CODA

Human-Machine Performance Envelope: a Controller Adaptive Digital Assistant evaluation

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SESAR Innovation Days 2025

SUPPORTED BY sesar JOINT UNDERTAKING

Co-funded by the European Union

Project Overview

CODA: COntroller adaptive Digital Assistant

- **SESAR Exploratory Research project** (TRL2)
- September 2023 -> February 2026
- **Technical work done:** final results available

With the contribution of

This project has received funding from the SESAR Joint Undertaking under the European Union's Horizon Europe research and innovation programme under grant agreement No 101114765

Project Overview

CODA: COntroller adaptive Digital Assistant

- **Strategic objective:** to develop a system in which tasks are performed collaboratively by hybrid human-machine teams and dynamically allocated through adaptive automation principles.
- **The rationale for the system:** to anticipate possible problems related to controllers' mental states (e.g. workload peak) and activate AI based supporting tools so to mitigate/avoid issues.
- **Expected impact:** efficiency, capacity, and safety, maximizing Human-AI teaming.

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Project Overview

CODA: COntroller adaptive Digital Assistant

Test an approach that combines:

- **neurophysiological monitoring,**
- **adaptive automation,**
- **human–AI teaming, and**
- **explainable autonomy**

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The CODA Solution

Adaptive System to improve Human AI Teaming

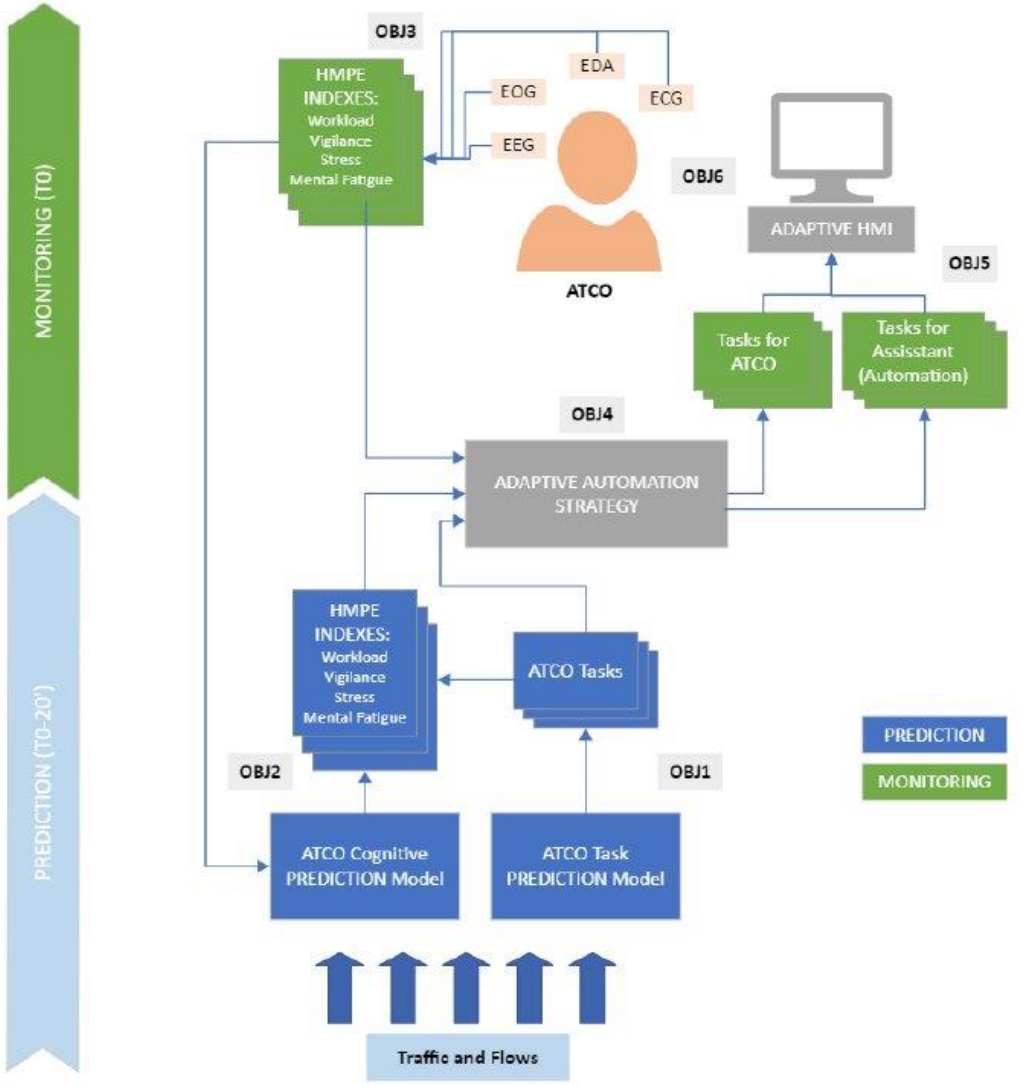
HOW DOES CODA WORKS?

