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RESHAPING AIRPOWER: DEVELOPMENT OF AN IMPRINT MODEL TO ANALYZE THE EFFECTS OF MANNED-UNMANNED TEAMING ON OPERATOR MENTAL WORKLOAD

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ABSTRACT

Due to the advent of autonomous technology coupled with the expense of manned aircraft, the Department of Defense (DoD) is developing affordable, expendable Unmanned Aerial Vehicles (UAVs) to be operated in conjunction with jet fighters. With a single pilot commanding the UAVs while piloting their aircraft, operators may find it challenging to manage all systems should the system design not be conducive to a steady state level of workload. To understand the potential effects of manned-unmanned teaming on the pilot's cognitive workload, an Improved Performance Research Integration Tool (IMPRINT) workload model was developed. The model predicts pilot workload in a simulated environment when interacting with the cockpit and multiple UAVs to provide insight into the effect of Human-Agent Interactions on workload and mission performance. This research concluded that peaks in workload occur for the pilot during periods of high communications load and this communication may be degraded or delayed during air-to-air engagements.

1 INTRODUCTION

Due to the advent of autonomous technology coupled with the extreme expense of manned aircraft, the DoD has developed an interest in constructing affordable UAVs to become autonomous wingmen for jet fighters in mosaic warfare (Drew 2016). Like a mosaic that forms a whole picture out of smaller pieces, battlefield commanders can utilize disaggregated capabilities, such as low-cost UAVs, to operate in contested environments (Magnuson 2018). Utilizing UAVs to complement manned aircraft may offer advantages such as increased pilot survivability as well as amplified firing power to fill capability gaps. However, there are complications with this new strategy. For example, in an envisioned architecture, command pilots will need to deploy capabilities from the UAVs in addition to controlling their own aircraft. The need to devote attention and mental resources to both controlling their own aircraft and the UAVs could be challenging for pilots should the system interface design not be conducive to maintaining a manageable level of workload.

To integrate pilots and UAVs into a cohesive system, designers must consider the effect that Human-Agent Interactions (HAI) have on the pilot's cognitive workload. In this context, workload is defined as a measure of the task load, mental effort, or stress perceived by the human, with more tasks, more difficult tasks, and increased pressure to multi-task generally inflicting higher perceived workload. To evaluate the workload that is imposed upon a pilot during air operations, engineers need a method to objectively determine the amount of workload produced within a given human-agent system. One approach is to perform Human-In-The-Loop (HITL) experimentation by prototyping and testing multiple system designs,

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including subjectively measuring the workload experienced by test pilots who fly simulated missions within the prototype system. While human research and prototyping of automation produces valuable information, it is inefficient and ineffective as the process is tedious, lengthy, and costly to complete, preventing the quantification of workload during important mission conditions. There can also be safety issues involved when performing risky HITL experiments. As such, to design a system using this approach as the only feedback mechanism constrains the number and variety of alternative system designs which can reasonably be considered within a design effort.

An alternative to HITL evaluations is to assess cognitive workload through analytical modeling. A modeling tool that estimates human workload is the Improved Performance Research Integration Tool (IMPRINT). IMPRINT quantitatively models operator workload across several different resource channels through the incorporation of the Visual, Auditory, Cognitive, and Psychomotor (VACP) scale (Bierbaum et al. 1989). The tool can be used to simulate various system configurations and their effects on pilot workload within a Discrete Event Simulation (DES). This method can provide a lower cost method than HITL evaluations and permit the opportunity to explore a greater number of alternative design options. This tool can be particularly effective when coupled with HITL evaluations to provide validation and to ground assumptions about human behavior in novel circumstances, where human behavior is unpredictable due to human innovation and adaptation (Goodman, Miller, Rusnock, & Bindewald 2017; Rosenberg 1982).

In this research, IMPRINT was used to construct a DES to assess the effects of human-agent teaming on operator cognitive workload and system performance. The DES represented tasks performed by human subjects enrolled in a previously-conducted HITL evaluation (Schumacher et al. 2017). The study replicated a dynamic, military, offensive counter-air scenario in which individual performance and mental workload could vary in real-time based on the operators' capabilities.

