Reframing Brain-Computer Interfaces as Plug-and-Play Assistive Peripherals for Existing Assistive Technologies

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Valentina Caracci
PhD student

Bio

- Bachelor Degree in Clinical Engineering, Sapienza University of Rome
  → 2019
- Master Degree in Biomedical Engineering, Sapienza University of Rome
  → 2022
- Research collaborator at IRCCS Fondazione Santa Lucia (NeiLab) in Rome
  → May 2022 - current
- PhD Student in Automatic Control, Bioengineering and Operations Research (ABRO), Sapienza University of Rome
  → Novembre 2023 - current

Research interests at a glance

- Advanced techniques for bio-signal processing (EEG, ECG) aimed at studying responsiveness' fluctuations in patients with Disorders of Consciousness (**GR-2019-12369824**).
- Brain-Computer Interface for communication and Assistive Technology (**PNRR POC-2023- 12377627**).

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Assistive Technologies (AT)

Rethinking Disability

"Medical problem belonging to a person" →

World Health Organization (**WHO**)

*"A complex phenomenon resulting from the **interaction between a person's health condition and the environment they live in**"*

Disability as a result of the **mismatch between a person's condition and their environment**

Assistive Technology

Any device, software, or system that allows individuals to perform tasks they would otherwise be unable to do

- Designed for anyone facing **physical** or **cognitive limitations**;
- From simple low-tech tools (e.g., a picture board) to high-tech electronic devices.

AT as a bridge

→ restoration of **autonomy**, **dignity**, **participation** in society and **communication**

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The "Glasses" Example

A person with a severe visual impairment, without eye doctors would face a huge disability

→ ***changing the environment*** *by providing glasses, their limitations disappear.*

ATs act like "glasses", designed to:

i. Remove **environmental barriers**;
ii. Improve **independence**;
iii. Promote **well-being**.

AT as a bridge

→ restoration of **autonomy, dignity, participation** in society and **communication**

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Open challenge

Digital assistive devices and access methods are powerful, but always **require a reliable physical/muscular movement** to press a button or explore a screen with the gaze

AT as a bridge

*what if a **severe neurological condition** (e.g., ALS, LIS, stroke) **impairs all motor abilities?***

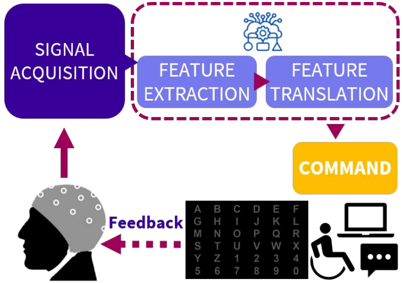
→ traditional technology is **inaccessible**

Brain Computer Interfaces (BCIs) for communication

Brain signals to provide a **non-muscular** outward channel → translation of intentions into commands

Possibility to control a **communication system** without any motor action

Suitable opportunity for people with severe muscular disability

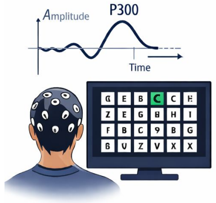


- **Invasive**: electrodes surgically implanted into brain tissue → ECoG, Intracortical
- **Non-Invasive**: surface electrodes, no surgery required → **EEG**

Input control signals

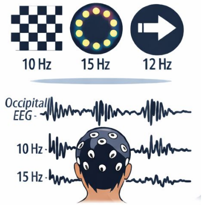
P300-based:
P300 Event-Related Potential

- positive ERP elicited by rare and relevant stimuli → **oddball paradigm**
- 300 ms after the stimulus
- high level of cognitive processing



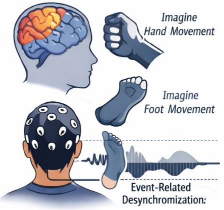
SSVEP-based:
Steady-State Visually Evoked Potential

- EEG sinchronization with the specific frequency of a steady flickering stimulus



MI-based: Motor Imagery

- imaging limb movements (hand, foot) → EEG changes in the **motor cortex**
- No external stimulation required
- Extensive training