CODA is a predictive adaptive system:

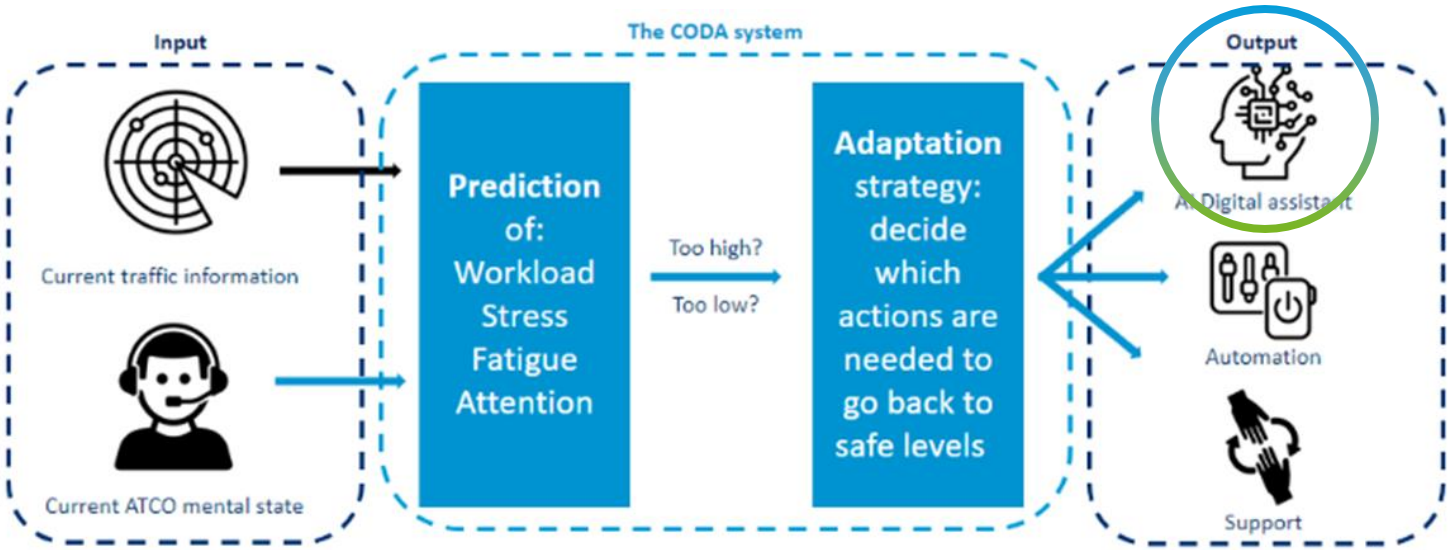
It proposes the **delegation of certain tasks/flights to the AI**

Considering:

- The **current and predicted traffic**
- The **current and upcoming control tasks**
- The curr**ent and predicted controller's mental state** (workload, fatigue, stress, and vigilance)



En-route use case, multiple other applications



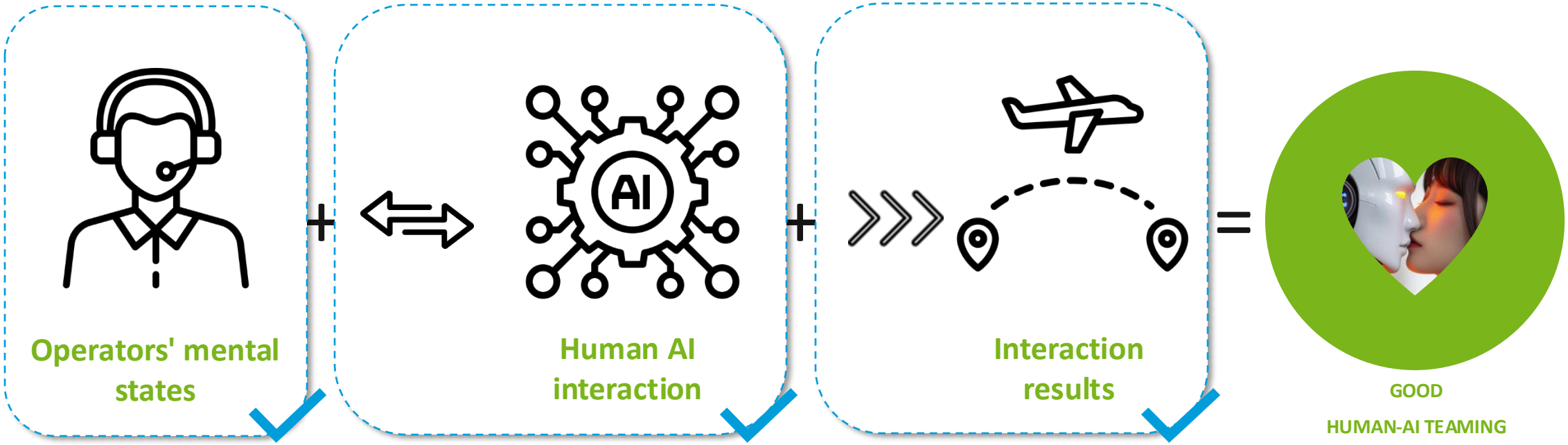
"ONE TOOL RULE THEM ALL"