An original baseline DES was developed to quantitatively capture the pilot's cognitive workload levels when controlling both UAVs and manned aircraft. An alternative system configuration was then created to compare the baseline model to traditional aviation techniques. The findings presented in this research provided a significant step towards simulating the complexities of real-world activities by mirroring the highly dynamic nature of realistic military operations in a simulated environment.

2 METHOD

2.1 Design of the ATACM Study

During development of a human workload model, it is useful to obtain HITL data to support model validation. In this effort an existing data set was obtained from a study referred to as the Autonomy for Air Combat Missions (ATACM) study. This section provides an explanation of this data set, the participants, mission scenario, and task environment. Nine experienced former military pilots participated in the ATACM study. The ATACM study was a HITL experiment that developed and tested critical autonomous decision and machine learning technologies in a virtual cockpit with the aim of enabling a single pilot to command multiple UAVs in flight while controlling his or her own aircraft in a highly contested environment (Schumacher et al. 2017). After initial training and practice, each pilot flew four air-to-air trial engagements in which the pilot commanded three UAVs, as well as their own simulated fighter aircraft against four adversaries. For each trial, participants were given ten minutes to employ their own aircraft and those of the UAVs to destroy the four adversaries. The scenario applied time pressure through the use of a bomber which would arrive on station in 10 minutes, after which it would be vulnerable to the adversaries, resulting in mission failure. The scenario ended when any of the following occurred: 1) all four adversary aircraft were killed, 2) all three UAVs were killed, 3) the pilot was killed, or 4) ten minutes elapsed. The general mission scenario is illustrated in Figure 1.

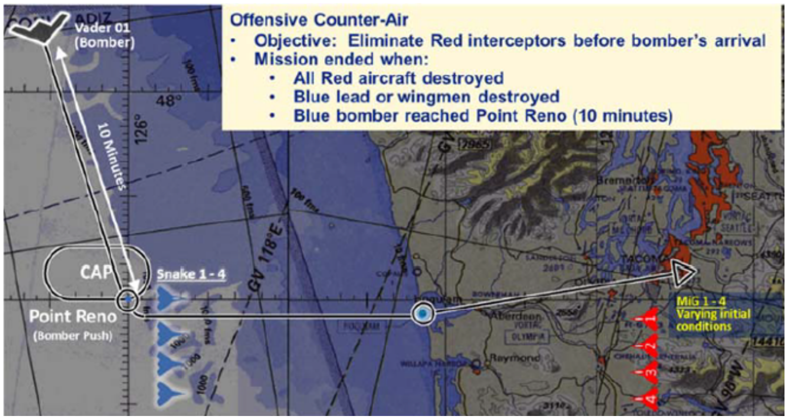

Offensive Counter-Air
- **Objective: Eliminate Red interceptors before bomber's arrival**
- **Mission ended when:**
  - **All Red aircraft destroyed**
  - **Blue lead or wingmen destroyed**
  - **Blue bomber reached Point Reno (10 minutes)**

Figure 1: ATACM mission scenarios.

The virtual simulation cockpit utilized in the ATACM experiment was composed of four major elements: 1) a pilot-vehicle interface, 2) a multi-UAV, artificial-intelligence-based multi-agent controller, 3) automated (scripted) low-level responses to commands, and 4) a virtual piloted mission simulation. Using these four resources, the test subjects were required to locate and target adversary aircraft by commanding three UAVs and their own aircraft to fire at targets. Video footage from the experiments was captured and used for analysis in this research.

2.2 IMPRINT Model Development

The information provided from the HITL was used to create the DES model for a single human pilot commanding three UAVs against four enemy targets. As shown in Figure 2, the task network model was composed of four primary task loops and one logic loop, including: 1) Aviate Personal Aircraft, 2) Utilize UAVs, 3) Utilize Personal Aircraft, 4) Receive Environment Noise, and 5) End Scenarios.

