Doctoral (PhD) Dissertation

Human Cognitive Load and Awareness Monitoring Using AI and Biosignals in Assembly Operations

Author: Abdulrahman Khalid Eesee Al-sabaawi

Supervisors: Dr. Tamás Ruppert, Dr. habil. György Eigner

University of Pannonia

Faculty of Engineering

Doctoral School of Chemical Engineering and Material Sciences

Department of System Engineering

University of Pannonia
Faculty of Engineering

2026

Introduction

Industrial work is increasingly shaped by digitalization, high product variability, and frequent process changes. As a result, workers must execute complex tasks while interpreting instructions, switching between subtasks, and maintaining quality under time pressure. These conditions can raise cognitive load and contribute to errors, slowdowns, fatigue, and reduced situational responsiveness, especially when instructions are dense, poorly structured, or mismatched to the worker's expertise and the task's demands.

This dissertation addresses the need for human-centric industrial systems that can recognize when task demands exceed an operator's momentary capacity and adapt work support accordingly. The core idea is that cognitive load is not only reflected in performance outcomes and subjective reports, but also in physiological responses that change with workload and arousal. By combining wearable sensing, such as cardiac and electrodermal activity, with self-report measures and performance indicators, it becomes possible to estimate workload-related state changes during realistic task execution, rather than relying solely on post-task assessment.

Building on this foundation, the dissertation investigates how different instruction and task-organization strategies influence perceived workload, physiological responses, and performance. It also develops and evaluates an approach for integrating these measurements into a human-centered architecture that can support comparison between the load required by a task and the load experienced by the operator. The ultimate goal is to contribute methods and evidence that enable safer, more effective, and more adaptive industrial work support.

Goals

The dissertation aims to develop a human-aware support framework and associated methods for quantifying and managing operator cognitive load across controlled assembly-like experimental scenarios, including variations in instruction presentation and task conditions.

- Extend the Human Asset Administration Shell with physiology-based modules so that required task demands derived from task, worker, and environment descriptors can be compared to evaluated load derived from EDA and HRV, enabling state-aware adaptation triggers.
- Determine whether EDA, HRV, and wrist acceleration features change systematically across repeated instruction-guided assembly attempts, so they can track within-session cognitive load and adaptation.
- Explain fluctuations in situational awareness during dual-task or multitask assembly by

combining event-based physiology with reaction time and related performance measures.

- Test whether alternating mental and physical work produces a different recovery and arousal pattern than blocked execution of the same work, using both physiological indicators and perceived workload.
- Quantify how visual-based versus code-based instructions affect subjective workload, task performance, and physiology, and evaluate whether a combined EDA, HRV, and acceleration feature set can discriminate between the two instruction conditions.
- Assess how adding a parallel attention-demanding task in collaborative human-robot assembly affects task time, assembly errors, secondary task misses, and perceived mental load.

Dissertation Methodology

Human-centered industrial systems can only adapt to the operator if they have a model that links tasks, worker characteristics, and context, and can read the current situation's demand during ongoing work. The methodology adopted in this dissertation is therefore organized around a single assistance architecture that connects these two requirements, as illustrated in Figure 1.