It has to be *emphasised* that the CODA system is not a tool per se. It is a **technological enabler, to be integrated into ATM systems** (not limited to en-route CWPs), providing adaptation capabilities.

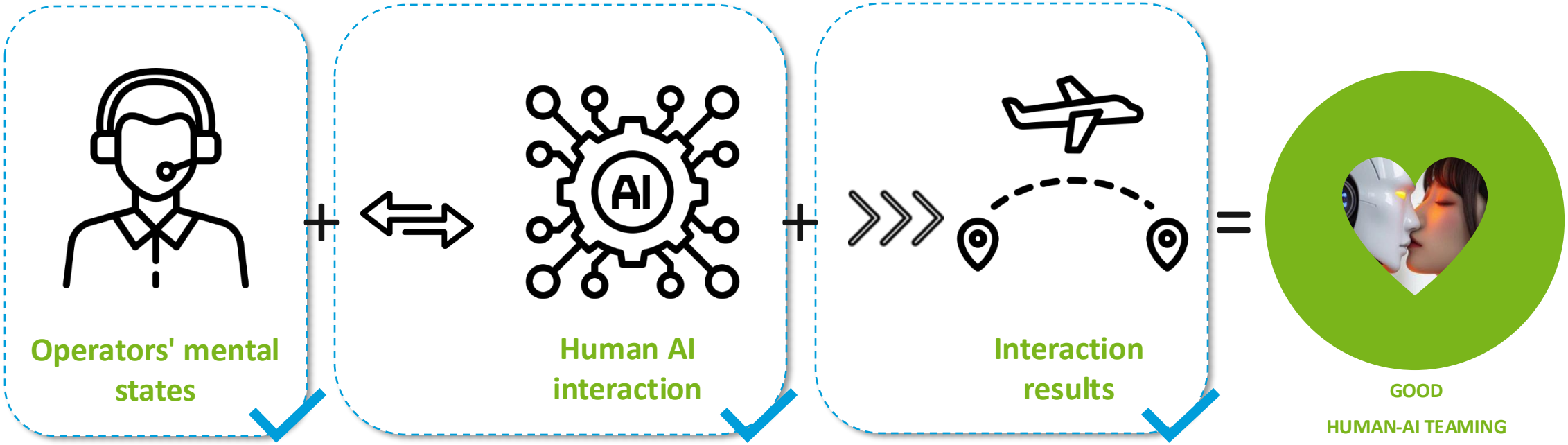
The AI tools/Digital assistants that are expected to be activated by the adaptation strategy are out of the scope of the project.

CODA Approach to Human AI Teaming

“A” definition for Human – AI Teaming

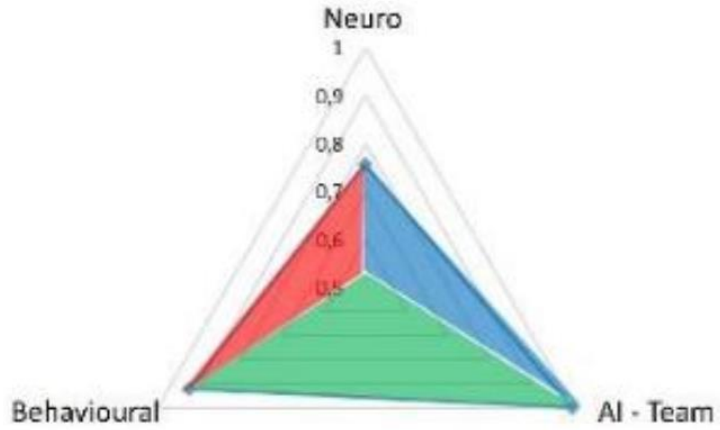


“A” way to measure teaming



“A” way to measure teaming

Human Machine Performance Envelope (HMPE)