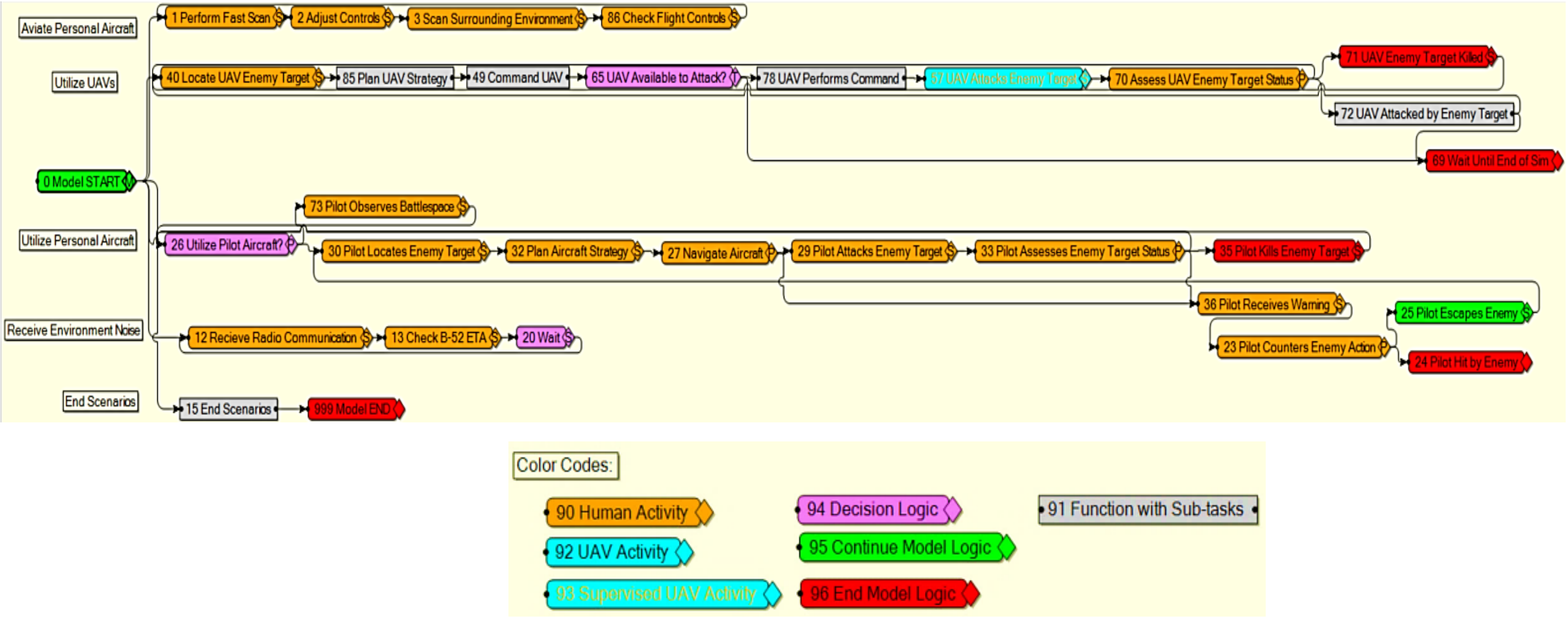


Figure 2: IMPRINT task network.

Each of the task loops, further described in Table 1, ran in parallel with one another as it was assumed that the pilot performed these activities concurrently. The final logic loop also ran concurrently with the other task loops to permit the software to evaluate whether or not the simulation satisfied one of the ending conditions. Once the task network was developed, each task was assigned a VACP workload value, task time, and decision probability. The task time distributions and probabilities for successful completion or failure of task nodes were calculated by extracting timing and decision data from the video footage of the nine test subjects in the ATACM study, and then fitting to probability distributions or assigning decision logic probabilities, respectively. The final model was then validated in comparison to results obtained from the ATACM study.

Table 1: IMPRINT model loop descriptions.