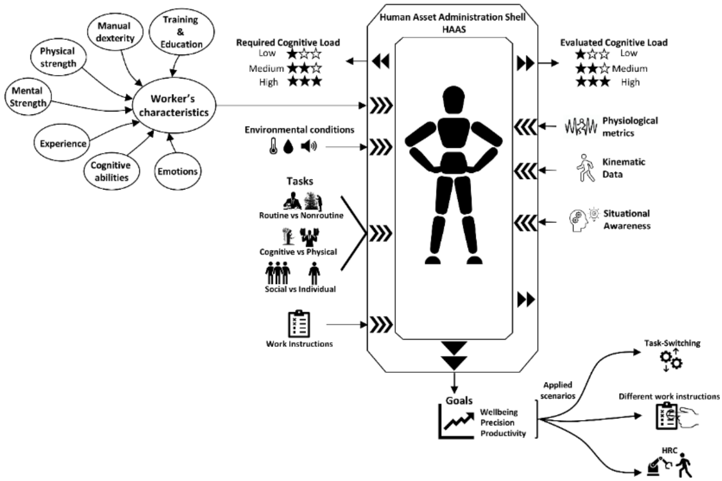

Figure 1 Overall concept of the dissertation. Worker characteristics and task/context descriptors are provided to the HAAS, which estimates the required cognitive load and compares it with the evaluated cognitive load derived from physiological and kinematic data, in order to support worker well-being, precision, and productivity

This figure summarizes the core methodology of the dissertation. At its center is the Extended Human Asset Administration Shell (HAAS), which is used to manage worker cognitive load by comparing what the situation is expected to require with what the worker is actually experiencing.

On the left side, the figure groups the inputs used to estimate the required cognitive load. These inputs describe the worker and the task context. Worker characteristics include physical and mental strength, manual dexterity, training and education, experience, cognitive abilities, and emotions. Task and context descriptors include environmental conditions, task type, and work instructions. In this conceptual model, these variables are combined within the HAAS to estimate the required cognitive load for a given situation and to classify it into three levels: low, medium, or high.

On the right side, the figure groups the measurable outputs that are used to evaluate how demanding the current situation actually is. These include physiological metrics, kinematic data from body motion, situational awareness indicators, and performance measures such as errors and task time. Together, these data provide the evaluated cognitive load, which is again categorized into low, medium, or high. By comparing the required and evaluated cognitive load, the Extended HAAS supports decisions that increase individual well-being, improve work precision, and maintain or enhance productivity.

The applied studies in this dissertation test this methodology in assembly-like scenarios. The same core logic is used to examine task switching, different work instruction formats, and attentional multitasking in human-robot collaboration, showing how the measured outputs can be aligned with task events and used to interpret changes in cognitive load across conditions.

Dissertation studies

Human-Asset Administration Shell for Cognitive Load Management

This study establishes the conceptual basis of the dissertation by extending the Human Asset Administration Shell into a framework for cognitive load management. It explains how worker, task, instruction, and environmental factors can be integrated with physiological measurements to estimate required and evaluated cognitive load, supporting adaptive and human-centered intervention.

Event-Based Physiological Markers of Cognitive Load: Viability and Limits

This study examines whether physiological and kinematic signals can track short-term cognitive load changes during repeated assembly-like tasks. Using event-aligned analysis of HRV, EDA, and wrist acceleration, it highlights both the potential and the limits of these signals for fine-grained monitoring.

Situational Awareness Monitoring via Reaction Times and Physiological Data

This study investigates situational awareness in a dual-task setting using reaction time, physiological, and kinematic measures. It shows that changes in awareness can be examined indirectly through workload-related markers during task execution.

Balancing Cognitive Load via Task-Switching

This study tests whether alternating mental and physical tasks changes the balance between recovery and arousal. The findings provide initial evidence that task sequencing can influence short-term cognitive load regulation in work design.

From Perception to Precision: How Instruction Format Shapes Workload and Accuracy

This study compares visual and code-based work instructions in an assembly-like task. It shows a trade-off: visual guidance supports faster performance and lower perceived load, while code-based instructions can support higher precision.

Attentional Multitasking in Human–Robot Collaboration

This study examines multitasking in human-robot assembly using a concurrent attention task. It shows that, although such multitasking is feasible, it can increase attentional demands and introduce productivity costs that should be considered in system design.

Results

- **Thesis I**

I developed an extended conceptual Human Asset Administration Shell (HAAS) model to manage cognitive load in human-in-the-loop systems.

Thesis I treats cognitive load in human-in-the-loop systems as a quantity that can be estimated, compared to task requirements, and influenced through specific support actions. It introduces a conceptual extension of the Human-AAS (HAAS) that connects four main modules within a single assistance architecture: physiology, worker characteristics, task type and level, and environment.