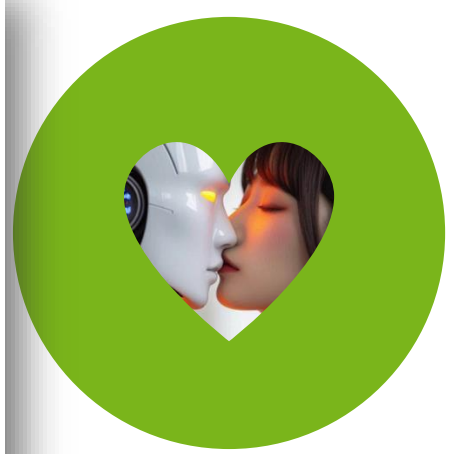


Area Triangle #1 = 1/2 * AI-Team * Behavioural * sin(120°)

Area Triangle #2 = 1/2 * Behavioural * Neuro * sin(120°)

Area Triangle #3 = 1/2 * Neuro * Behavioural * sin(120°)

Area = Area Triangle #1 + Area Triangle #2 + Area Triangle #3



GOOD

HUMAN-AI TEAMING

Human Machine Performance Envelope INDEX

HUMAN-AI TEAMING

ASSESSMENT

VALIDATION

“A” way to manage teaming

ADAPTATION STRATEGY

Sharing the work with an AI may mean:

- Distribute specific **tasks** (e.g. assuming flights)
- Assign specific **flights** (e.g. an overflying a/c with no interaction with the traffic)
- Receive support for specific **cognitive functions** (e.g. information analysis to lower workload in a busy sector)

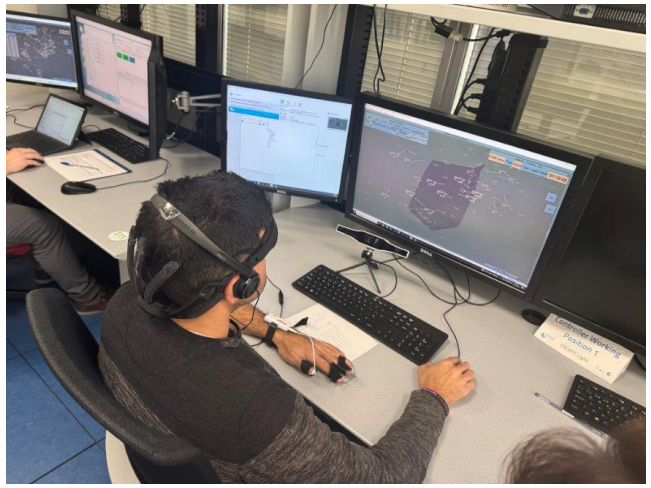
In order to support the ATCO in the best way possible, the adaptation strategy needs to take into consideration operational, safety, ethics and liability aspects.