IMPRINT Loop	**Description**
Aviate Personal Aircraft	The first task loop included basic tasks such as adjusting the flight controls or scanning the surrounding environment that the pilot performed when operating his or her own aircraft.
Utilize UAVs	The second task loop included tasks such as commanding the UAV or supervising UAV attacks, which the pilot executed to deploy the UAVs. The pilot commanded the UAVs using commands which varied on a continuum of autonomous control abstraction that ranged from simple commands such as “turn left” or “fly at an altitude” to more complex commands such as “fly formation” or “attack target.”
Utilize Personal Aircraft	The third task loop included tasks such as aviating the manned aircraft or attacking the adversary target, which the pilot performed to utilize his or her own aircraft to attack the enemy.
Receive Environment Noise	The fourth task loop included the workload associated with receiving audio notifications over the radio.
End Scenarios	The final logic loop included tasks that would trigger the DES to end if any of the stopping scenarios were fulfilled.

Within the DES, the independent variable was the use of UAVs in the DES. The dependent variables were mission performance and mental workload of the pilot. In the first model, both the manned aircraft and UAVs were employed to attack the adversaries. In the second model, only the manned aircraft was employed to attack the adversaries. Mission performance was measured by calculating the number of enemy targets that survived. The workload of the pilot was determined using the VACP scores gathered from each model for a subset of thirty trials, producing a time-averaged workload value for the models. The workload demand input for each task within the model is shown in Table 2.

Table 2: IMPRINT task workload demand levels.

Task		**Total Workload Demand**
Aviate Aircraft	Perform Fast Scan	9.8
	Adjust Controls	11.4
	Scan Surrounding Environment	11.2
	Check Flight Controls	9.8
Utilize UAVs	Locate UAV Enemy Target	11.2
	Plan UAV Strategy for 1 UAV	10.8
	Plan UAV Strategy for 2 UAVs	11.2

Utilize UAVs	Plan UAV Strategy for 3 UAVs	11.8
	Check UAV Status	9
	Initiate Call	4.2
	High Level Command (TBM)	6.6
	Medium Level Command (PDE)	7.0
	Low Level Command (VS)	7.3
	Confirm Command	4.2
	Pilot Decides Whether to Override UAV	11.2
	Pilot Overrides UAV	7.0
	Pilot Overrides UAV	4.2
	UAV Performs High Level Command (TBM)	10.8
	UAV Performs Medium Level Command (PDE)	11.2
	UAV Performs Low Level Command (VS)	11.8
	UAV Attacks Enemy Target	7.6
	Assess UAV Enemy Target Status	7.6
	Assess UAV Enemy Target Status	6.6
	UAV Employs Counter Measure	7.6
	Pilot Observes Battlespace	11.2
	Pilot Locates Enemy Target	8.6
	Plan Aircraft Strategy	9.8
	Navigate Aircraft to Target Point	11.2
	Navigate Aircraft to Target Point	11.4
	Pilot Attacks Enemy Target	12.8
	Pilot Attacks Enemy Target	13.4
	Pilot Assesses Enemy Target Status	7.6
	Pilot Assesses Enemy Target Status	6.6
	Pilot Receives Warning	4.0
	Pilot Receives Warning	3.0
	Pilot Counters Enemy Action	12.8
	Pilot Counters Enemy Action	11.4
Noise	Receive Radio Communication	6.6
	Check B-52 ETA	3.0

3 ANALYSIS & RESULTS

One thousand DES trials were run to study the effect of HAI on the pilot's cognitive workload when commanding three UAVs against four enemy targets. In the first "manned-unmanned teaming" model setup, both the manned aircraft and UAVs were employed to attack the adversaries. In the second "manned-only" model set up, only the manned aircraft was employed to attack the adversaries. For each condition, the mission performance and mental workload of the pilot were calculated and then analyzed to compare how the system was affected by the incorporation of human-agent teaming technology.

3.1 Mission Performance Analysis

Figure 3 shows the percent of trials as a function of the number of enemy targets remaining at the end of each trial. A comparison of the UAV survival rate was not analyzed, since there were no UAVs used in the manned-only model. According to the data, the number of surviving enemy targets was reduced when the UAVs were incorporated into the model. The manned-only condition had 3.78 enemy targets survive per trial on average, while the manned-unmanned teaming condition only had 1.58 enemy targets survive per trial on average.