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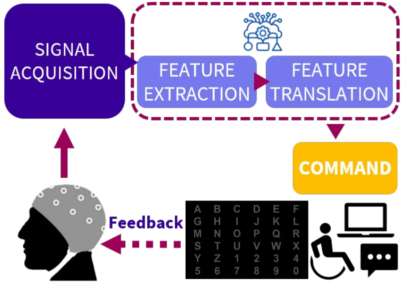

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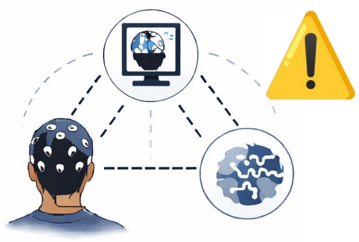
BCIs OPTIMIZATION FOR ASSISTIVE TECHNOLOGIES

BCIs are still rarely adopted in real-world AT services



BCI- centered design

Communication interfaces, control applications and interaction logic all incorporated within the BCI system

- ⚠ Lack of **personalization**, **flexibility** and **usability**;
- ⚠ Requirements for specialized BCI technicians → limited **scalability** and **sustainability** in home and clinical settings;
- ⚠ Lack of **modularity** → reduced **interoperability** and possibility of hybrid access strategies through different input devices.

Purpose

Mitigation of some of the main barriers to BCI adoption in real-world AT ecosystems

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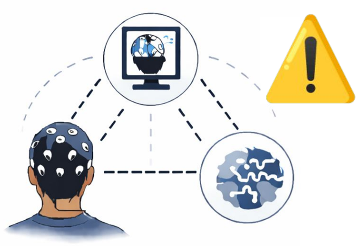

Conceptual and architectural shift

BCI- centered design

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AT- centered design

BCIs as components within the existing assistive ecosystem

Core idea: BCIs as **plug-and-play peripherals** integrated into the AT-software analogous to standard AT input devices

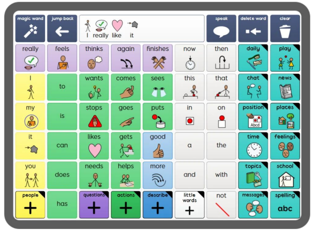
Conceptual architecture

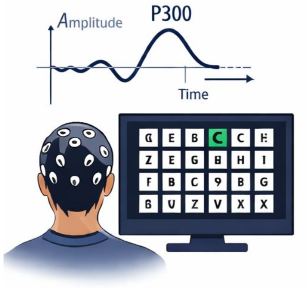
Grid3 AT-software (Smartbox)

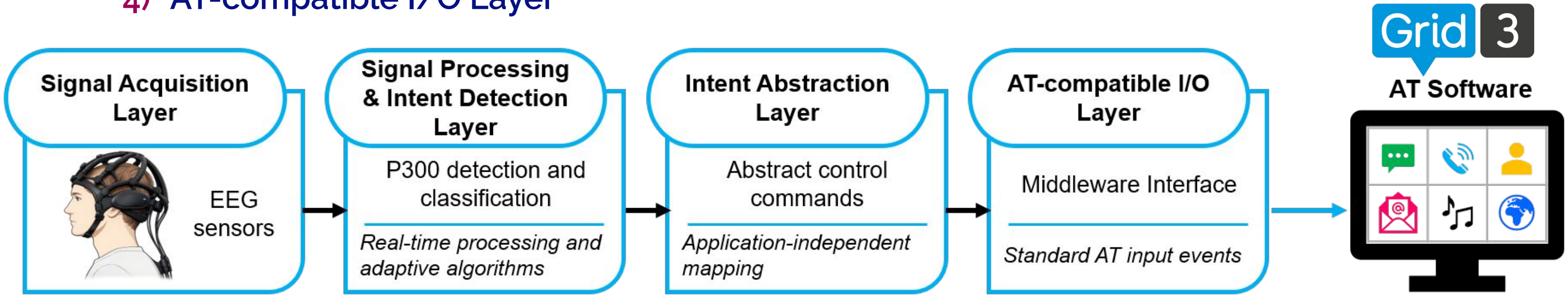
P300-based control → overlay of visual stimuli (i.e., flashing elements as in a **P300-Speller**) onto the interface icons

