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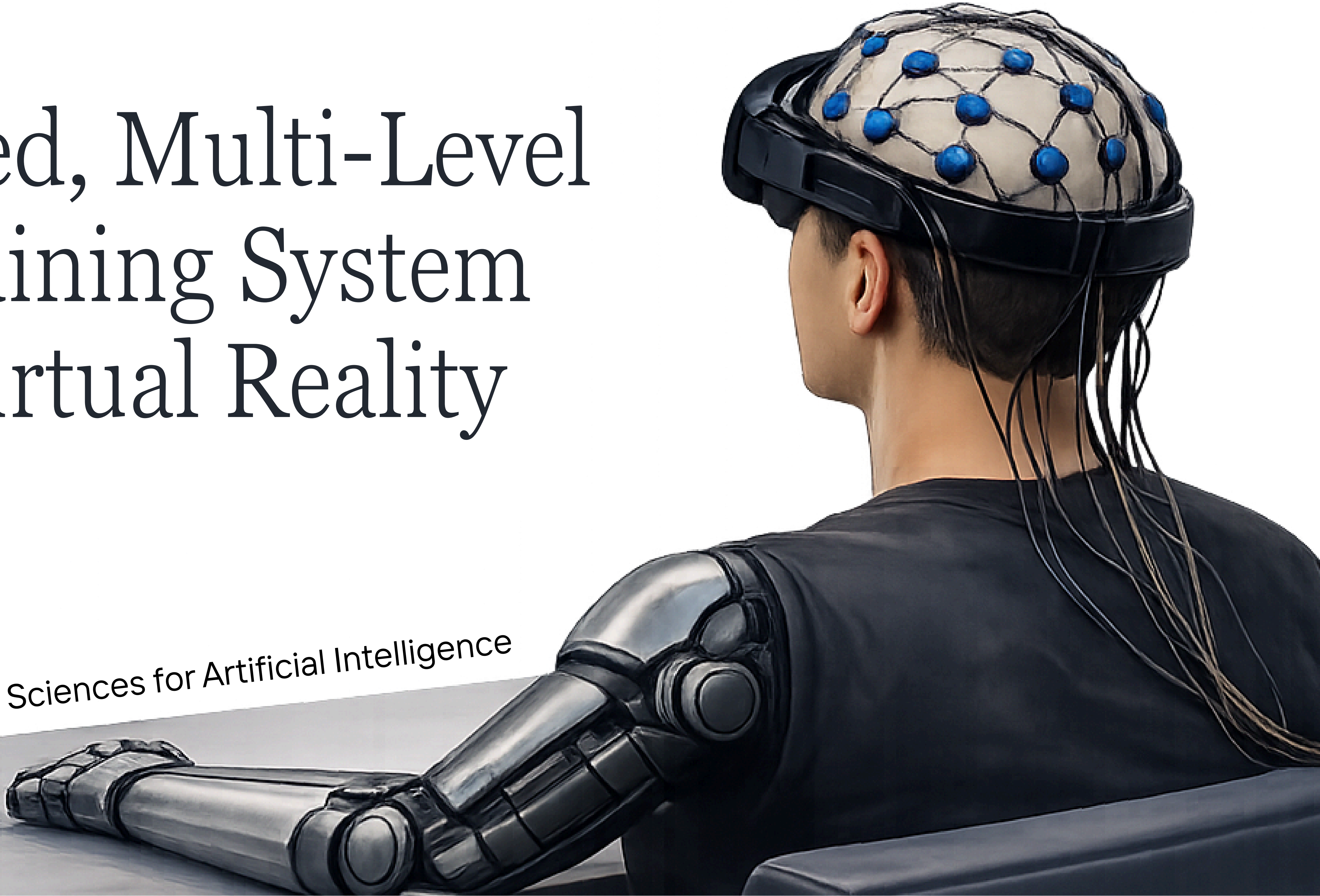
UniSR Università Vita-Salute San Raffaele

A Human-Centered, Multi-Level Rehabilitation Training System Using EEG and Virtual Reality



Giulia Caffi: MSc in Medicine and Surgery
Rebecca Metallo: BSc in Mathematical and Computing Sciences for Artificial Intelligence

Motor Impairment & Rehabilitation Challenges

Individuals with complete or partial motor impairment face long, demanding rehabilitation paths.

GOALS

- Recovery or compensation of motor function,
- Restoration of autonomy,
- Long-term engagement and motivation.

CLINICAL NEEDS

- Safe environments for repeated practice
- Adaptation to different motor profiles
- Support for motivation and adherence over time

CHALLENGES

Rehabilitation requires repetition, consistency, and progressive difficulty.

Traditional approaches are often:

- Physically demanding,
- Monotonous,
- Frustrating

Virtual Reality in Motor Rehabilitation

VR is widely used as:

- A safe and controlled environment
- A tool to increase engagement and motivation
- A platform for repetitive, task-oriented training

VR enables users to:

- Observe movements
- Interact with embodied avatars
- Practice safely, without physical risk

Clinical benefits of VR-based rehabilitation:

- Improved motor learning
- Increased training adherence
- Support of neuroplasticity through repetitive, goal-directed tasks

Sveistrup, 2004; Baldominos et al., 2015

EEG-Based Rehabilitation & Neuroplasticity

EEG enable access to motor intentions without physical movement.
Relevant for individuals with absent/inconsistent motor output, for whom traditional rehabilitation approaches are limited

EEG-based motor imagery training can:

- activate motor-related cortical areas,
- support functional reorganization and neuroplasticity.

Learning stable EEG patterns is difficult, slow, and cognitively demanding.
Visual Feedback reinforces:

- motor learning processes,
- user awareness and agency.

Feedback-driven BCI training has shown potential for rehabilitation and motor recovery (Saito et al., 2023)

Project Proposal

VR
Supports engagement and repetition

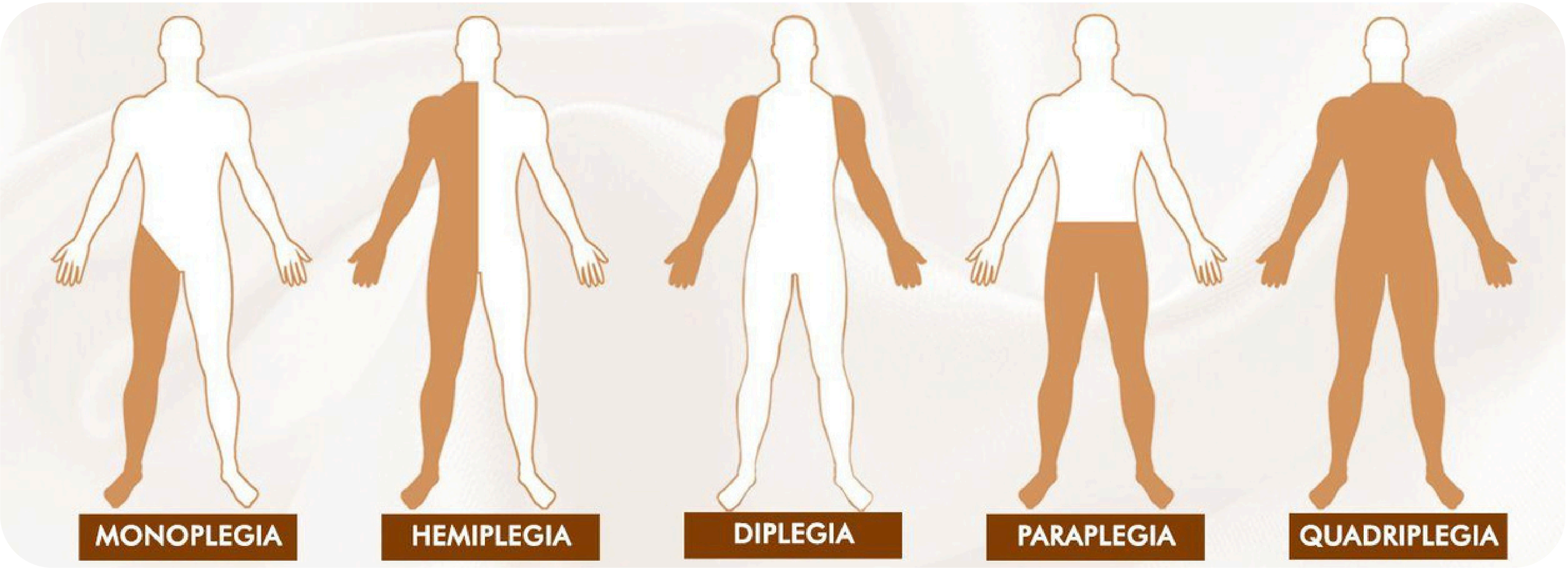
\+

EEG
Enables interaction without movement

A powerful rehabilitation tool

Target Users

User Type	Motor Function	Goal
Complete Paralysis	No voluntary muscle activation	Assistive control of prostheses or exoskeletons
Incomplete Paralysis	Residual motor function	Rehabilitation and improvement of motor execution



Context of Use

CLINICAL SETTING

Users perform supervised sessions with clinicians or therapists, following structured rehabilitation protocols and integrating existing exoskeleton or prosthesis systems.

HOME-BASED

Users engage in independent training routines according to personalized schedules, with a platform designed for high usability and minimal setup.

Personas

From the analysis, the key user needs are:

1. Feedback
2. Progression
3. Motivation
4. Adaptivity
5. Cognitive Load
6. Tracking
7. Safety

Marco Rossi "The determined Assistive User"

Motivated | Tech-Savvy | Patient | Hopeful

"I just want to feel in control again."