→ **Generic guidelines**

CODA system validation

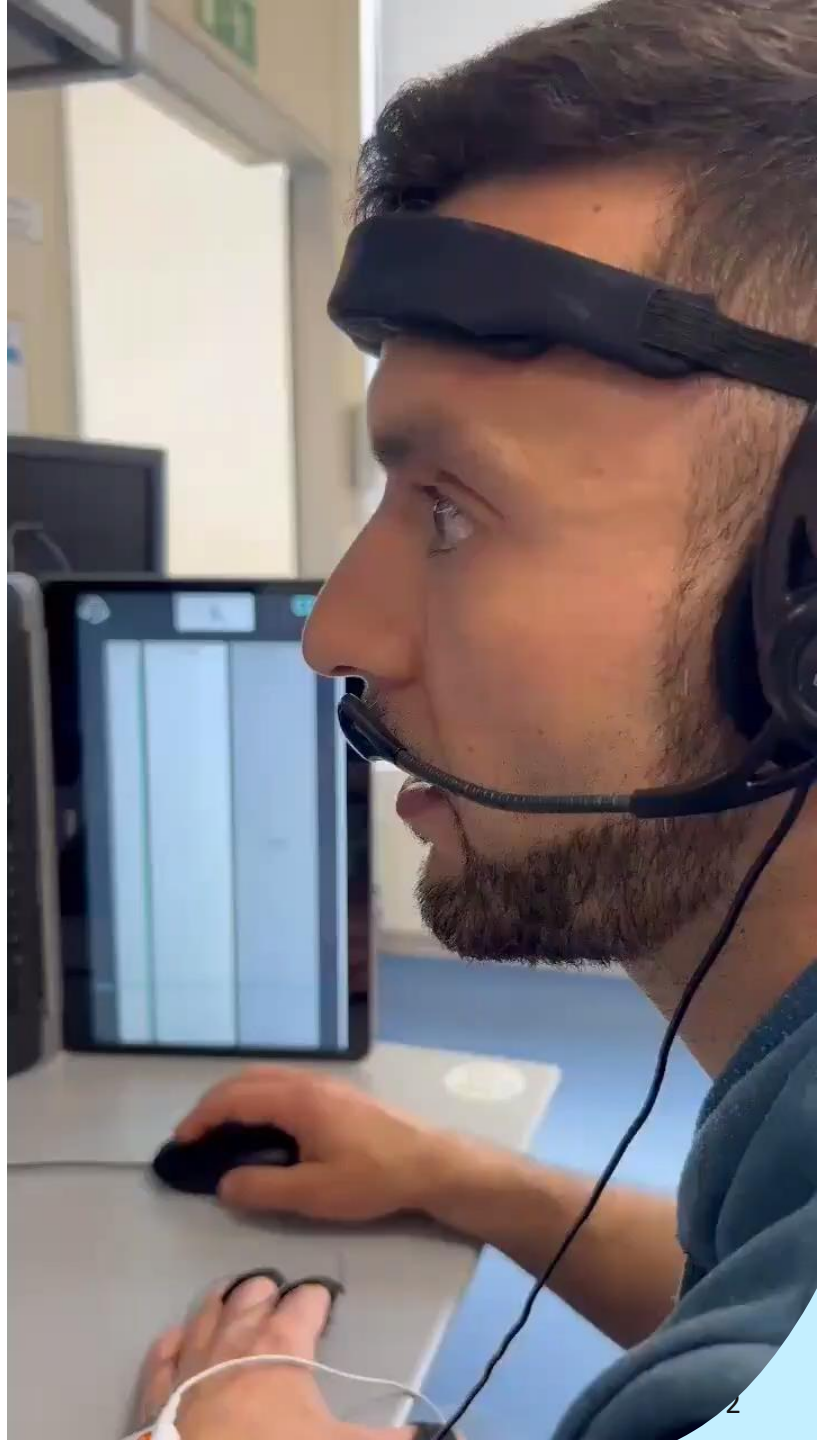
System final validation

Human in the Loop simulation



- **When:** 17–21 March 2025
- **Where:** CRIDA premises at Universidad Politécnica de Madrid
- **Who:** 4 ATCOs (IFATCA)
- **Objective:** Validate CODA system

- Real-time ops with ATCO+CODA system + AI Digital assistant
- Realistic CWP and traffic (ESCAPE platform)
- Pseudopilots (voice communication)
- Yellow circle marked AI flights