System architecture organized into **4 conceptual layers**

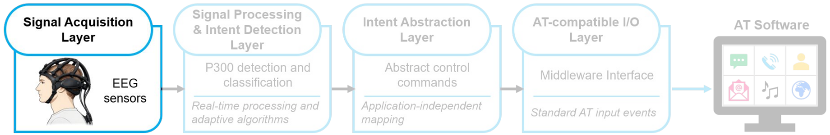
1) Signal Acquisition Layer
2) Signal Processing and Intent Detection Layer
3) Intent Abstraction Layer
4) AT-compatible I/O Layer







Conceptual architecture
Signal Acquisition Layer



Non invasive EEG sensors to capture brain signals related to user intentions

Gold standard in laboratories: **gel-based caps**

Ag/AgCl sensors with conductive gel

Translation to home-settings: **commercial semi-dry caps**

Sponges with electrolyte solutions

✓ Pros

good signal quality; **flexible configurations** according to the specific signal to acquire

✘ Cons

EEG cap **discomfort**; need to **wash hair** after use;
time consuming setups by specialized **technicians**

✓ Pros

good signal quality; increased **comfort**;
no need to wash hair after use; **fast and easy** setups;
no interference with activities of daily-living

✘ Cons

fixed configurations not always optimized for the signal of interest (i.e., P300-applications)

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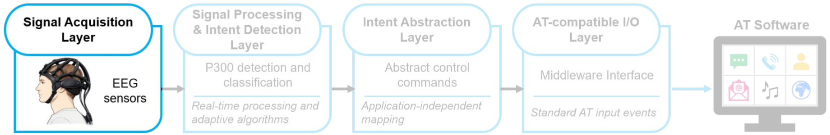
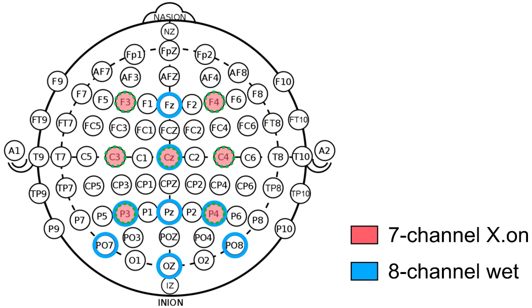
Conceptual architecture
Signal Acquisition Layer

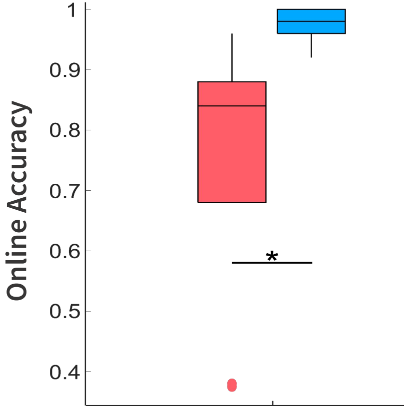


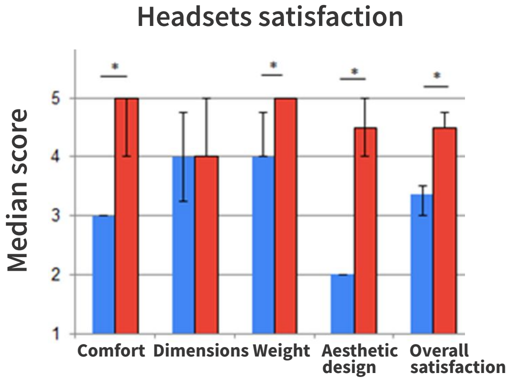
Experiment 01

Comparison of a traditional **gel-based cap** (**8-channel montage optimized for P300 applications**) with the commercial semi-dry **X.on headset** (**7 channels**)

- 10 subjects
- traditional **P300-speller** performed
- **online accuracy** evaluation
- participants' **satisfaction** assessed