Age: 32
Gender: Male
Work: Former engineer (now unemployed)
Family: Lives with partner
Location: Milan, Italy
Character: Determined, analytical

Goals

- Regain a sense of independence in daily activities
- Reduce reliance on caregivers for basic tasks
- Improve emotional well-being by feeling capable and autonomous

Motivation

Incentive
Fear
Growth
Power
Social

Frustrations

- Fear of not improving despite his motivation
- Emotional fatigue from repetitive failed attempts to regain control
- Difficulty finding technologies that truly meet his needs

Personality

Introvert – Extrovert
Thinking – Feeling
Sensing – Intuition
Judging – Perceiving

Bio

Marco, 32, suffered a complete C5 spinal cord injury two years ago. A former engineer, he is currently unemployed due to the loss of motor function, which has deeply impacted his sense of identity and independence. Although he has no voluntary limb movement, his cognition remains fully intact, and his technical background fuels his strong motivation to engage with innovative assistive technologies. Living at home with his partner, he regularly attends physiotherapy and actively explores new solutions that might help him regain autonomy in daily life.

Preferred Channels

Traditional Ads
Online & Social Media
Referral
Clinician Referrals

Design Implications

1. Feedback
2. Progression
3. Motivation
4. Adaptivity
5. Cognitive Load
6. Tracking
7. Safety

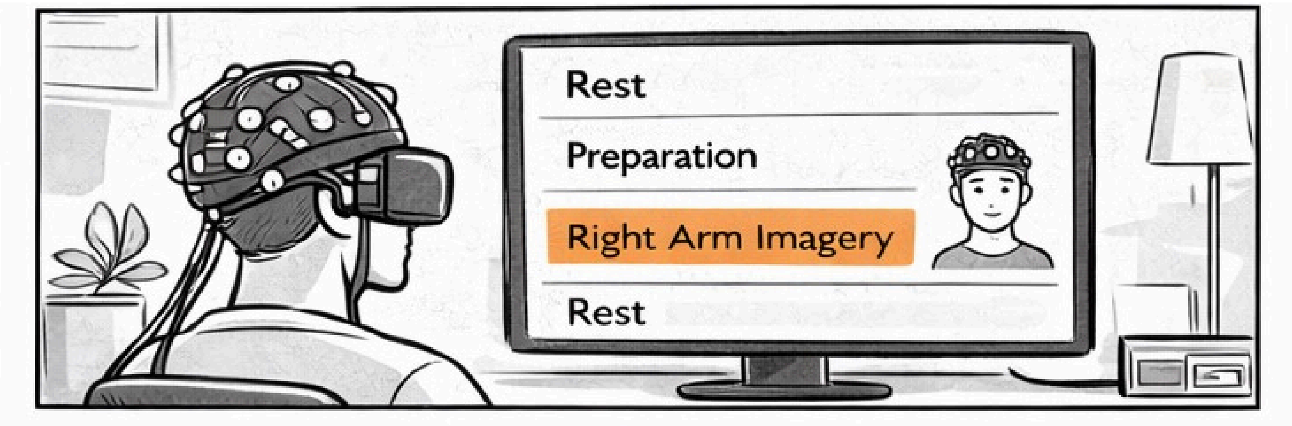
1. **Visual Feedback** explicitly representing task state and classification outcome.
2. **Multi-Level Training** with progressive difficulties unlocked only when performance criteria are met
3. **Game-like interaction design** and **customizable environment**
4. **Dual Interaction Paths**: EEG-only (if complete paralysis), EEG + EMG + IMU (if residual motor function).
5. **Interface** designed to minimize frustration and maximize sense of agency.
6. **Monitoring**: Access to session summaries and longitudinal performance data via the companion application.
7. **Assistive device control** is enabled only after reliable and stable intention decoding is achieved.

Storyboard

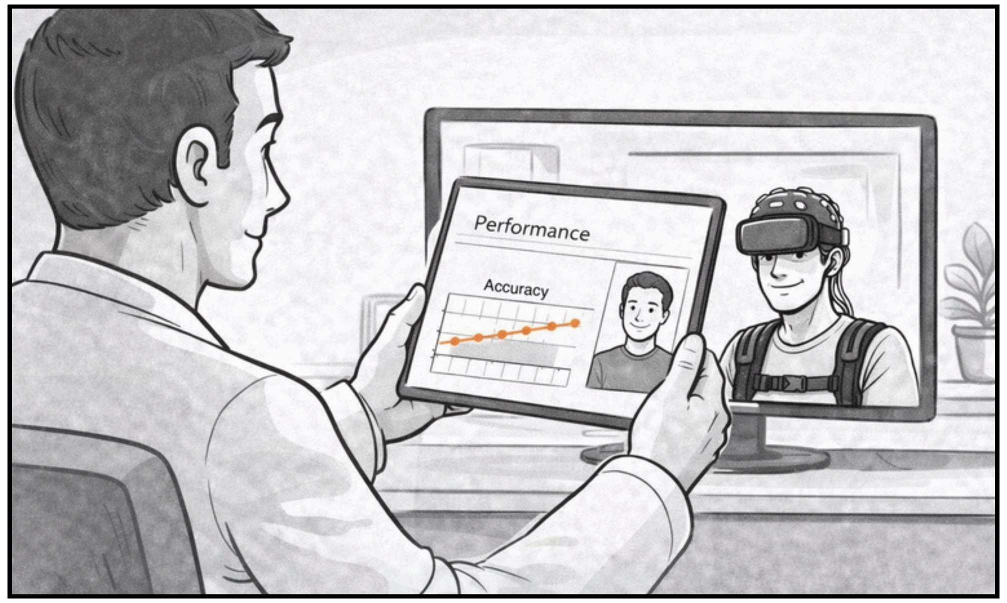
Clinician and patient define goals and realistic outcomes.

A personalized avatar is created via the app.

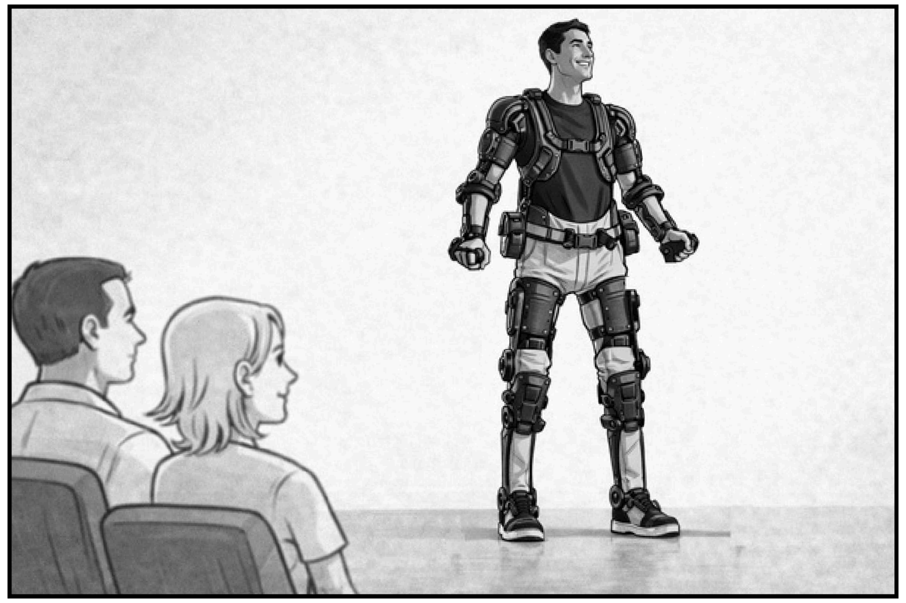
Home training starts with caregiver support.



Execution of the training session.