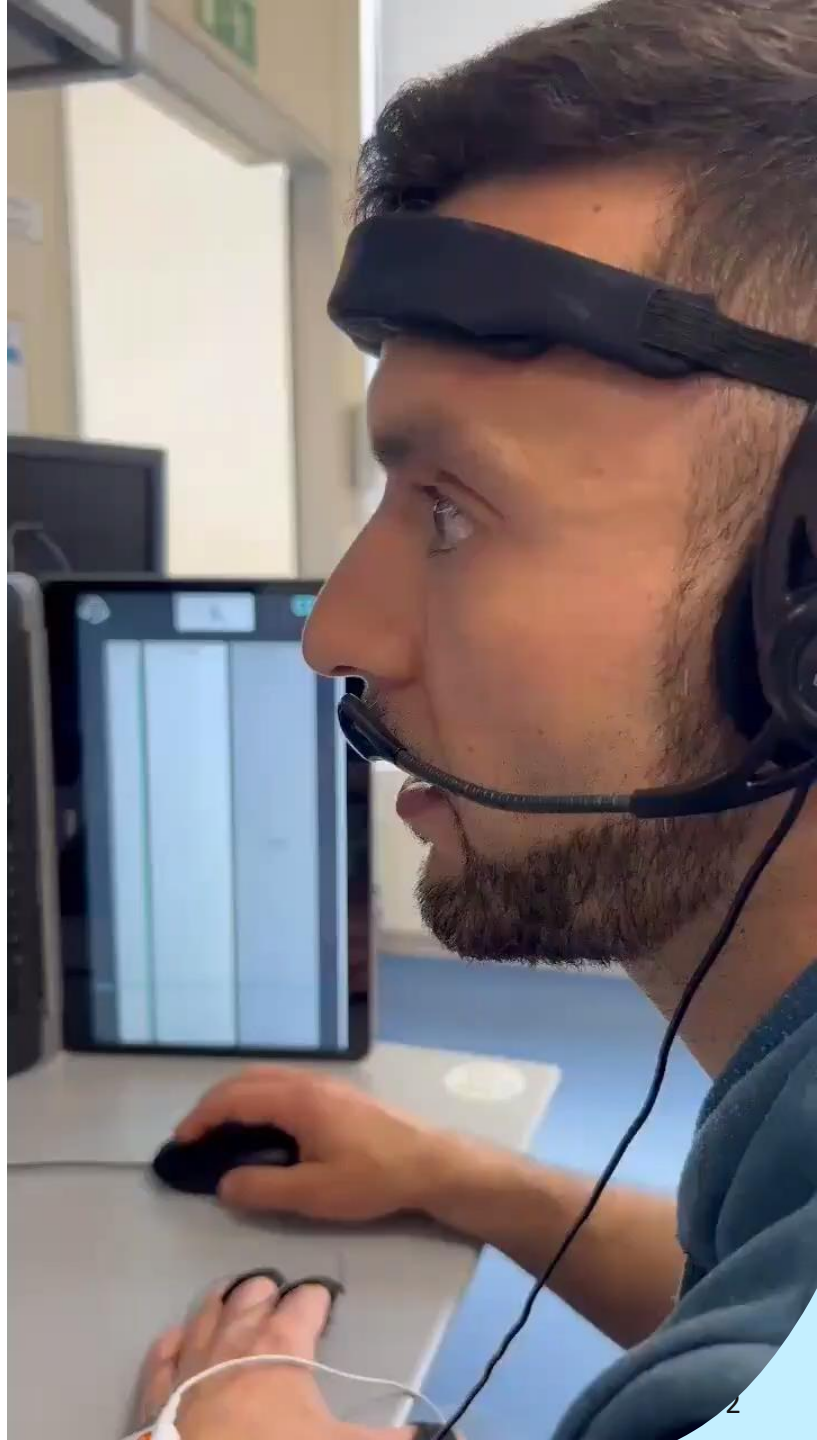


System final validation

Human in the Loop simulation

SCENARIOS

- Steady Progression (SP): **gradual increase in traffic**, allowing assessment of CODA's capability to support workload buildup.
- Baseline Perturbation (BP): **progressive reduction in traffic**, enabling analysis of recovery and adaptation processes after high-demand phases.
- Sudden Burst Application (SBA): **two pronounced traffic peaks** separated by medium-load intervals, testing the system's responsiveness under fluctuating complexity.



The CODA system HMI

THE CODA PROTOTYPE

Due to technical constraints, we focused our prototype development of **flights allocation** between ATCO and AI.

We set different level of autonomy:

- **Low:** ATCO need to approve CODA proposals for AI managed flights
- **High:** Selected Flights are assigned automatically to AI, the ATCO can regain control

→ HMI used in the final HITL simulation

From the interface, the controller can:

- **consult** traffic status, mental state and task load (present and predicted;
- get an **explanation** of why CODA has been activated;
- see flights **before** they are entering the sector;
- **modify** the flights it manages in order to assign them to CODA or regain control of flights already assigned

Input

From UPM

- Task load
- Predicted task load

From BrainSigns

- Mental state

From CRIDA

- Predicted Mental state
- Traffic
- Predicted traffic
- Real traffic

API

LSL

Java Archive & csv files

CODA

Determine whether Coda automation is needed, and display the input.