From these input modules, the HAAS derives two core quantities. The first is the evaluated cognitive load, estimated from physiological signals. The second is the required cognitive load, derived from task and context descriptors. Person-specific thresholds are set from neutral baselines, and an OODA loop compares evaluated and required load in real time. When a mismatch is detected, the system can, in principle, adapt task pacing, instruction format, difficulty, or selected aspects of the surroundings.

- **Thesis II**

I designed and validated a physiological and kinematic analysis pipeline to track attempt-level changes in cognitive load during repeated assembly-like tasks.

Thesis II evaluates whether physiological signals can track dynamic changes in cognitive load when operators repeat assembly-like tasks. It focuses on signal processing, windowing, feature extraction, and validation for HRV, EDA, and wrist acceleration.

Short analysis windows aligned to task attempts are used to capture within-session variation. Heart activity and skin conductance show consistent shifts between baseline and task and across repetitions. Wrist acceleration provides contextual information by indicating segments dominated by hand movement. The analyses show that multimodal features from EDA and HRV, supported by acceleration, can distinguish baseline from task and remain sensitive to within-session changes. At the same time, reliability is reduced during periods with substantial hand motion, which motivates using acceleration to flag motion-heavy segments and support quality control.

- **Thesis III**

I implemented the assistance architecture and multimodal physiological methods in four manufacturing-like studies to quantify how dual tasks, task sequencing, instruction formats, and human-robot collaboration influence worker attention, workload, and performance.

Thesis III applies the assistance concept and a multimodal physiological and kinematic analysis framework in four experimental studies. Each study examines a different aspect of cognitive load and attention in manufacturing-like settings and contributes to one or more of the remaining research questions. The framework is applied in the following scenarios:

- **Situational awareness and dual task attention**: Event-based analysis combines reaction times with ECG, EDA, and wrist acceleration to examine momentary fluctuations in attention during dual task assembly.
- **Task sequencing and the balance between recovery and arousal**: Alternating versus continuous mental and physical task blocks are compared using perceived workload and HRV, EDA, and kinematic responses to characterize recovery and arousal patterns.

- **Instruction format, workload, and precision**: Visual-based versus code-based instructions are evaluated using NASA-TLX, short DSSQ, task completion time, task repetitions, assembly precision, and multimodal physiology to quantify speed precision trade-offs and discriminability of instruction conditions.
- **Attentional multitasking in human-robot collaboration**: A wire harnessing task with a cobot is combined with a Go No Go task at two attentional difficulty levels to assess effects on task time, errors, secondary task misses, and perceived mental load.

Publication list

[1] Eesee, A. K., Jaskó, S., Eigner, G., Abonyi, J., & Ruppert, T. (2024). Extension of HAAS for the Management of Cognitive Load. *IEEE Access*, 12, 16559-16572.

[2] Eesee, A. K., Varga, V., Eigner, G., & Ruppert, T. (2025). Impact of work instruction difficulty on cognitive load and operational efficiency. *Scientific Reports*, 15(1), 11028.

[3] Eesee, A. K., & Ruppert, T. (2025). Evaluating the Reliability of Physiological and Kinematic Features

for Tracking Cognitive Load Changes During Repetitive Task Execution. *Results in Engineering,* 108657.

[4] Eesee, A. K., Kostolani, D., Kang, T., Schlund, S., Medvegy, T., Abonyi, J., & Ruppert, T. (2024). May I have your attention?! Exploring multitasking in human-robot collaboration. *IFAC-PapersOnLine*, 58(19), 241-246.

[5] Eesee, A. K., Kostolani, D., Varga, V., Kang, T., Schlund, S., & Ruppert, T. (2025, June). Studying Dual-Task Awareness in Industrial Settings Through Reaction Times and Physiological Signals. In 2025 *IEEE Conference on Cognitive and Computational Aspects of Situation Management (CogSIMA*) (pp. 151-156). IEEE.