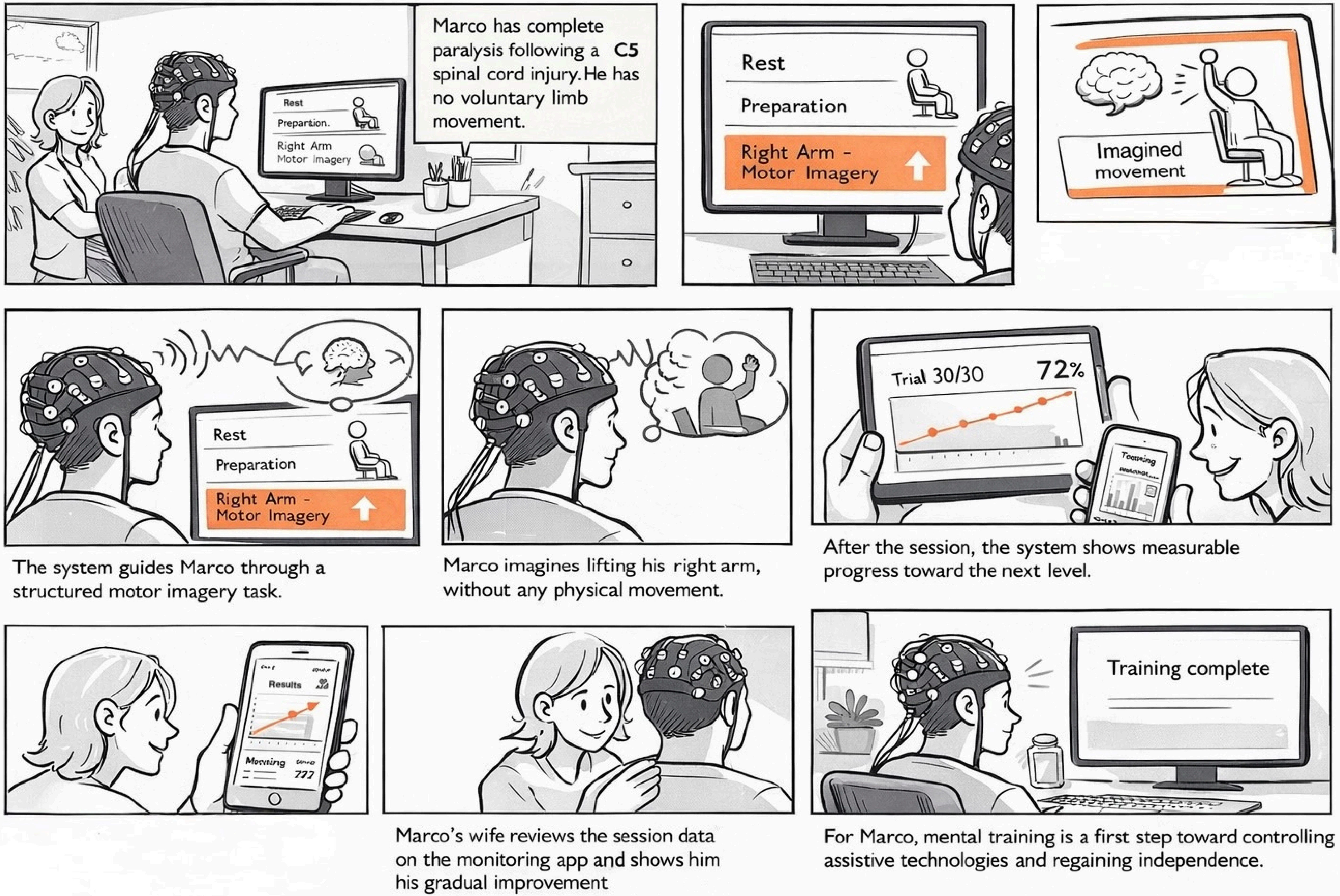


The clinician reviews the app and session reports.



Exoscheletron control.

Scenario


Rest
Preparation.
Right Arm Motor Imagery
Marco has complete paralysis following a C5 spinal cord injury. He has no voluntary limb movement.
Rest
Preparation
Right Arm - Motor Imagery
Imagined movement
Rest
Preparation
Right Arm - Motor Imagery
The system guides Marco through a structured motor imagery task.
Marco imagines lifting his right arm, without any physical movement.
Trial 30/30
72%
After the session, the system shows measurable progress toward the next level.
Results
Morning
Marco's wife reviews the session data on the monitoring app and shows him his gradual improvement
Training complete
For Marco, mental training is a first step toward controlling assistive technologies and regaining independence.

System Components

Hardware Components

- EEG cap with gel electrodes
- EMG and IMU sensors (optionals)
- Computer running acquisition
- Computer to process data
- VR headset

Software Components

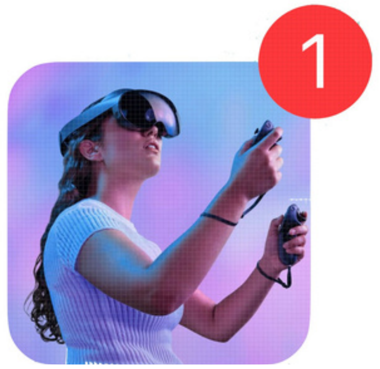
- EEG acquisition software
- LSL for Real-time Stream Synchronization
- Unity-based avatar environment
- Python-based processing pipeline
- Smartphone Application

ant neuro

Unity

python™

LSL
Community Forums



Level structure

Duration: **~20** minutes
Total repetitions: **60** for each movement
Structure: **2** phases × **30** repetitions (**Offline** + **Online**)

Rest → **Preparation** → **Movement / Motor Intention**

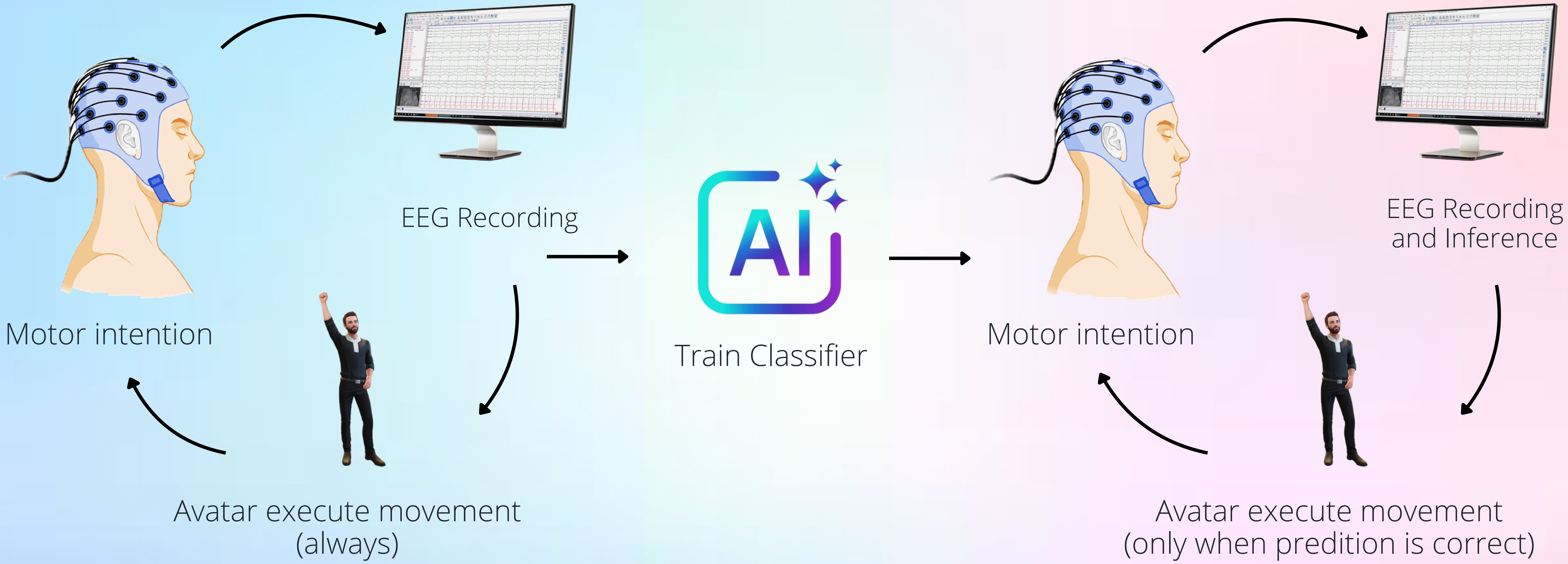
Evaluate level completion
- Real time accuracy **≥85%** →unlock next level
- Real time accuracy **< 85%** →recommend level repetition with supportive feedback

https://doi.org/10.3389/fnins.2023.XXXXXX

EEG Setup

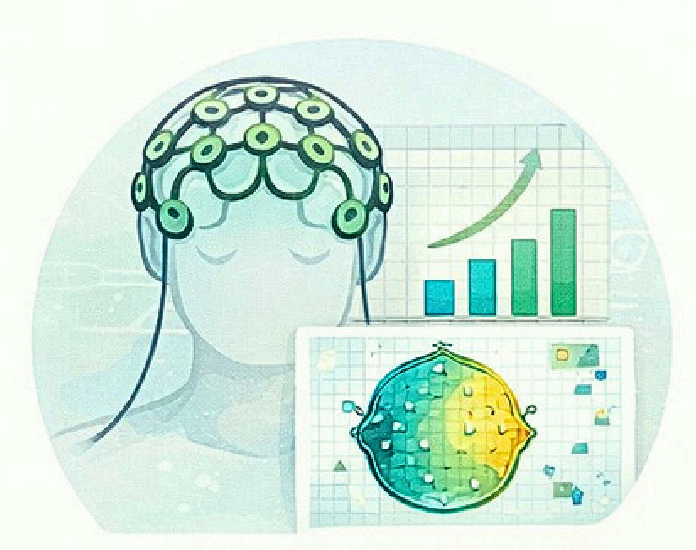
OFFLINE PHASE

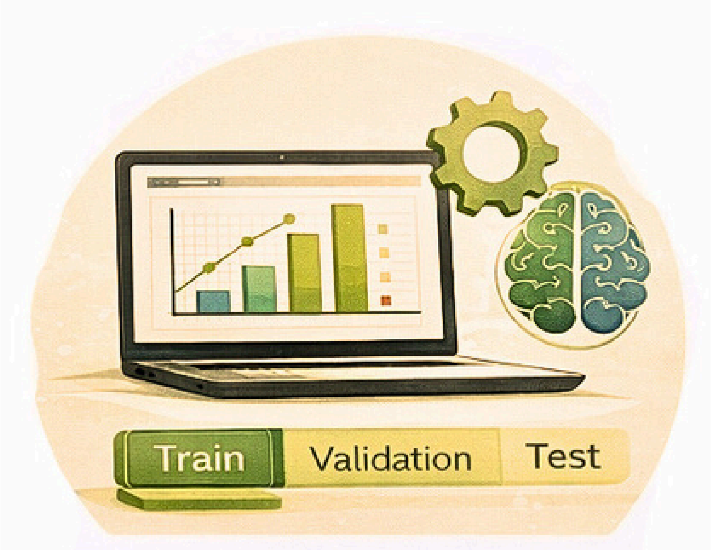
ONLINE PHASE



EEG Analysis

EEG data analysis are implemented in **Python** using the **MNE** library for EEG signal processing.