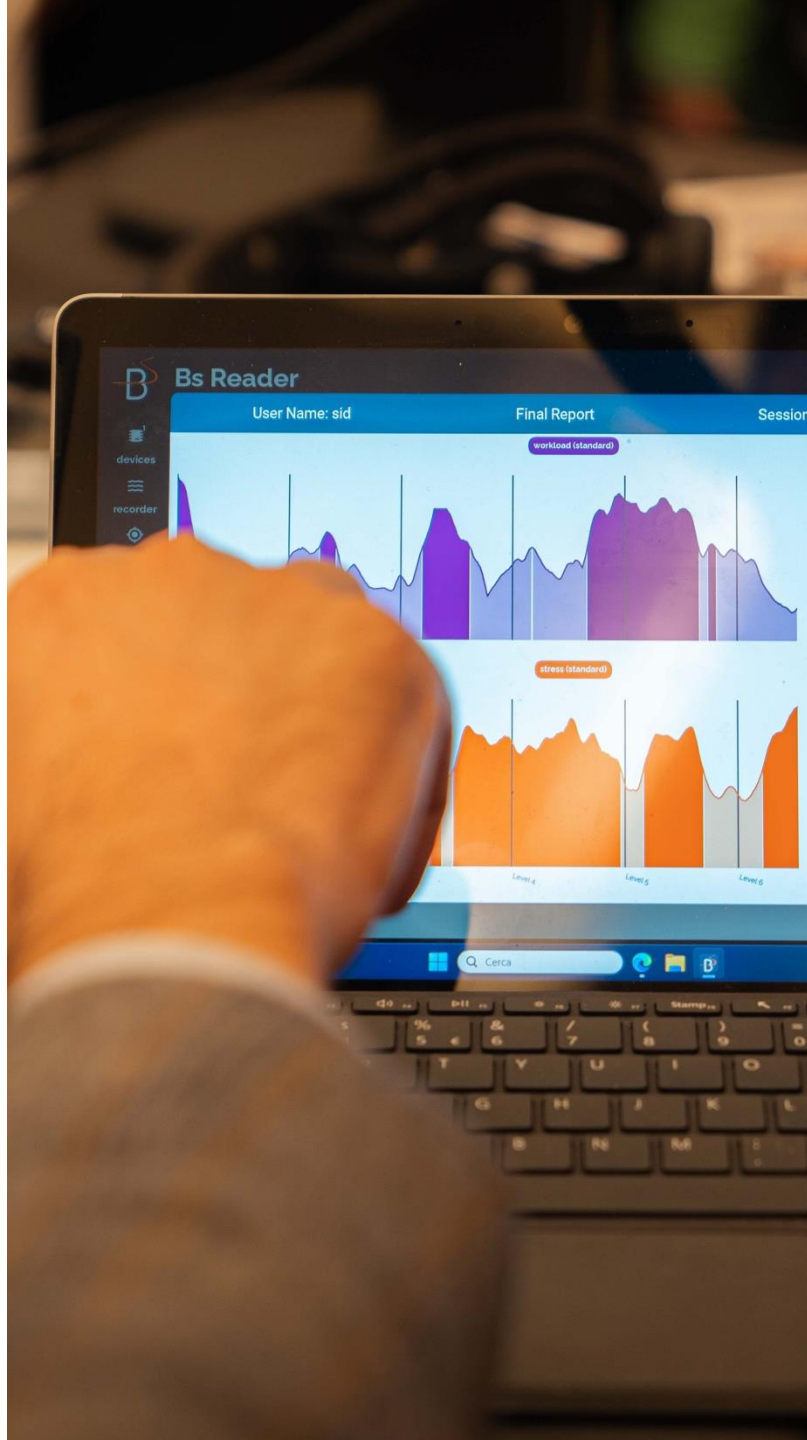
Transfer the information to the interface

Real-time traffic is displayed on the interface

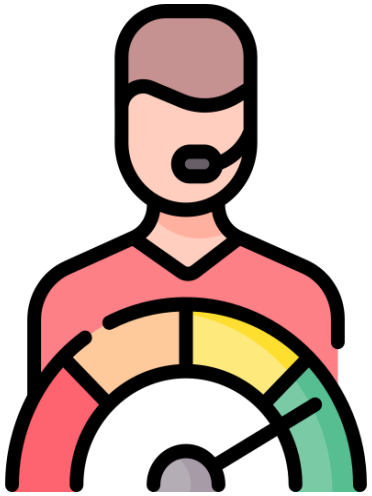
High level results

Results per system module

- **Tasks prediction:** probabilistic, different approaches depending on the tasks type
- **Mental states prediction:** workload and fatigue predictions aligned reasonably well with expectations, stress and vigilance predictions were less accurate and more static.
- **Mental state real time monitoring:** all states reliably assessed with EEG
- **Adaptation strategy:** feasibility of prototyping a simple, flight based one. Guidelines for a more comprehensive one provided.
- **HMI**: modular HMI with basic view + detailed one.



HITL Validation Final results (Human Performance)



Human Performance

- A generally positive impact on **teaming**
- Improved **vigilance and situation awareness,** reduced **stress and fatigue**
- Not significant change in mental **workload** (due to learnability curve plus a need for monitoring AI-managed aircraft)
- Relatively clear **responsibilities and tasks** as well as new procedures for ATCOs
- CODA's **allocation strategy** was reported to be logical and efficient
- The **HMI** was relatively supportive but there's still room for improvements

➡ The **HMPE framework** proved to be a strong indicator of controller-AI collaboration

HITL Validation Final results (Other KPAs)

- CODA maintained **safety** in normal conditions and measurably reduced conflicts during peak traffic
- CODA delivered slight improvements in **operational efficiency**
- No measurable improvement in **cost efficiency** was observed
- No measurable impact on en-route throughput was observed, CODA will likely enable an increase in **capacity**

OTHER KPAs

Conclusions

The results identified three key factors influencing **human–AI teaming effectiveness:**

- accurate trust calibration,
- context-aware adaptive behavior, and
- Efficient explainability.