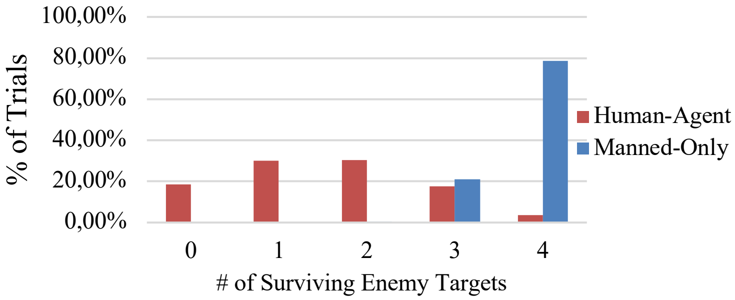


Figure 3: Graph of enemy target survival results.

Furthermore, the incorporation of the UAVs resulted in all of the enemy targets being killed in 18.40% of the simulation trials. Conversely, 0% of the simulation trials resulted in all of the enemy targets being killed in the manned-only condition. This significant difference was expected due to the added attack capability that the pilot had with the three UAVs attacking four enemy targets instead of a single pilot carrying the weight of the battle. For this reason, the incorporation of UAVs improved the human-agent team's mission performance. Despite this result, the workload levels must also be analyzed to determine whether or not the pilot would be oversaturated with tasks when utilizing this supplementary technology. It is important to understand the expected workload for the human-agent team, to evaluate the feasibility of achieving the increased performance gains and to understand the potential for unintended consequences from cognitive overload.

3.2 Workload Profile Analysis

In this section, the total objective workload experienced by the operator was compared between the manned-unmanned and manned-only DES models. IMPRINT calculated a workload profile based on the length of time the pilot spent performing a specific activity in relation to the combined VACP value(s) assigned for the interfaces of each task node. Events that were above a workload level of 60 were considered to be near or above the saturation threshold where the system imposed more work than the pilot could effectively perform (Mitchell 2003; Schneider & McGrogan 2011). In an ideal mission scenario, all workload levels would be below 60.

The workload graph for a standard simulation run is shown in Figure 4 to provide insight into some of the interactions and implications from incorporating manned-unmanned teaming technology into flight operations.

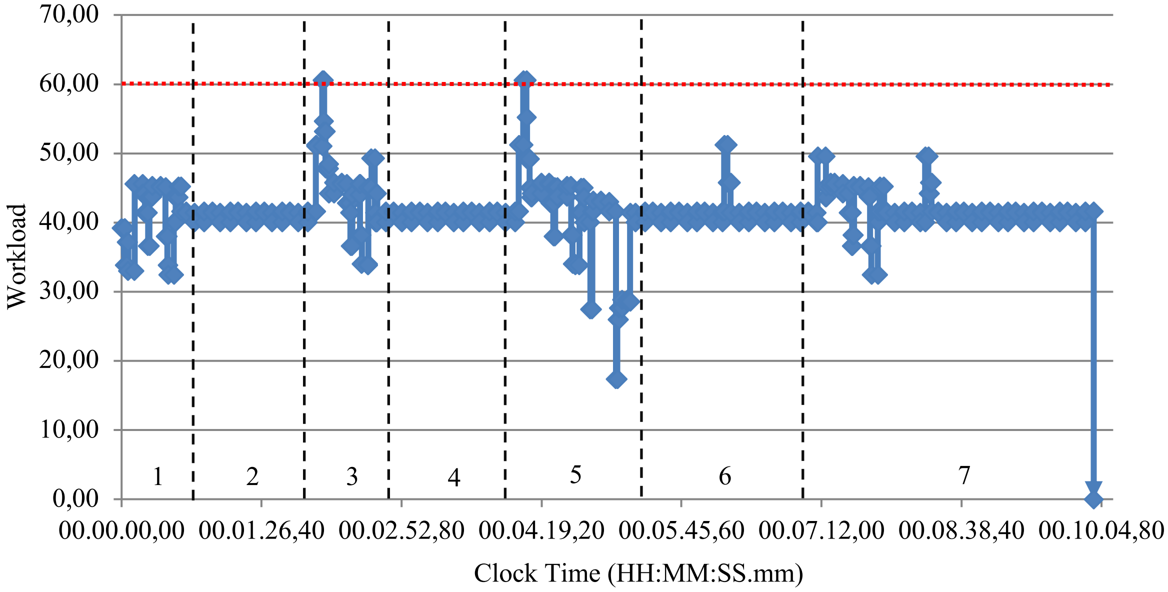


Figure 4: IMPRINT workload profile for pilot operator in manned-unmanned teaming model.