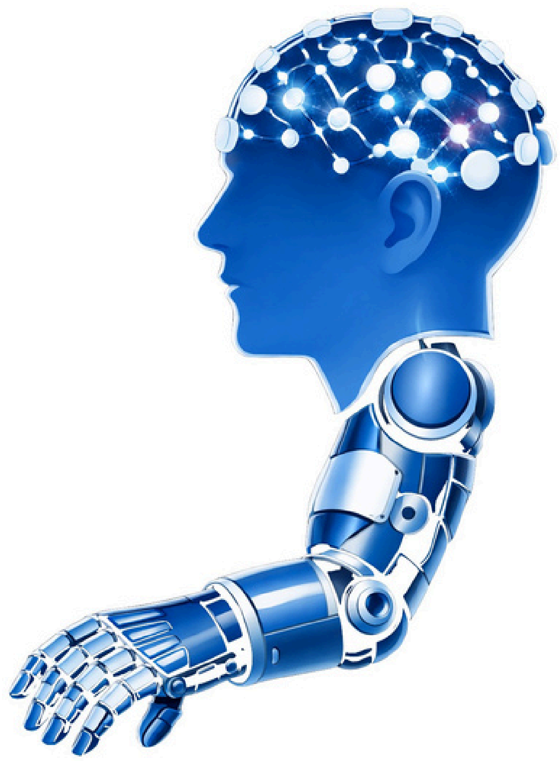


Data Preprocessing:
- Save raw files
- Remove bad channels
- Band-Pass filter
- Epoching

Feature Extraction:
Extract task-related features using CSP

Training Model:
- Train-Val-Test Split
- Train Model (LDA)
- Model Evaluation

Adaptive multi-level training



Complete Paralysis

1. Right arm Movement vs Rest
2. Right arm vs Left arm Movement
3. Upper Limb vs Lower Limb Movement
4. Different Movements of the same limb

Incomplete Paralysis

1. Assisted reaching movements of the impaired upper limb
2. Repeated flexion and extension of the wrist or elbow
3. Bilateral arm movements for coordination training
4. Functional movement patterns such as reach-and-grasp

Game interface

The training flow was implemented using a **Python**-based game development library (**pygame**).

Design Principles:

- Simplicity and clarity
- Minimal visual elements
- Personalized environment (avatar + background)
- Pauses adapted to user fatigue
- Clearly defined phases
- Visual feedback integrated according to the training phase

The GUI runs on a dedicated computer, which is connected via **Ethernet** to the EEG recording system. Inter-device communication are handled using the **Lab Streaming Layer (LSL)** framework, ensuring precise temporal alignment between signal acquisition, classification, and visual feedback.

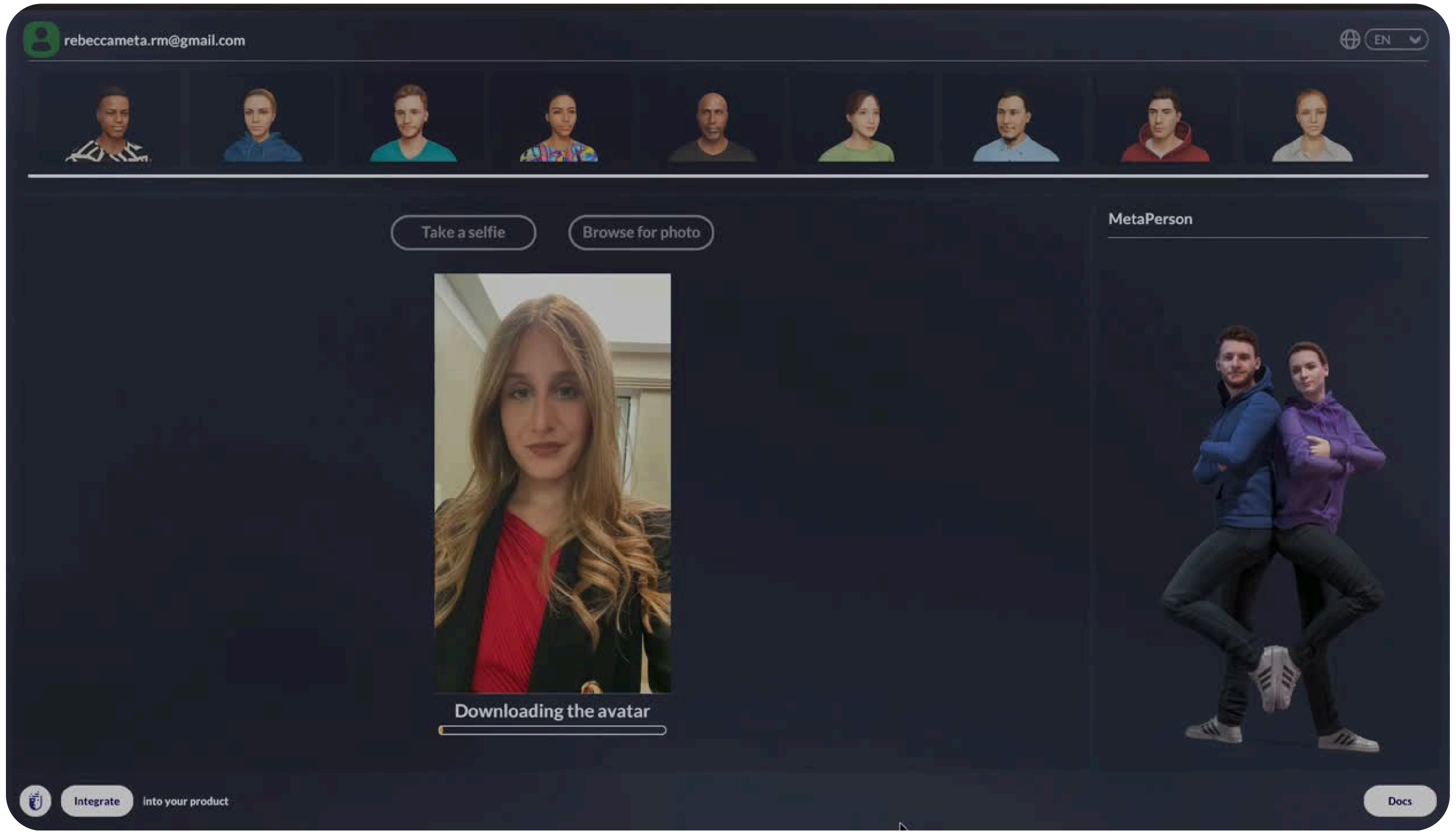
Avatar-Based Visual Feedback

Visual feedback is provided through a virtual avatar developed in **Unity**, which reflects the classifier output in real time and can be personalized to resemble the user.

Users can create a personalized avatar through two main approaches:

- **Automatic generation** from a photograph: using AI-based services (https://avatarsdk.com)
- **Manual avatar creation**: using dedicated applications (https://readyplayer.me)

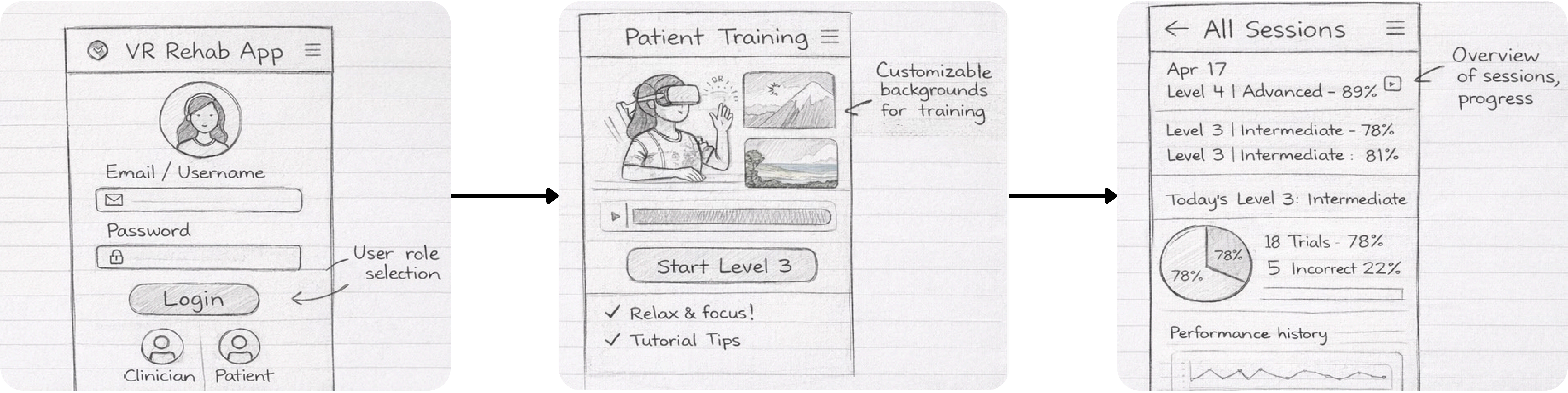
Avatars can be automatically rigged and animated using **Mixamo**, enabling rapid integration within Unity. (https://www.mixamo.com/#/)



