



UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

Executive Summary: Measuring Operator Response to Simulated Adaptive Automation

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Summary

Over three years, this project moved adaptive automation from a broad design problem into a working U.S. Army Aeromedical Research Laboratory (USAARL) research capability and a more clearly defined set of human-factors requirements. The strongest finding was not that automation should simply reduce workload, but that how work is transferred matters. Aviators trusted and used automation more when they retained authority over routine handoffs, even though making that decision added some momentary workload. Additional transparency was not consistently beneficial and could impose its own attentional cost. The flight simulator study further showed that adaptive systems should respond to a developing pilot-aircraft-automation state, rather than treating physiology as an isolated workload trigger. Together, the project produced practical guidance for automation design while leaving USAARL with the synchronized data, workload-modeling, automation, and high-fidelity simulation capabilities needed to continue toward prospective operator-state-driven automation.

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Executive Summary

This project was developed around a practical problem in Army aviation. Automation can take work from an aviator, but it does not make that work disappear. It changes who is responsible for the task, what the aviator must monitor, and what has to happen when control is passed back and forth. The original proposal therefore treated adaptive automation as a function-allocation problem. The planned progression was straightforward: establish what was known in the state of the art, build the tools needed to study the problem, test the major design variables under controlled conditions, and then carry the problem into a higher-fidelity flight environment with rated aviators. That progression was retained across the three years of work, from fiscal year (FY) 24 to FY26.

The first phase showed that the literature was much better at identifying concerns than prescribing an architecture. The same questions appeared repeatedly: When should automation act? Which function should be transferred? How much explanation does the operator need? Who should have authority over the transition? Those questions shaped the experimental work for the laboratory and simulator phases. They also exposed a practical limitation at the U.S. Army Aeromedical Research Laboratory (USAARL). If operator state, aircraft state, automation state, and performance are to be studied together, the data have to exist on the same timeline. The Lab Streaming Layer (LSL) implementation addressed that problem by moving simulator, physiological, and event data into a common Extensible Data Format (XDF) workflow that could be accessed during data collection in real-time, reconstructed after the flight, and expanded as new sensors were added (Vogl, Atchley, Persson, et al., 2025). This development set the foundation for this effort to be executed successfully.

The laboratory phase provided the first controlled test of the design problem. The USAARL Multi-Attribute Task Battery (MATB) was expanded with the custom developed Virtual Offloading Guidance Logic (VOGL) system, while the Improved Performance Research Integration Tool (IMPRINT) and computational Multiple Resource Theory (cMRT) methods were used to model task demand over time. These approaches in combination allowed for real-time adjustments based on task demand, performance, and information acquisition strategies. The USAARL MATB experiment showed two things that carried forward. First, transparency was not free. In a demanding multitask setting, a continuously visible explanation of automation state could become another display to process and add additional cognitive burden. Second, authority over the transfer was a primary driving factor. Voluntary handoffs generally produced a more favorable pattern of trust and situation awareness. The opaque-voluntary condition performed best overall in the laboratory, but the later flight work showed why that result should be treated as a starting point rather than a universal design rule (Vogl, Atchley, Basso, et al., 2025).

The UH-60 simulation phase was the more useful test of what persisted into the operational space. Transparency did not produce reliable improvements in workload, situation awareness, or trust. However, handoff authority did. When aviators retained a role in accepting the suggestion of a task control transfer, they reported greater trust in system performance and understanding and showed greater behavioral reliance. More importantly, giving aviators a choice did not make them avoid automation. Voluntary conditions contained about 13 percent more automation exposure than forced conditions. Retrospective National Aeronautics and Space

Administration-Task Load Index (NASA-TLX) workload and flight error were also lower under voluntary handoff, even though Instantaneous Self-Assessment of Workload (ISA) was higher. That pattern is more informative than a simple claim that voluntary handoffs reduced workload. Accepting a recommendation adds a decision at the moment of transfer, but preserving that decision can reduce frustration, improve the broader interaction, and lead to more rather than less use of automation (Vogl et al., 2026).