At the beginning of the simulation, the VACP value varied from 32 to 46 as the pilot planned the attack and deployed the UAVs in addition to his or her own aircraft to track the enemy targets. In the next phase, the workload consistently fluctuated between 40 and 42 when the pilot navigated the aircraft and supervised the UAV activity. This moderate level of workload was well below the saturation threshold, which suggested that these activities were manageable for the pilot as long as the aircraft did not experience any emergencies.

The attack began in the third phase, causing the workload to spike above the red-line to a maximum of 61 when the pilot needed to scan the surrounding environment, assess the enemy target's status, navigate the aircraft, and receive radio communications. It slowly declined to a minimum workload level of 32 when the attack subsided. Then the workload resumed to a manageable and steady pattern when the pilot subsequently returned to navigating the aircraft and supervising the UAVs in the fourth phase. However, this manageable level of workload did not last long. The mean workload immediately increased above the saturation threshold in the fifth phase when the pilot received radio communications for the second time and then slowly declined once again. The sharp spikes in workload indicated that the incorporation of communications is a failure point. The workload level is generally manageable, but it will require the pilot to employ workload mitigation strategies when communicating with other aircraft beyond the UAVs.

In the sixth phase, the pilot returned to supervising the UAVs and navigating the manned aircraft. For an instant, the pilot experienced a sharp spike to 51 due to the pilot receiving radio communication and supervising the UAVs to attack an enemy target at the same time. While this level of workload is not ideal, the high workload levels suggest that there is a trade-off between the workload experienced by the pilot and mission performance in this scenario. The over-saturation points may be worth the excess workload for a short period of time. From a design-standpoint, this suggests that the current design for manned-unmanned teaming has some areas for improvement. In the final phase, there were some workload fluctuations, but the overall workload levels within this segment of the mission indicate an acceptable situation for human-agent teaming with all of the aircraft in a benign mission mode.

The workload graph shown in Figure 5 provided insight into some of the interactions and implications when human-agent technology is eliminated from flight operations.

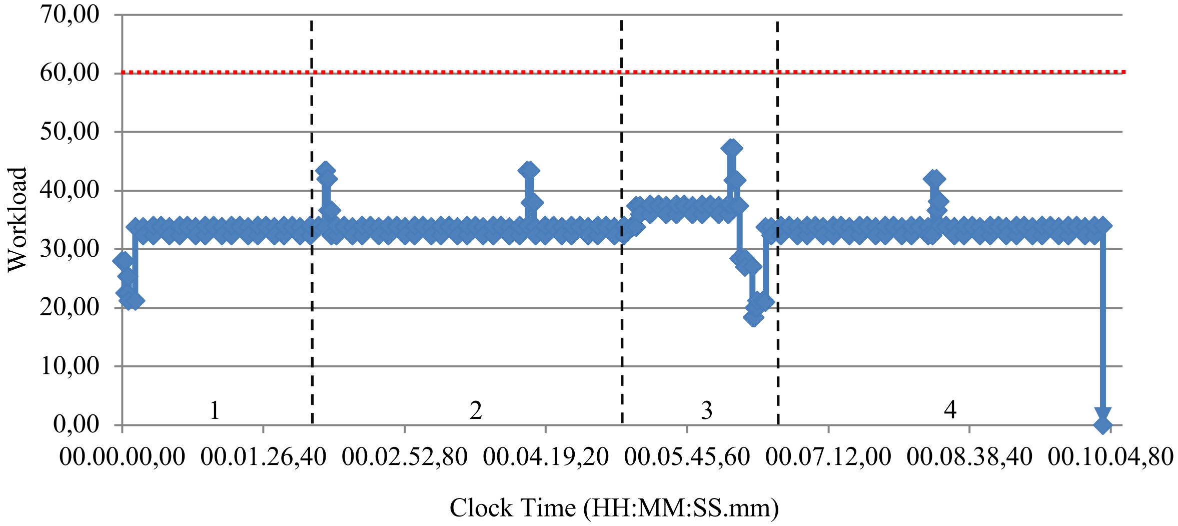


Figure 5: IMPRINT workload profile for pilot operator in manned-only model.