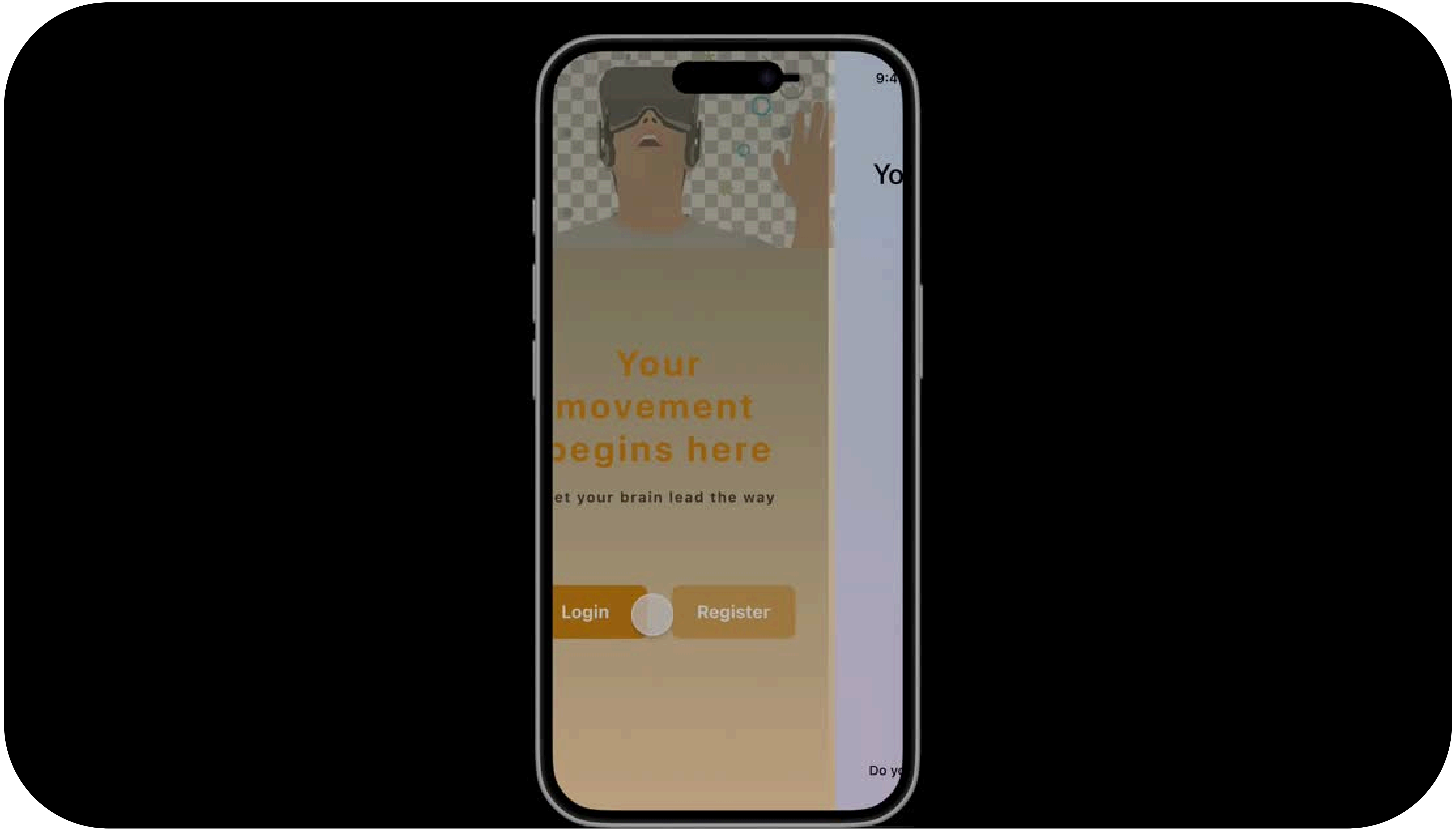
Monitoring Application

Designed for patients, caregivers, and clinicians to:

- Review performance summaries
- Track longitudinal improvement
- Compare level progression across sessions
- Document clinical notes and recommendations
- Customize the gaming experience

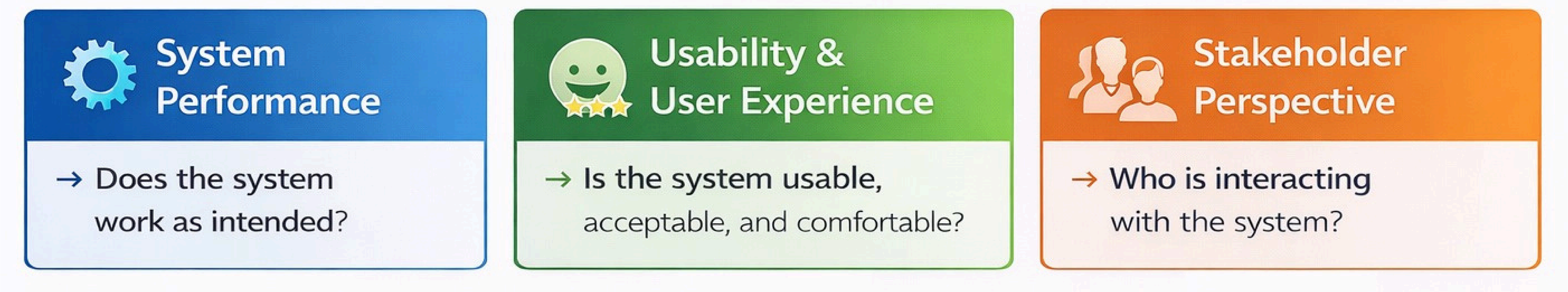


Monitoring Application Prototype



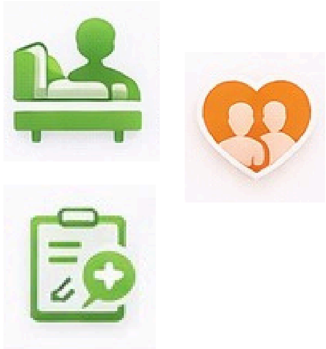
Evaluation Framework

3 evaluation dimensions



Evaluation targets:
- Training Game (VR interaction)
- Monitoring Application

Users Target:
- Patients
- Caregivers
- Clinicians



System Performance

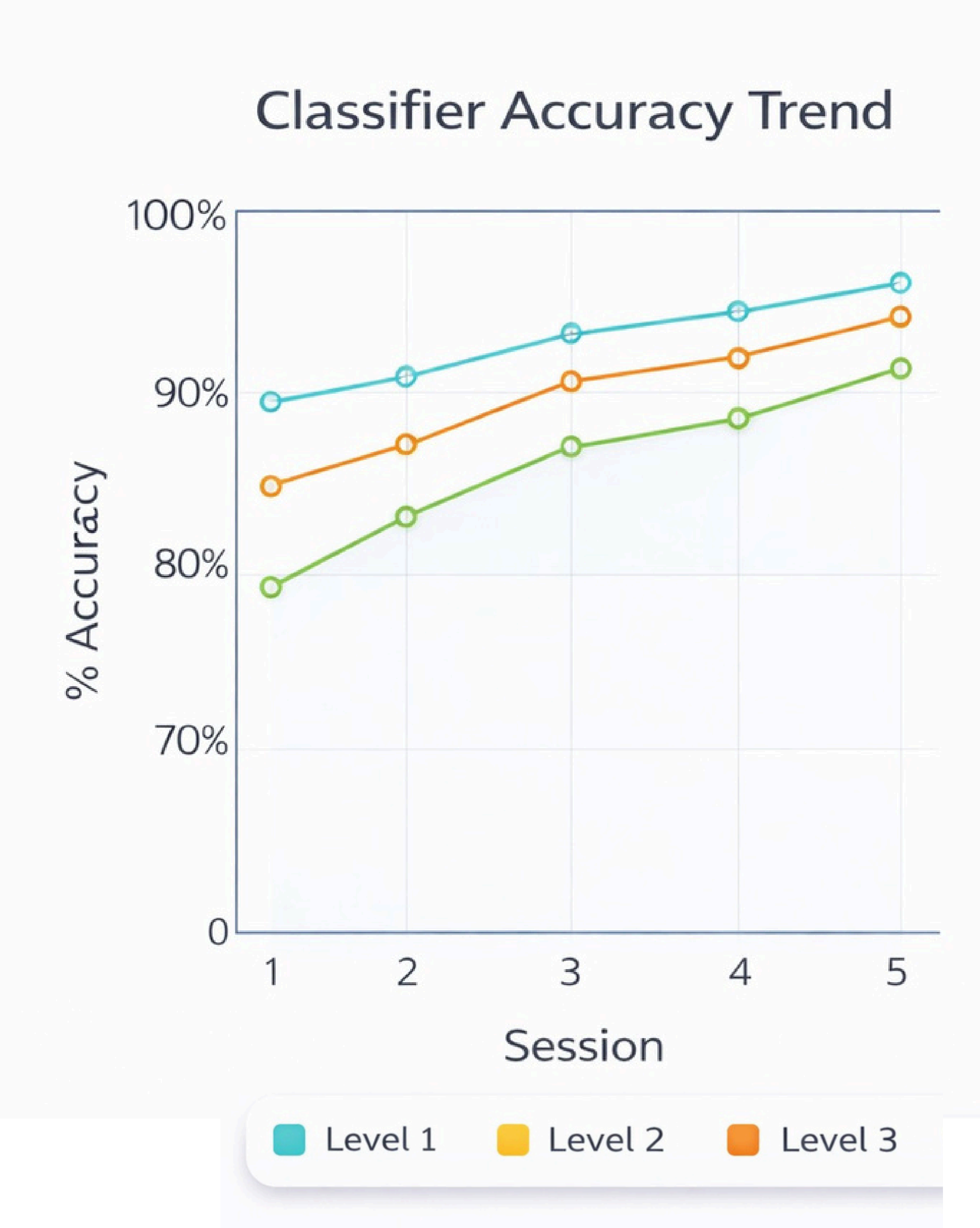
Quantitative system-level metrics

Classifier-related

- Classification accuracy
  - Computed over 30 repetitions per level
  - Performance threshold: ≥ 85%
- Accuracy trends across levels and sessions

