamaría-Vázquez, Víctor Martínez-Cagigal, Diego Marcos-Martínez, Roberto Hornero, EEGSym: Overcoming Inter/subject Variability in Motor Imagery Based BCIs with Deep Learning, IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 30, pp. 1766-1775, Junio, 2022, DOI: 10.1109/TNSRE.2022.3186442
4. Diego Marcos-Martínez, Eduardo Santamaría-Vázquez, Víctor Martínez-Cagigal, Sergio Pérez-Velasco, Víctor Rodríguez-González, Ana Martín-Fernández, Selene Moreno-Calderón, Roberto Hornero, ITACA: An open-source framework for Neurofeedback based on Brain-Computer Interfaces, Computers in Biology and Medicine, vol. 160, Junio, 2023, DOI: 10.1016/j.combiomed.2023.107011
5. Selene Moreno-Calderón, Víctor Martínez-Cagigal, Eduardo Santamaría-Vázquez, Sergio Pérez-Velasco, Diego Marcos-Martínez, Roberto Hornero, Combining brain-computer interfaces and multiplayer video games: an application based on c-VEPs, Frontiers in Human Neuroscience, vol. 17, Agosto, 2023, DOI: 10.3389/fnhum.2023.1227727
6. Álvaro Fernández-Rodríguez, Víctor Martínez-Cagigal, Eduardo Santamaría-Vázquez, Ricardo Ron-Angevin, Roberto Hornero, Influence of spatial frequency in visual stimuli for cVEP-based BCIs: evaluation of performance and user experience, Frontiers in Human Neuroscience, vol. 17, Noviembre, 2023, DOI: 10.3389/fnhum.2023.1288438
7. Víctor Martínez-Cagigal, Eduardo Santamaría-Vázquez, Sergio Pérez-Velasco, Diego Marcos-Martínez, Selene Moreno-Calderón, Roberto Hornero, Non-binary m-sequences for more comfortable brain-computer interfaces based on c-VEPs, Expert Systems With Applications, vol. 232 (120815), Diciembre, 2023, DOI: 10.1016/j.eswa.2023.120815
8. Sergio Pérez-Velasco, Diego Marcos-Martínez, Eduardo Santamaría-Vázquez, Víctor Martínez-Cagigal, Selene Moreno-Calderón, Roberto Hornero, Unraveling motor imagery brain patterns using explainable artificial intelligence based on shapley values, Computer Methods and Programs in Biomedicine, vol. 246, pp. 108048, Abril, 2024, DOI: 10.1016/j.cmpb.2024.108048



Questions?



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Practical Workshop



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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



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Module 1: Configure MEDUSA© Platform

Task 1.3: Configure plots panel

Module 2: Learn to work with apps



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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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