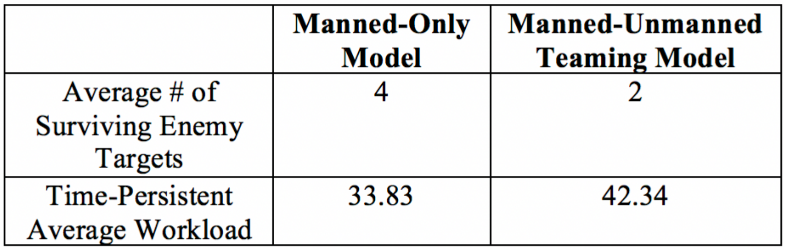
With the exception of commanding any UAVs, the pilot performed the same tasks as described in the analysis of the manned-unmanned team model workload profile. At the beginning of the simulation, the VACP values over the first part of the profile generally varied from 32 to 34 as the pilot planned the attack and deployed his or her own aircraft to track the enemy targets. In the next phase, the workload momentarily spiked in two instances when radio communication was received. Despite these cases, the workload consistently fluctuated from 32 to 34 as the pilot performed aircraft navigation and control. Even with the slight uptick in workload, the level of workload experienced by the pilot was well below the saturation threshold. As would be expected, this reasonable level of workload suggested that basic aircraft control and navigation activities with no enemy engagement are manageable for the pilot.

The attack began in the third phase, causing the workload to spike to a maximum of 47 when the pilot needed to use the aircraft to attack the enemy target and receive radio communications. It steadily declined to a minimum of 18 when the attack subsided and pilot resumed normal aircraft navigation and control in the fourth phase. Despite the slight spike to 42 in workload due to the transmission of radio communication, the workload levels were generally stable for the remainder of the mission. Throughout the mission, the pilot's workload was manageable and much lower than the workload experienced in the DES including UAVs. This trend was expected considering the pilot only needed to focus on his or her aircraft and did not need to command three other UAVs in addition to the manned plane.

3.3 Time-Persistent Average Workload Analysis

Using the VACP workload values from IMPRINT, a single representative workload value was also computed by taking the time-persistent average across 30 DES trials. The time-persistent average illustrated how hard the pilot worked as a whole to command the three UAVs by weighting the workload values by the duration the workload was experienced. According to the data, the pilot experienced a time-persistent average workload value of 42.34 for the manned-unmanned teaming model. On the other hand, the pilot experienced a time-persistent average workload value of 33.83 for the model lacking UAV involvement. The results indicated that the pilot's average cognitive workload was mostly below the saturation level for both scenarios. However, as illustrated by the workload traces, it varied significantly throughout the simulations.

Table 3: Comparison of model performances.



	Manned-Only Model	**Manned-Unmanned Teaming Model**
Average # of Surviving Enemy Targets	4	2
Time-Persistent Average Workload	33.83	42.34

Through an analysis of the mission performance, workload profiles, and time-persistent averages, the model implies that the increase in mission capability is likely worth the difference in the pilot's cognitive workload levels (summarized in Table 3). The incorporation of manned-unmanned teaming in flight operations improved the pilot's ability to successfully strike enemy targets and was manageable as long as the pilot did not require immediate attention for anything critical such as aircraft emergencies or prolonged external communication. In the simulation setup, both the manned and unmanned aircraft were utilized to attack four enemy targets. There were two moments in time when the threshold saturation of 60 was exceeded due to incoming radio transmissions. However, these spikes were infrequent and most of the workload was well below the saturation threshold. This suggested that the operator workload is manageable for the pilot with some communications offloading, when necessary. In the event of higher levels of radio communications, which are likely in operational air missions, workload mitigation strategies will be required to ensure that there is no mission degradation.