Task execution

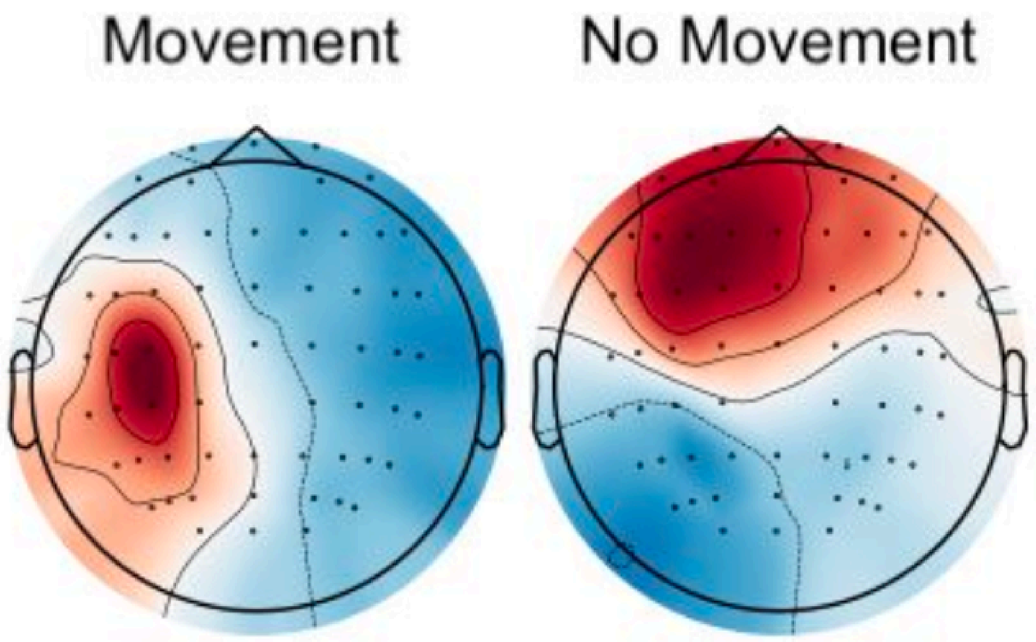
- Task completion rate (without interruption)
- Time-on-task: Setup, Calibration, Level execution
- Numbers of times the user has accessed the VR



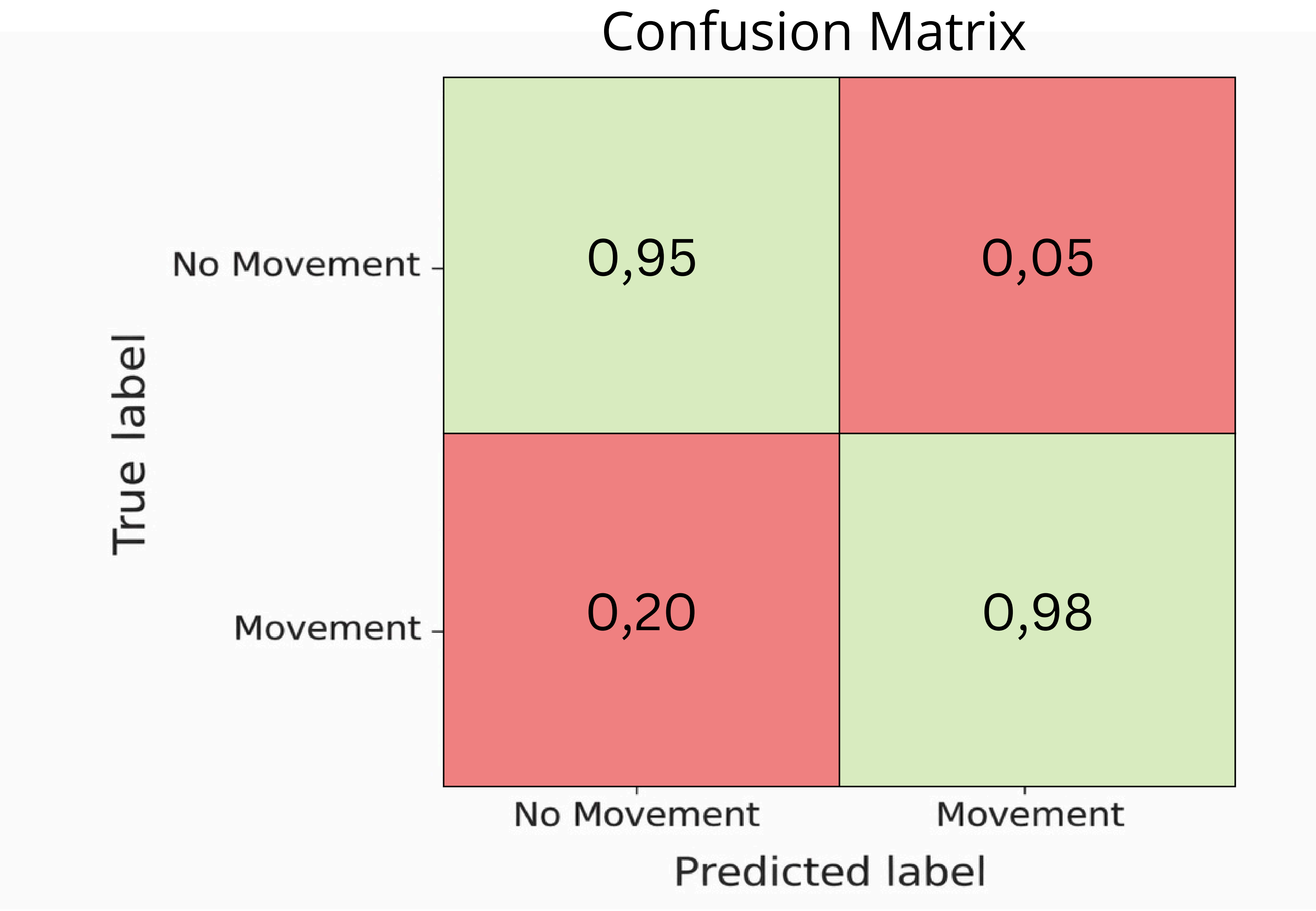
Example Results: Movement vs No Movement

Results from a representative subject show clear cortical differentiation between motor imagery and rest.

High performance: 97% accuracy



Topomaps



Usability & User Experience

GAME EVALUATION

- ***System Usability Scale*** *(SUS)*:
  Overall usability
- ***NASA-TL***:
  Perceived cognitive workload
- ***Presence Questionnaire*** *(PQ)*:
  VR immersion
- ***Simulator Sickness Questionnaire*** *(SSQ)*:
  Cybersickness
- ***GUI evaluation questionnaire***:
  Custom items + User Experience Questionnaire

MONITORING APPLICATION EVALUATION

- Think-aloud during app interaction

Visual and Interaction Experience Questionnaire

Thank you for taking part in this study!

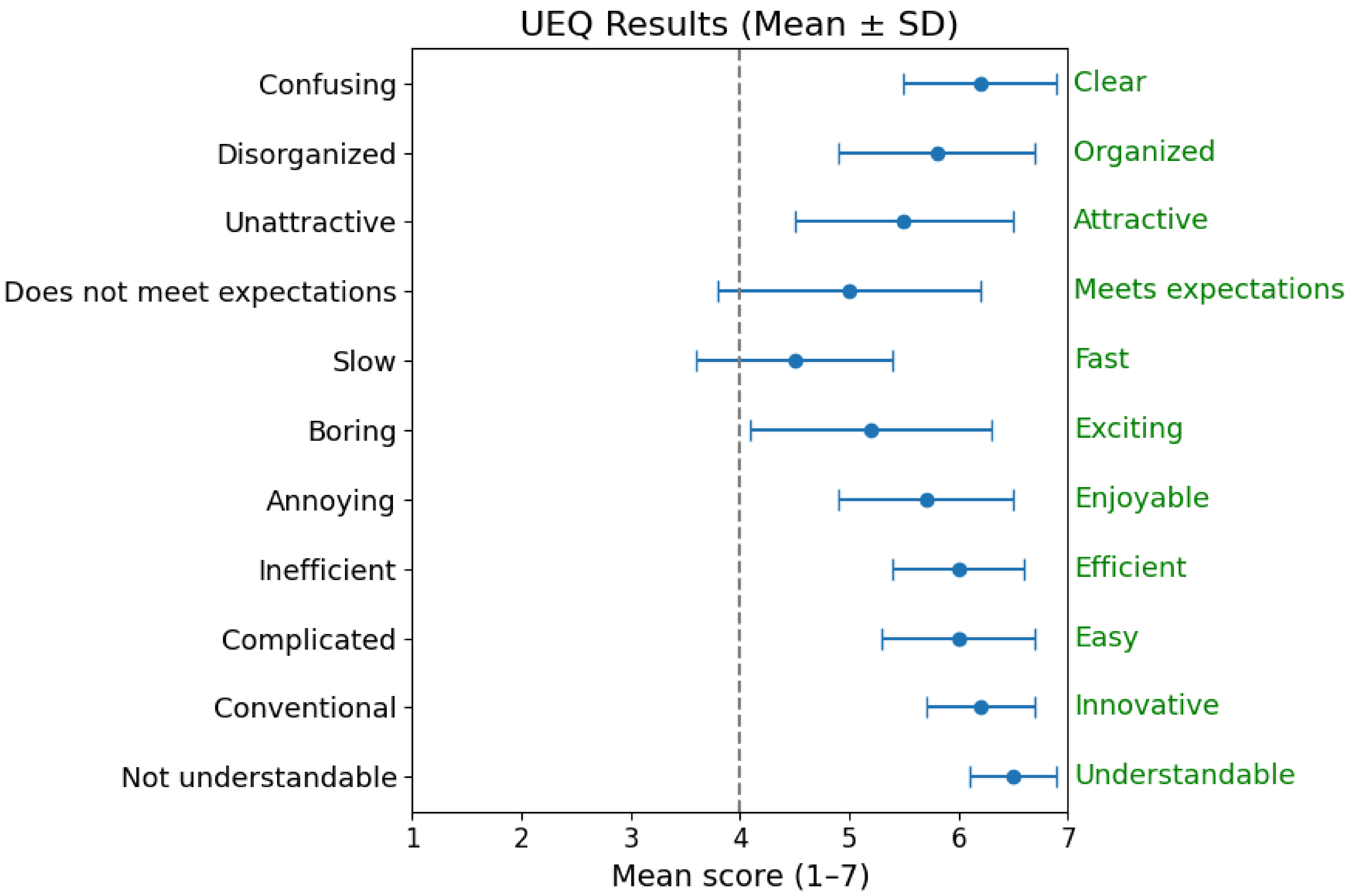
You have interacted with a prototype of an EEG-based gamified training system. The purpose of this questionnaire is to collect your feedback on the overall user experience, as well as on the visual design and interaction clarity of the system.