The flight study also honed the operator state monitoring problem. The useful target does not appear to be a context-free workload number. The more practical target is an emerging operational state in which assistance is likely to become useful. Before many requests for greater automation, manual-flight instability was already increasing and selected cardiac and pupillary measures were changing in notable and traceable ways. Those physiological measures are not unique measures of workload, nor can we say they cause the handoff decision itself. They did, however, contain information about the state from which the handoff became relevant. This shifts the engineering question from, 'What is the pilot's workload?' to, 'Is the pilot-aircraft system moving toward a state in which a change in task allocation would improve performance?' The distinction is a meaningful outcome of this work because the latter can be evaluated against an operational consequence rather than an abstract label and USAARL now has the capacity to address the more operational question.

At closeout, the main contribution is therefore more than a set of physiological associations or individual automation effects. The project determined how an adaptive system should be approached. Routine transitions benefited from keeping the aviator involved in the allocation decision. More information was not automatically better information. A handoff was shown to have a history before the transfer and a recovery after it, making the handoff strategy as important as the trigger itself. Finally, physiological state alone was not sufficient to characterize the condition of the operator. Its meaning depended on the surrounding operational context, including aircraft performance, current automation configuration, and recent changes in control allocation. The project did not deliver a field-ready physiological controller, nor was that a reasonable endpoint for this stage of work. However, this effort did leave the Army and USAARL with the tools and a much narrower set of questions needed to test one responsibly.

Project Overview

Table 1. Project Overview by Year

Period	Primary Focus	Representative Output	Capability Carried Forward
FY24	Evidence base and early software development	Adaptive automation literature review; initial simulator and automation development	Literature-guided design requirements and an experimental roadmap
FY25	Workload modeling, synchronization, and controlled automation	IMPRINT/cMRT models; LSL/XDF architecture; MATB/VOGL experiment report	Synchronized multimodal data backbone and configurable laboratory testbed
FY26	High-fidelity validation of handoff authority, transition state, and operator state monitoring	UH-60 adaptive automation capabilities; UH-60 automation experiment report	Reusable flight-simulation automation capability and joint pilot-aircraft-state analysis methods

Note. The original three-phase sequence was preserved, although several enabling products, particularly LSL/XDF synchronization and automation software, became substantive deliverables in their own right.

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Major Outputs and Deliverables

Table 2. Major Outputs and Deliverables by Year

Year	Output/Deliverable	Status at Closeout	Contribution to the Project
2024	Optimizing adaptive automation in aviation: A literature review on dynamic automation system interaction (USAARL-TECH-TR--2025-09)	Published technical report	Established the evidence base and reduced the adaptive automation problem to recurring design questions involving function allocation, handoff authority, transparency, operator engagement, and dynamic state assessment
2024-2025	USAARL MATB/VOGL adaptive automation platform development	Operational research software	Created a configurable platform for testing reliability, transparency, voluntary/forced handoff, workload thresholds, and task allocation rather than treating automation as a single experimental factor
2025	Toward data synchronization and real-time processing methodologies for operator state monitoring at USAARL (USAARL-TECH-TR--2025-27)	Published technical report	Placed simulator, physiology, and event streams on a common time base, making later reconstruction of automation transitions and operator-aircraft state possible
2025	Accounting for the impact of automation use on cognitive workload of aviators during simulated aviation tasks	Human Center of Gravity (HCOG) Symposium 2025 oral presentation	Presented results regarding a theory-based alternative to coarse demand labels by linking cMRT/IMPRINT estimates with performance, subjective workload, and cardiac activity
2025-2026	Advancing adaptive automation in aviation: A simulation approach integrating IMPRINT and MATB	In press, The International Journal of Aerospace Psychology	Provides peer-reviewed dissemination of the workload-modeling approach used to connect IMPRINT with adaptive automation design and MATB experimentation