4 ASSUMPTIONS & LIMITATIONS

Creating the IMPRINT model required task analyses, direct observations, and data collection of a system. However, manned-unmanned teaming had yet to be deployed in an operational environment. Consequently, this research was reliant on information provided by Subject Matter Experts and data collected from the ATACM study (Schumacher et al. 2017).

While the pilots were non-experts within a virtual environment, it was assumed that the human participants and tasks were sufficiently representative of operators and manned-unmanned teaming operations to effectively evaluate performance and workload impacts of automation. It was also assumed that the human subjects involved in the ATACM study gave their maximum effort and were trained to a stable skill level prior to data collection, minimizing any learning effects across the trials. Furthermore, it was assumed that the randomized order of the conditions resulted in no order effects and did not affect the workload or physiological changes in this investigation. Finally, the SMEs estimates were assumed to be accurate approximations to real-world data, which was justified because the SMEs had experience developing and using the ATACM environment.

With the inherent complexity of HAI, this study made several assumptions in order to create a simplified IMPRINT model that could be analyzed towards the understanding of general HAI behavior. First of all, the DES assumed that all command pilots have similar levels of ability, expertise, competence, and speed. Therefore, the single model did not account for learning effects or different strategies that participants may have used. It was also assumed that all pilots utilized a "backseat" strategy to command the UAVs, meaning that the pilots forward deployed the UAVs before getting involved in the engagement themselves. The model also did not attempt to include activities, such as instrument and airspace scans that the pilots may perform to maintain situation awareness or increases in workload that may occur with physiological stressors which may occur during typical missions, such as one might experience during aggressive maneuvers of their own aircraft. Inclusion of these effects would have likely further increased workload.

Moreover, the model focused on conditions in the peak performance region in which the human subjects arrived at their checkpoint and were actively engaged with the opponents. This meant that the segment of time in which the operators were traveling to the engagement zone was not included in the model. It was also assumed that any deviations in recording times did not trigger a significant decrease in model accuracy and each of the distributions applied in the model were an accurate representation of the participant pool. Each simulation had the same conditions and did not feature any abnormal or unanticipated changes. Finally, workload values and task times were based on ATACM data, and as such, its applicability may be limited beyond this scope.

5 CONCLUSION

The research performed in this study sought to use DES to understand the effects of HAI on the pilot's cognitive workload when commanding UAVs. This was accomplished by examining the tasks performed by human subjects in the ATACM study, and then designing a simulated task environment modeled after these tasks. The model was built in IMPRINT to investigate how human cognitive workload and mission performance was impacted when a pilot commanded three UAVs in addition to his or her personal aircraft. The DES was validated by comparing the mission performance and timing results to that of the ATACM study. The results of the simulation indicated that mission performance was improved by the use of 3 UAVs against 4 enemy targets in an air-to-air operation.

Furthermore, system designers should be cognizant of the potential for pilots to experience peaks in workload levels when commanding a manned-unmanned team. The command pilot bears the weight of the combat effort and will need to deploy capabilities from the UAVs in addition to controlling the manned aircraft. The challenge of maintaining close control of the UAVs could be difficult for pilots to maintain during periods of high communications load, which could degrade or delay communication capabilities during air-to-air engagements. Using this information, system designers could predict potential workload issues when the pilots command the UAVs and communicate with other aircraft or ground stations in future manned-unmanned teaming systems. Accordingly, there should be focus placed on developing a pilot-vehicle interface that is conducive to maintaining a manageable level of workload for the pilot controlling a manned-unmanned team.

6 FUTURE WORK

For future development, the DES should be updated to examine additional alternative scenarios. While these results provided insight into using different automation controls for manned-unmanned operations, the presented research was limited to data provided by the ATACM experiment. The next step would be to gather data that exists outside of a HITL experiment in order to develop a model that more realistically captures HAI between pilots and their UAVs in an operational environment. Once this type of data becomes available, an improved model could be used to determine how many UAVs a single pilot can effectively operate simultaneously and in what type of formation are they best commanded. The improved model would further examine the relationship between stages and levels to discern which combinations work together optimally to better capture human-agent system behavior. This information could enable system designers to test and evaluate multiple configurations of human-agent systems in a short period of time and at a marginal cost.

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