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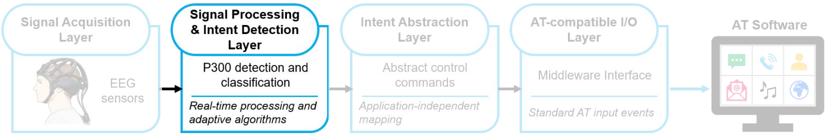
Conceptual architecture

Signal Processing & Intent Detection Layer

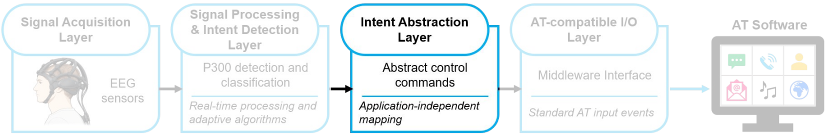


Embedded processing units with straightforward procedures to perform real-time signal processing and classification of the P300 feature

- **BCI2000 framework** (modified)
- Calibration phase required
- P300-based **synchronous** classification:
  - fixed number of stimuli → constant selection speed
  - no adaptation to user attention levels
- Classifier → **SWLDA**

- Development of a **dedicated framework** for signal processing and classification
- Automated and adaptive calibration
- P300-based **asynchronous** classification
  - online adaptation of the number of stimuli
  - sensibility to user attention's decrease
  - self-adaptive algorithms to address signal non-stationarity

Conceptual architecture
Intent Abstraction Layer



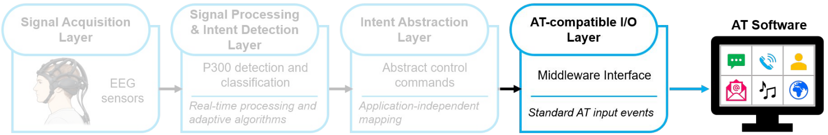
Mapping of detected intentions to abstract control commands, independent of specific AT applications

Flexibility and different interaction strategies supported → interoperability with **different AT software**; possibility for an extension toward **hybrid** control paradigms (e.g., combining EEG and residual motor inputs)

1. The **BCI2000 framework** operates the classification
2. The selected stimulus is **mapped** onto the buttons' locations of the AT-software interface

No more dependency from the BCI2000 framework

Conceptual architecture
AT-compatible I/O Layer



Translation of commands into standard inputs compatible with commercial AT software

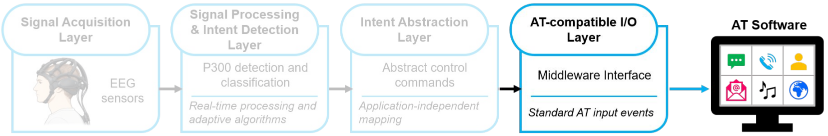
- **Software application** for the communication between the BCI and the AT software to:
  - **synchronize** the stimulation
  - **perform actions** on the AT software interface

- A **click** is performed in the location of the button corresponding to the mapped classified stimulus from the **Intent Abstraction Layer**
- Software application for **buttons detection** → computational costs, FP and FN risk, manual verification required

Access to the **APIs** of the AT software:

- customization of the control command from the click to the **direct activation** of the button
- **buttons detection** → lower computational costs, FP and FN reduction, no need for manual verification

Conceptual architecture
AT-compatible I/O Layer



Translation of commands into standard inputs compatible with commercial AT software

- Connection of the BCI device to the user's PC as a **conventional input peripheral**
  - all demanding operations are performed within the BCI device