Year	Output/Deliverable	Status at Closeout	Contribution to the Project
2025	Designing adaptive automation for aviation: Transparency and handoff effects on cognitive workload, situational awareness, and trust (USAARL-TECH-TR--2026-02)	Published technical report	Provided the controlled USAARL MATB test showing that transparency and handoff authority influence different parts of the human-automation interaction and that additional transparency can carry a processing cost
2026	Autonomy by consent: How transparency and control handoff shape workload, situation awareness, and trust in adaptive automation	Aerospace Medical Association (ASMA) annual conference 2026 oral presentation	Translated the laboratory findings into an applied message centered on autonomy-by-consent, selective transparency, and the costs of control transitions
2026	Behind the curtain of adaptive automation: Physiology, handoff methods, and human performance in flight	Final project manuscript; planned submission to Frontiers in Neuroergonomics	Extended the work into a high-fidelity UH-60 simulation and showed that operator authority, automation use, flight performance, and the state leading into a handoff must be interpreted together
FY24-FY26	High-fidelity simulator automation and multimodal analysis capability	Enduring USAARL capability	Leaves reusable automation, synchronization, transition reconstruction, and joint-state analysis capability for follow-on operator state monitoring (OSM) and human-autonomy teaming research

Status Note. Publication status and the planned venue for the final flight manuscript reflect project status at closeout on September 30, 2026.

What Was Learned?

Adaptive Automation is a Coordination Problem, Not a Workload-Minimization Problem

Across the three phases, the most consistent lesson was that automation changes the distribution of work more often than it eliminates work. When a function moves to automation, direct control demand may fall, but new demands appear in monitoring, acceptance, supervision, and eventual reacquisition. As such, the success of an adaptive system cannot be judged only by whether a workload score goes down immediately after automation is engaged. The better criterion is whether the allocation leaves the joint pilot-automation system in a more effective state. This is a subtle distinction, but it changes the design objective from minimizing human

effort to assigning effort where it is most useful and prepares future research to examine what happens when abrupt reassignment of tasks changes the workflow.

Operator Authority Affected Both Trust And Actual Automation Use

The laboratory experiment suggested that voluntary handoff was beneficial, and the flight study provided the more important result: Aviators did not respond to retained authority by simply declining automation. They used it more. Voluntary conditions produced greater trust in system performance and understanding, greater behavioral reliance, and about 13 percent more automation exposure than forced conditions. This separates two ideas that are often treated as the same thing. A system can act faster when it takes control automatically, but faster implementation is not the same as better cooperation. In these data, preserving a meaningful role for the aviator increased subsequent use of the automation rather than suppressing it. This demonstrates that pilots want to use the automation tools to facilitate their mission, but it also demonstrates how increased automation use can incur skill degradation over time and/or inappropriate overreliance on the system unless an appropriate balance is struck with adaptive automation.

Automation Redistributed Workload Rather Than Simply Reducing It

The workload results help explain why authority should not be described as cost-free. Voluntary handoffs were associated with lower retrospective NASA-TLX scores and lower flight error, while instantaneous ISA ratings were higher. Frustration was also substantially lower under voluntary handoff. These findings are not well represented by asking which condition had the 'lowest workload.' A voluntary architecture inserts a decision into the handoff, and that decision requires attention when the recommendation is made. At the same time, participation in the decision can make the overall interaction less frustrating and can support better control across the flight. The broader lesson is that adaptive automation should be expected to redistribute cognitive work across time and task rather than remove it uniformly.

Transparency Is Useful Only When It Earns The Operator's Attention

The literature review identified transparency as a recurring recommendation, but the experiments placed an important limit on that recommendation. In the MATB, keeping automation state and rationale continuously visible increased workload and affected situation awareness outcomes. The UH-60 experiment did not reproduce a reliable transparency effect. Taken together, the studies do not show that opacity is inherently better. They show that transparency is information, and information consumes resources. If an explanation improves prediction, diagnosis, training, or coordination, the cost may be worthwhile. If it is simply another panel to scan during an already demanding phase of flight, it can compete with the task it was meant to support. Transparency should therefore be tied to a purpose and built into the task workflow rather than treated as a standing requirement.

The Useful OSM Target Is An Emerging Need For Assistance, Not A Generic Workload Value

The final analyses suggest a more useful way to think about OSM. A future system does not necessarily need to know the operator's 'true workload' in an abstract sense. It needs to

recognize a developing condition that has operational consequences and decide whether assistance is likely to improve the joint system. Heart rate, heart rate variability, and pupil diameter were informative because their recent trajectories corresponded with manual-flight instability at particular time scales, not because any one of them uniquely identified cognitive workload. This is a narrower claim, but it is also much closer to the decision an adaptive system actually has to make.