The questionnaire is divided into two parts. The first part focuses on your general user experience using pairs of opposite adjectives. The second part includes statements related to visual clarity, interaction feedback, aesthetics, and engagement.

There are no **right or wrong** answers. Please answer spontaneously based on your personal experience with the system.

All responses are anonymous and will be used exclusively for research purposes!

Results: GUI questionnaire (UEQ)



Results: GUI questionnaire (Customized)

Scale: 7-point Likert (1 = strongly disagree, 7 = strongly agree)

Question	Mean ± SD
The avatar's behavior clearly reflected the required action.	**6.67 ± 0.58**
The traffic-light cue used during the Preparation phase was intuitive and easy to understand.	**6.57 ± 0.68**
The system was intuitive despite its technical nature (EEG-based interaction).	**6.55 ± 0.69**
Overall, the visual interface helped me understand how to interact with the system.	**6.48 ± 0.75**
The interface did not appear visually cluttered.	**6.38 ± 0.67**
The different phases of the game (Rest – Preparation – Movement) were visually clear.	**6.38 ± 0.80**
The transition between phases was easy to follow.	**6.33 ± 0.73**
I felt comfortable interacting with the interface.	**6.33 ± 0.73**
The game-style design made the repetitive task less monotonous.	**6.24 ± 0.94**
The timing of the visual feedback was appropriate.	**6.19 ± 0.93**
Visual feedback increased my motivation to perform the task correctly.	**6.19 ± 0.81**
I would be willing to repeat the training session based on this visual experience.	**6.19 ± 0.87**
I always knew which action was required from me.	**6.14 ± 1.06**
The visual feedback (e.g. animations) was easy to interpret.	**6.05 ± 1.00**
Positive and negative feedback were visually distinguishable.	**5.90 ± 1.14**
The graphics made the task more engaging.	**5.90 ± 1.14**
The interface appeared modern and well designed.	**5.57 ± 1.16**
The overall visual design of the game was aesthetically pleasing.	**5.52 ± 0.98**

Technical/scientific background

- 66.7% YES
- 47.6% NO

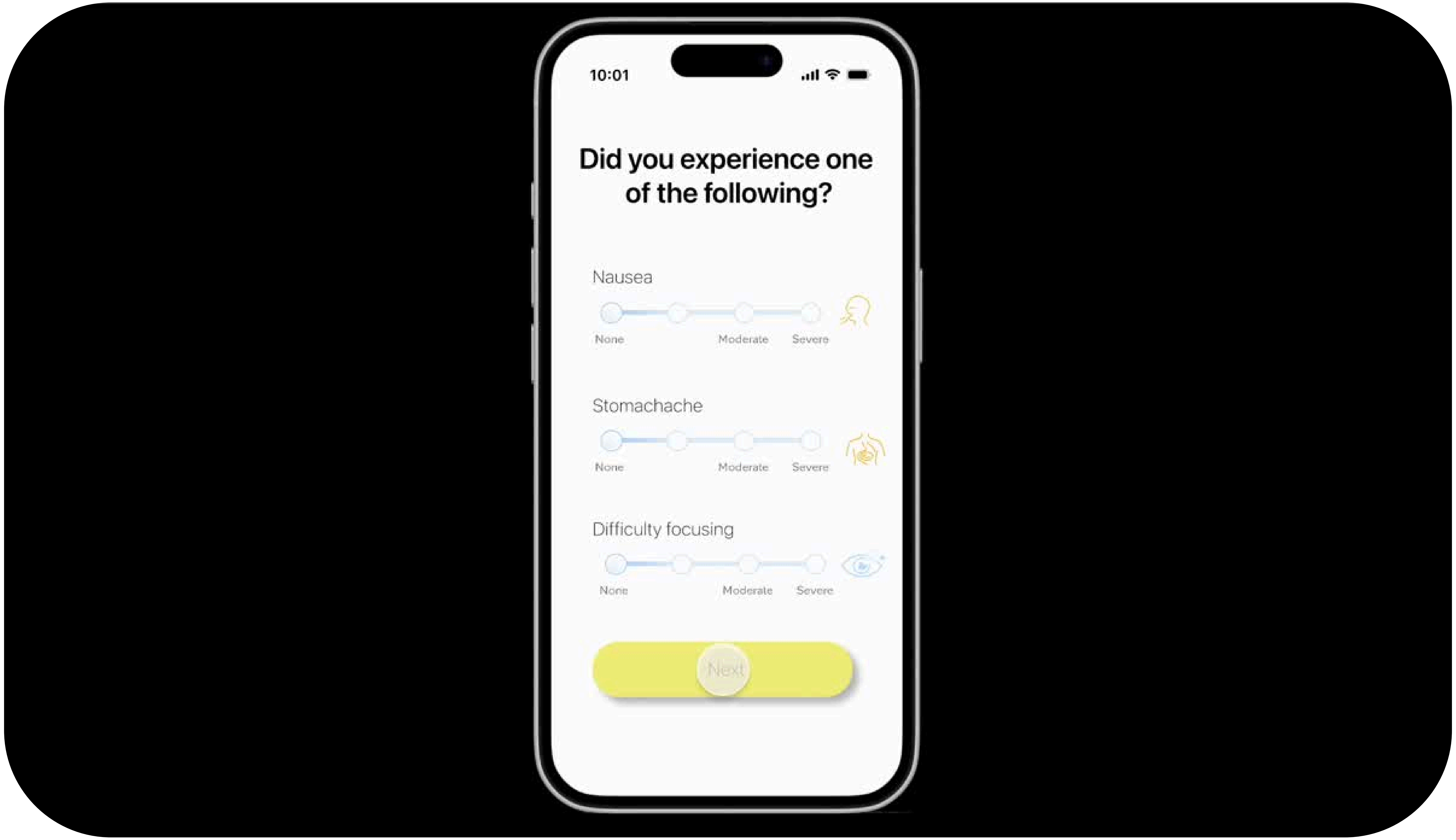
Most useful visual elements

- Avatar
- Traffic-light cue

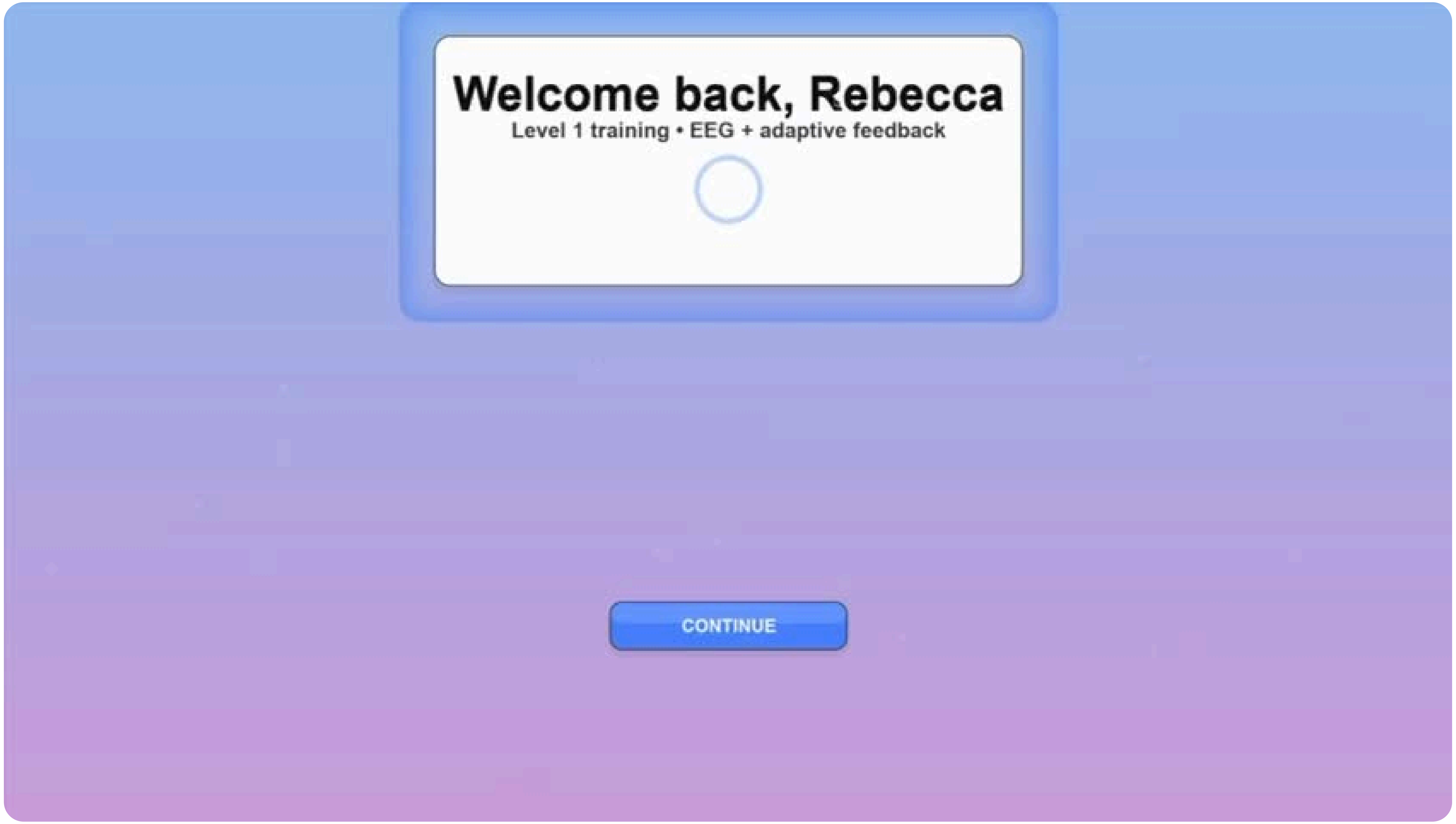
Suggested improvements

- No major changes needed
- Improved visual clarity (contrast, image quality)
- Larger cursor and text size