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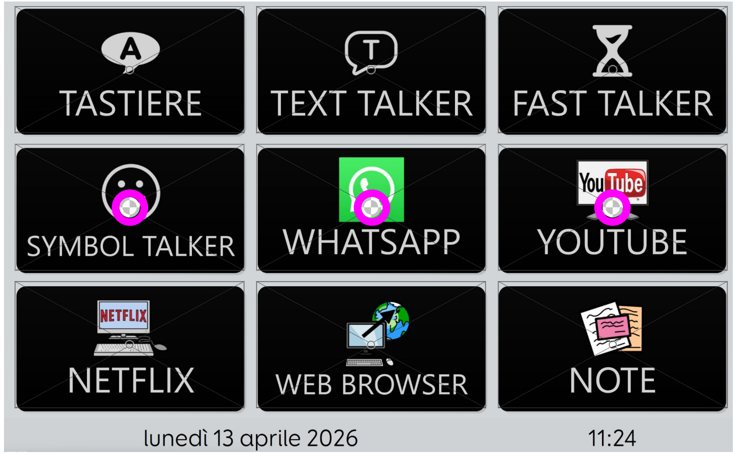
Conceptual architecture

AT-compatible I/O Layer

Translation of commands into standard inputs compatible with commercial AT software

- **Graphical overlay** for the stimulation
  - stimuli to elicit the P300 are directly overlaid on the AT interface



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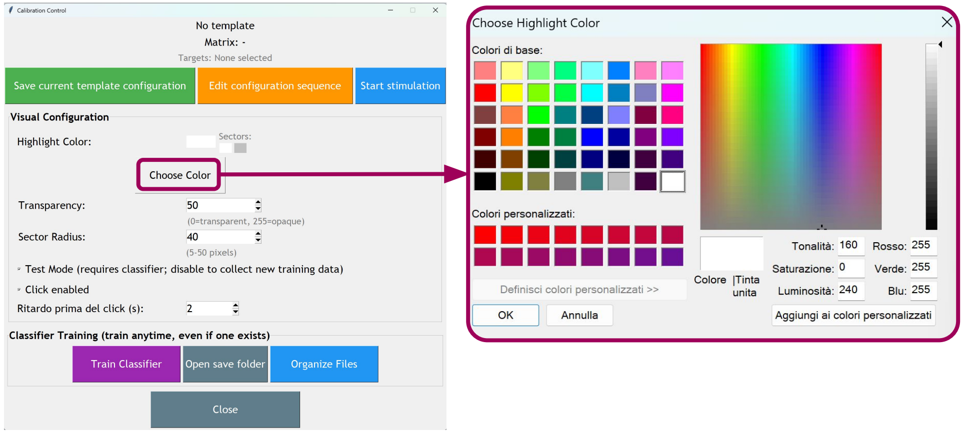
Conceptual architecture

AT-compatible I/O Layer

Translation of commands into standard inputs compatible with commercial AT software

- High **customizable stimulation** settings in terms of shape, color and stimulation speed



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Validation Strategy

User-centered process in collaboration with AT services → professional and end-users involved to evaluate technical feasibility, ecological validity and integration within AT workflows

Qualitative feedback to assess:

- Usability
- Setup simplicity (e.g., cap montage, calibration time, caregiver workload)
- Reliability
- Robustness in real-world settings
- User acceptance
- Perceived benefit

ISO 9241-210 User-Centered Design Framework

- **Effectiveness** → min 70% accuracy for satisfactory communication
- **Efficiency** → Information Transfer Rate and NASA Task Load Index (perceived cognitive load)
- **Satisfaction** → QUEST 2.0 for AT acceptance and setup

Advantages and challenges

Advantages of the proposed approach

- ✓ **Interoperability** → BCI supported by any AT software
- ✓ **Personalization** → full costomization
- ✓ **Sustainability** → no BCI experts needed for setup, calibration, troubleshooting, maintenance
- ✓ **Hybrid control system** → the AT software "sees" standard inputs: the control signal (e.g., **SSVEP**, **MI**) or sensors can vary according to the user's evolving condition
- ✓ **Hybrid access strategies** → BCIs to complement, rather than replace, other assistive input devices
- ✓ Compact and integrated solutions with **low computational load** for the user's PC
- ✓ Usability validation and successful criteria **directly evaluated by end users and AT experts**

Challenges

- ! Individuation of reasonable **trade-offs** between generality and performance
- ! Ensure **robustness** and **stability** across heterogeneous and evolving conditions, and over the long term

Thank you for your attention

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