The practical implication is that future OSM validation should be performance criterion-based. Candidate signals should be tested against what the system is trying to prevent or improve: worsening flight-path control, loss of stable monitoring, delayed response, or some other consequential state. Physiological evidence can then be combined with aircraft state, task demand, and automation configuration to estimate whether assistance is becoming appropriate.

A Handoff is a Coordination Episode, Not a Trigger Point

The event-centered analyses showed that the handoff itself occupied a period of time. Manual-flight instability was already increasing before requests for greater automation, and higher-resolution reconstruction showed declining root mean square of successive differences (RMSSD) and increasing pupil diameter during portions of that pre-request period. After greater automation was engaged, flight error declined during later recovery and the cardiac pattern shifted in the opposite direction. As such, treating the handoff as a single timestamp leaves out much of the problem. Recommendation, decision, execution, and recovery are distinct parts of the coordination process and should be designed and measured as such.

Operator State is Inseparable From The Control Context

Some physiology-performance relationships weakened after local automation allocation was included in the model, and greater-automation transitions occurred from different starting states than greater-manual transitions. This is not an analytical nuisance that has to be statistically accounted for, it is a basic property of adaptive automation. The system acts because something is happening, which means physiology, task demand, aircraft performance, and automation state become coupled. A future model that watches only the aviator will confuse some of these effects. Useful state estimation will need to include the context of what the aircraft is doing, what the automation is controlling, where the mission is in time, and what has happened recently in the allocation of control.

Impact and Benefits

Warfighter Impact

The immediate Warfighter value is a better basis for deciding how assistance should enter the cockpit. The project does not support a simple recommendation to automate more. It supports retaining aviator authority over routine transitions when time permits, because that authority was associated with greater trust, greater reliance, and greater realized use of automation. It also supports reserving forced intervention for cases in which the cost of waiting is greater than the cost of taking control. This distinction becomes increasingly important as Army aircraft gain autonomy. The issue will not be whether the system can act, but whether it acts in a way that keeps the aviator appropriately involved in the mission.

The longer-term Warfighter benefit is a more defensible target for OSM. Rather than searching for a generic physiological workload index, follow-on work can test whether a combination of operator and aircraft measures identifies a developing need for assistance early enough to matter. The current project identified candidate cardiac and pupillary patterns that occurred while manual control was becoming less stable and before some greater-automation requests. Those signals are not ready to drive an aircraft. They do, however, define a practical next experiment: determine whether physiological signals tuned to the operator through extensive baselining procedures improve prediction of an impending need for assistance beyond aircraft state and automation context alone.

Army Impact

For the Army, the project contributes design evidence that is directly relevant to future crewed-autonomy systems. It separates three questions that are often collapsed: how task demand should be represented, who should control a transition, and what information should accompany that transition. IMPRINT and cMRT supplied a theory-based application to describe competing perceptual, cognitive, and response demands. The automation experiments then showed that authority and transparency are not interchangeable design levers. This gives Human Systems Integration and Future Vertical Lift efforts a more specific set of variables to consider than a general requirement to 'reduce workload' or 'increase transparency.'

Just as important is the ability to test candidate concepts before they are treated as aircraft solutions. The LSL architecture, configurable automation software, workload models, and UH-60 environment now allow sensors, displays, algorithms, and handoff policies to be evaluated while the consequences of failure remain experimental rather than operational. This makes it possible to discard weak concepts earlier, refine promising ones against known human-performance criteria, and enter later stages of development with a clearer statement of what the technology is expected to improve.

USAARL Impact

A substantial part of the project's return to USAARL is the research capability that remains after the individual studies are complete. The LSL implementation placed simulator, physiological, and event data on a common time base and moved collection away from disconnected device-specific workflows. That common timeline is what made the later transition analyses possible. It also gives future studies a practical way to reconstruct what the operator, aircraft, and automation were doing at the same moment, which is a prerequisite for credible OSM and adaptive automation work.