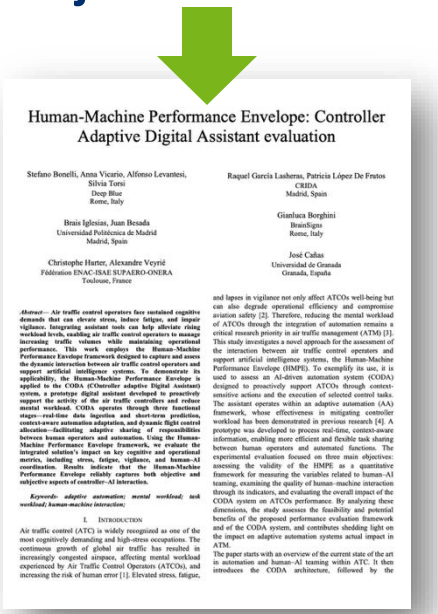
Beyond these empirical results, the study highlights the potential of the HMPE as a **diagnostic and design tool** for human–AI joint systems. By providing a quantitative view of cognitive states and team dynamics, the HMPE offers a means to monitor and adapt human–machine interaction in real time.

This could inspire AI based, **adaptive interface management approaches in ATC**, enabling automation to dynamically adjust its level of assistance according to operators' personal and contextual-driven cognitive boundaries rather than fixed operational thresholds.

Main outcomes you may be interested into:

Detailed description + Final test/validation results for:

- **Tasks prediction approach**
- **Mental states prediction approach**
- **Adaptation strategy**
- **Human Machine Performance Envelope**
- **Project final results**



Human-Machine Performance Envelope: Controller Adaptive Digital Assistant evaluation

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Abstract— Air traffic control operators face sustained cognitive demands that can elevate stress, induce fatigue, and impair vigilance. Integrating assistant tools can help alleviate rising workload levels, enabling air traffic control operators to manage increasing traffic volumes while maintaining operational performance. This work employs the Human-Machine Performance Envelope framework designed to capture and assess the dynamic interaction between air traffic control operators and support artificial intelligence systems. To demonstrate its applicability, the Human-Machine Performance Envelope is applied to the CODA (COntroller adaptive Digital Assistant) system, a prototype digital assistant developed to proactively support the activity of the air traffic controllers and reduce mental workload. CODA operates through three functional stages—real-time data ingestion and short-term prediction, context-aware automation adaptation, and dynamic flight control allocation—facilitating adaptive sharing of responsibilities between human operators and automation. Using the Human-Machine Performance Envelope framework, we evaluate the integrated solution's impact on key cognitive and operational metrics, including stress, fatigue, vigilance, and human–AI coordination. Results indicate that the Human-Machine Performance Envelope reliably captures both objective and subjective aspects of controller–AI interaction.

Keywords- adaptive automation; mental workload; task workload; human-machine interaction;

I. INTRODUCTION

Air traffic control (ATC) is widely recognized as one of the most cognitively demanding and high-stress occupations. The continuous growth of global air traffic has resulted in increasingly congested airspace, affecting mental workload experienced by Air Traffic Control Operators (ATCOs), and increasing the risk of human error [1]. Elevated stress, fatigue, and lapses in vigilance not only affect ATCOs well-being but can also degrade operational efficiency and compromise aviation safety [2]. Therefore, reducing the mental workload of ATCOs through the integration of automation remains a critical research priority in air traffic management (ATM) [3]. This study investigates a novel approach for the assessment of the interaction between air traffic control operators and support artificial intelligence systems, the Human-Machine Performance Envelope (HMPE). To exemplify its use, it is used to assess an AI-driven automation system (CODA) designed to proactively support ATCOs through context-sensitive actions and the execution of selected control tasks. The assistant operates within an adaptive automation (AA) framework, whose effectiveness in mitigating controller workload has been demonstrated in previous research [4]. A prototype was developed to process real-time, context-aware information, enabling more efficient and flexible task sharing between human operators and automated functions. The experimental evaluation focused on three main objectives: assessing the validity of the HMPE as a quantitative framework for measuring the variables related to human-AI teaming, examining the quality of human–machine interaction through its indicators, and evaluating the overall impact of the CODA system on ATCOs performance. By analyzing these dimensions, the study assesses the feasibility and potential benefits of the proposed performance evaluation framework and of the CODA system, and contributes shedding light on the impact on adaptive automation systems actual impact in ATM.

The paper starts with an overview of the current state of the art in automation and human–AI teaming within ATC. It then introduces the CODA architecture, followed by the

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CODA

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