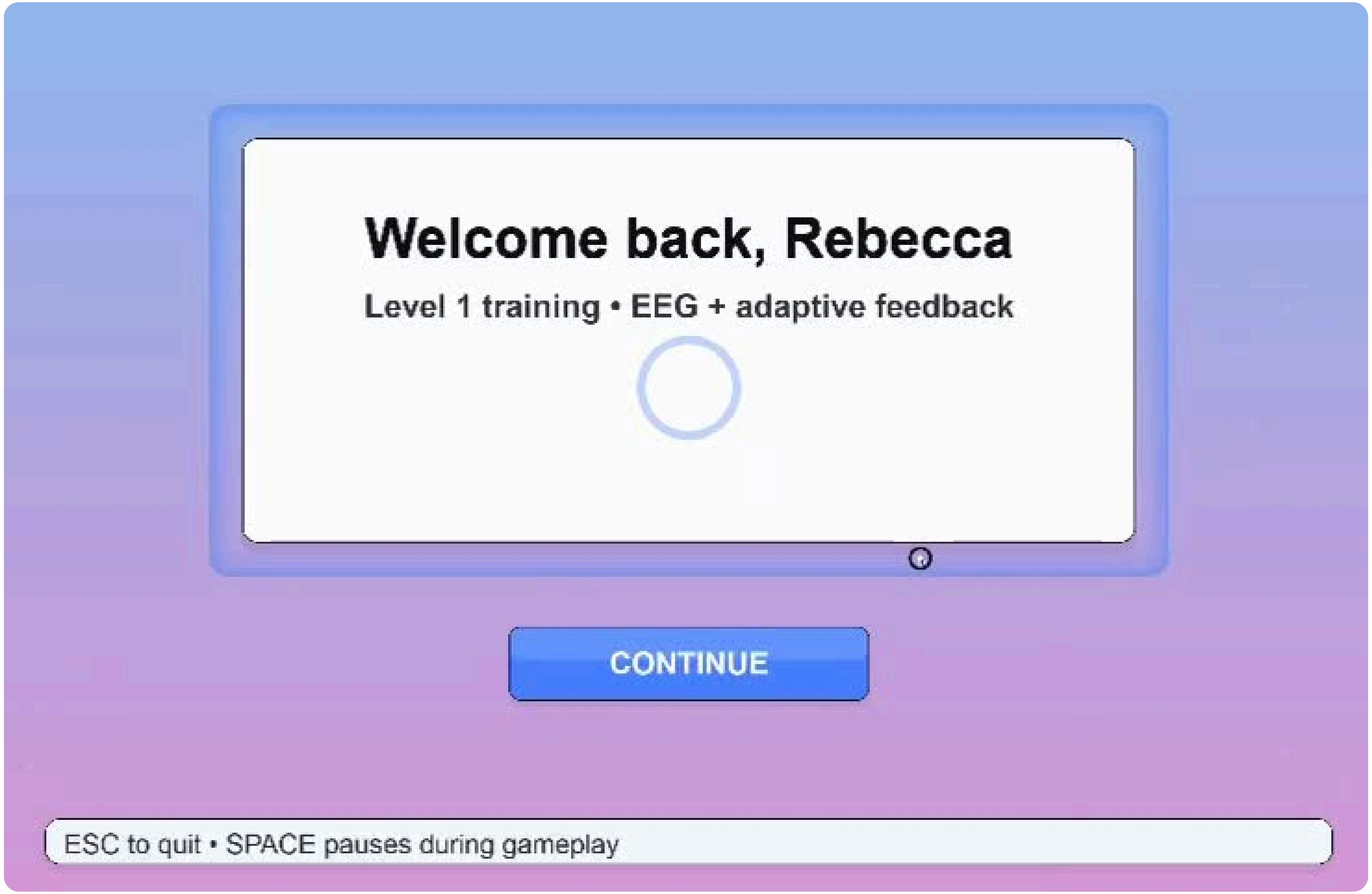
Simulator Sickness Questionnaire

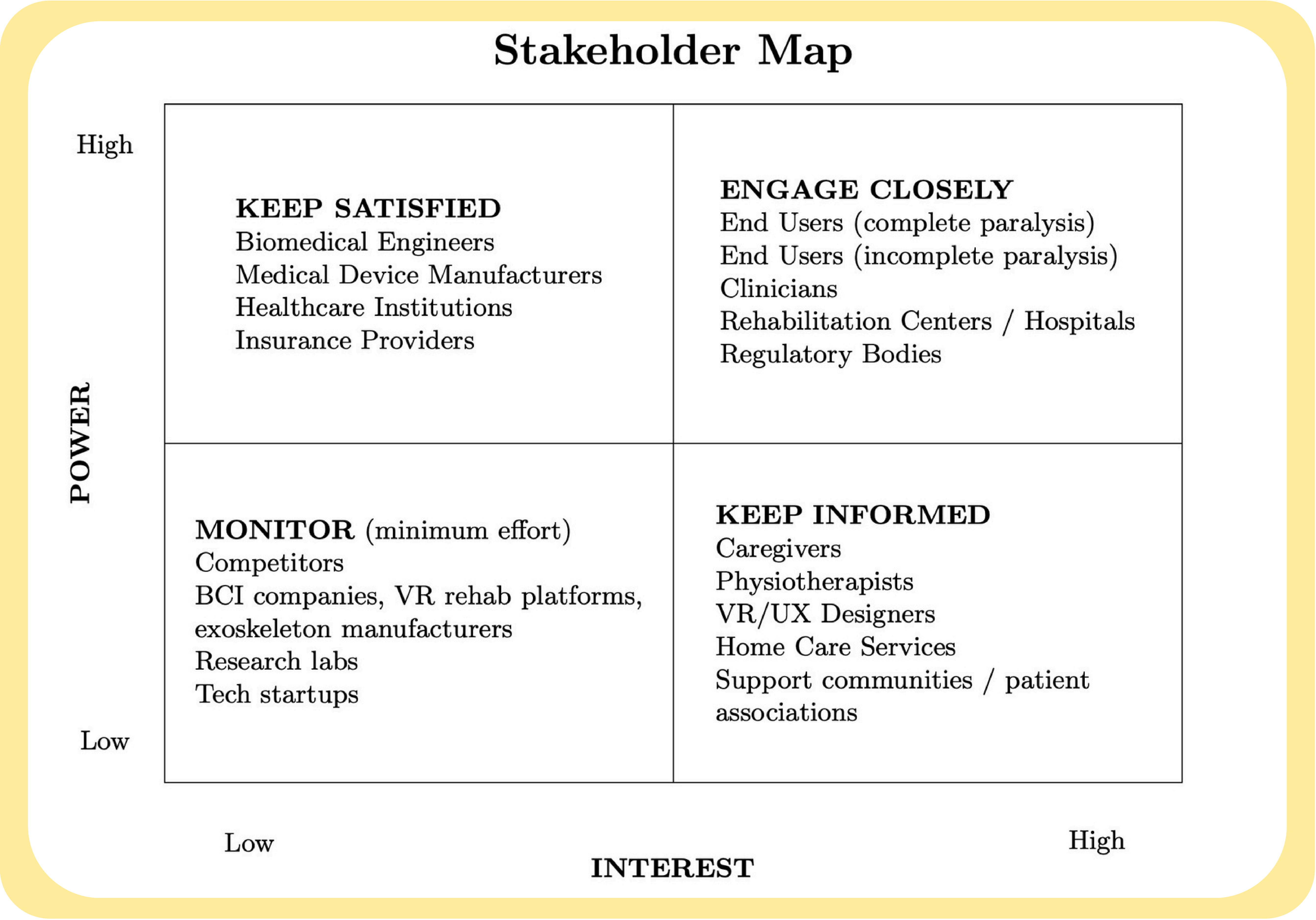


Demo Version 1



Demo Version 2





Stakeholder Map
High
KEEP SATISFIED
Biomedical Engineers
Medical Device Manufacturers
Healthcare Institutions
Insurance Providers
ENGAGE CLOSELY
End Users (complete paralysis)
End Users (incomplete paralysis)
Clinicians
Rehabilitation Centers / Hospitals
Regulatory Bodies
POWER
MONITOR (minimum effort)
Competitors
BCI companies, VR rehab platforms, exoskeleton manufacturers
Research labs
Tech startups
KEEP INFORMED
Caregivers
Physiotherapists
VR/UX Designers
Home Care Services
Support communities / patient associations
Low
Low
INTEREST
High

Thank you

EMAIL

r.metallo@studenti.unisr.it

g.caffi@studenti.unisr.it

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