The automation platforms provide a similar return. VOGL turned the USAARL MATB into a configurable automation testbed rather than a fixed multitask battery. The UH-60 implementation carried the same general problem into a setting in which aircraft performance and automation allocation could be examined together. These tools now make it possible to study adaptive cueing, authority, automation reliability, sensor performance, and human-agent coordination without rebuilding the basic experimental architecture for each protocol. The enduring value is therefore not one software package, but the ability to move a question from controlled task analysis to a higher-fidelity aviation setting within the same research program.

Contribution to The Research Field

The contribution to the research field is broader than the observation that physiological data are more informative when time is retained. First, the studies show that handoff authority can affect trust, reliance, and actual automation use even when transparency does not produce a comparable effect. Second, they show that adaptive automation events are endogenous: Greater-automation handoffs tended to occur from poorer flight-control states than greater-manual handoffs. Before-and-after comparisons can therefore be misleading if the state that produced the intervention is ignored. Finally, the work argues for evaluating OSM by its operational usefulness rather than by whether a sensor can be labeled a pure workload measure. These points move the problem closer to the joint-system questions that a fielded adaptive controller would actually have to solve.

Capabilities Retained at Closeout

- **Synchronized multimodal data collection.** LSL and XDF provide a common temporal backbone for simulator, physiological, event, and future sensor streams, with metadata and remote recording support.
- **Configurable adaptive automation testbed.** MATB/VOGL can vary reliability, transparency, voluntary or forced handoff, workload thresholds, and task allocation while retaining standardized performance measures.
- **Theory-based workload modeling.** IMPRINT and cMRT provide a priori estimates of resource demand that can be tied to task combinations, automation logic, and comparisons among scenarios.
- **High-fidelity human-autonomy experimentation.** The UH-60 simulator can support controlled changes in automation while recording flight performance, physiology, subjective state, situation awareness, trust, and automation use.
- **Joint-state and criterion-based OSM analysis.** Operator measures can be evaluated together with aircraft performance, task demand, current automation, and recent control history to determine whether a developing state has operational significance.
- **Transition reconstruction.** Automation request, operator response, execution, direction of transfer, and recovery can be treated as parts of a coordination episode rather than collapsed into a single handoff marker.

Project Closeout

The project began by asking how an adaptive system should take work from an aviator and how that work should be returned. Three years later, the most useful answer is not a preferred automation level. It is a set of constraints on how control should be coordinated. Routine authority over the transfer mattered more consistently than additional transparency. Aviators used automation more, not less, when they retained a role in accepting it. The workload cost of that decision appeared immediately, while some of the broader benefits appeared in trust, frustration, automation use, and flight performance.

The project also changed the technical question facing follow-on OSM work. The goal should not be to produce a physiologically derived workload number and attach an automation threshold to it. The more useful goal is to determine whether the operator-aircraft system is

moving toward a condition in which assistance will improve the outcome, then coordinate the transfer in a way the aviator can understand and, when time permits, authorize. IMPRINT supplied a principled representation of task demand, LSL supplied the common time base, VOGL supplied experimental control of automation behavior, and the UH-60 implementation supplied the operational context needed to put these pieces together.

Not every original hypothesis was supported, and that is useful information. The project reduced uncertainty about which assumptions deserve to follow the technology forward. More transparency is not automatically better. Faster, forced transfer is not automatically better. Lower workload at every moment is not a sensible design objective. A physiological signal is not useful merely because it correlates with a workload label. What matters is whether the joint system can recognize a developing problem, allocate the right function at the right time, preserve the aviator's role where it has value, and recover cleanly after the allocation changes. The project closes with published knowledge products, a reusable USAARL test capability, and a substantially narrower path toward a prospective test of true operator-state-driven adaptive automation.

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Appendix A. Acronyms and Abbreviations

cMRT	Computational Multiple Resource Theory
FY	Fiscal Year
IMPRINT	Improved Performance Research Integration Tool
LSL	Lab Streaming Layer
MATB	Multi-Attribute Task Battery
NASA TLX	National Aeronautics and Space Administration Task Load Index
OSM	Operator State Monitoring
RMSSD	Root Mean Square of Successive Differences
USAARL	U.S. Army Aeromedical Research Laboratory
VOGL	Virtual Offloading Guidance Logic
XDF	Extensible Data Format

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