Designing HMI for Mission Assessment of Human-Machine Teaming

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ABSTRACT

With the emergence of human-machine teaming, Human-Machine Interface (HMI) design needs to change the paradigm of how displays are used to eliminate the "fog of war" through increased situational awareness and informed decision-making to improve performance. The modern battlespace is extremely complex with disruptive technologies being integrated into dynamic, sociotechnical environments. Vast amounts of data are available due to the growth of computer power and data analytic techniques, making it challenging to determine the relevant data and its appropriate use for improving performance.

This paper describes the application of an ecological design interface approach used to develop real-time HMIs with an automated warfighter readiness assessment. The use case focused on a human-machine team Air Warfare domain with Naval Flight Officers providing command and control to fighter pilots with an artificial intelligent (AI) Agent flying their ownship while pilots were controlling up to four Unmanned Aerial Vehicles performing air-to-air intercepts.

Cognitive engineering models were used to develop computational models of cognitive workload and mission performance. These models were also used as the foundation to design HMI solutions that provide the right data, with the appropriate level of abstraction and navigation mapping for the organization of displays. Instructors and mission commanders have persistent and personalized, human-centered technology capable of quantifying individual and human-machine team performance in a dynamic and distributed environment. This system is designed to be used for designing HMI, selecting and training warfighters, and assisting instructors and mission controllers in protecting and effectively conducting operations for improved mission effectiveness.

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INTRODUCTION

Assessing the interrelationship between humans and artificially intelligent systems is essential to understanding how technology can best utilize data analytics to understand why a mission failed or succeeded. If adequate information is provided, users can apply this feedback to adapt strategies and ultimately improve warfighter performance during training and in operational environments. Having the capability to monitor and quickly process individual and team performance in real-time is critical for modifying strategic approaches during complex battles. Being able to respond quickly to dynamic environments can mitigate potential points of failure.

The training industry has made significant strides in objectively assessing performance in a controlled training environment by collecting task performance measures through system state data. The Pilot Training Next program sponsored by the Air Force is an example of how objective performance data is being used to reduce time to train (Lewis & Livingston, 2018). Objective measures are often displayed on Graphical User Interfaces (GUI) for instructors to monitor performance. These displays can provide real-time and post-processed information for assessment. There are several challenges with developing effective interface solutions, such as what data should be collected, how the data should be used, and how to design displays for large amounts of data (Dideriksen & Williams, 2019). Many user interfaces provide feedback in the form of charts and graphs for multiple systems and warfighters in a battlespace as shown in Figure 1.

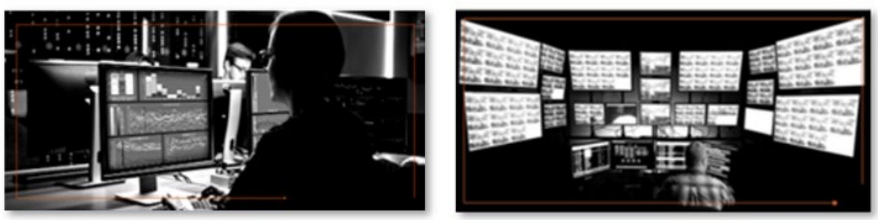

Figure 1. Scientific Data Display (right) and Multiple Monitors (left)

Research has shown that metacognitive feedback (immediate performance results) is the most effective method for adaptation (Milham et al., 2013; Dorneich et al., 2017). However, when performing in high-cognitively demanding environments, humans do not have spare capacity to process large amounts of data and continue to perform well on primary tasks. GUI development has been studied for decades, but the military has struggled to assess individual and collective performance in a naturalistic, dynamic, and tactical environment for joint operations. The Department of Defense (DoD) desperately needs a performance assessment system capable of measuring, tracking, processing, and storing quantitative measures to allow for monitoring and adapting strategies during mission execution (Defense Technical Information Center, 2018). This display system must drastically change traditional systems to reduce the amount of information processing that is required to enable strategic decision-making.

Building upon insights from psychology and neuroscience, Human-Machine Interfaces (HMIs) are systems and interfaces designed for cognitive enhancement. The interface must enhance cognitive skills by seamlessly supplementing users' natural cognitive abilities to support real-life studies and interventions. The Apollo Guidance Computer (AGC) was the first HMI manufactured by Raytheon, under the direction of the Massachusetts Institute of Technology (MIT) Instrumentation Laboratory (National Aeronautics and Space Administration, n.d.). The AGC was installed onboard each Apollo Command Module and Lunar Module. Designed to safely take astronauts to the moon, the Display and Keyboard quickly became Apollo's most important crew member. It allowed the team to effectively communicate and deliver a complex mission while commanding the AGC, which provided computation and electronic interfaces for guidance, navigation, and control of the spacecraft.

Today, HMI work is highly interdisciplinary and combines insights and methods from human-computer interaction, sensor technologies, machine learning, brain-computer interfaces, psychology, and neuroscience to create new opportunities for human machine teaming and learning in live, virtual, and constructive (LVC) environments. Figure 2 outlines the HMI evolution. Since its inception, recent advances in display technology. and approaches to dynamic interface design have enabled the most dramatic enhancements to HMI to date.

Figure 2. HMI Evolution

This paper describes the selected domain for our use case and outlines the application of cognitive engineering models that maps to a cognitive processing model for developing HMI, allowing instructors to monitor and adapt performance during training missions.

HUMAN-MACHINE AIR WARFARE DOMAIN

The use case for our project focused on the air warfare domain that included Naval Flight Officers (NFOs) providing command and control to military fighter pilots performing air-to-air intercepts.

NFO Crew

The NFO crew is responsible for high-level coordination of surface and air warfare assets (Department of the Navy, CNATRA P-825, 2017). A crew consists of a Combat Information Center Officer (CICO) and two Air Intercept Controllers (AICs). They typically perform missions in the E-2D Advanced Hawkeye aircraft; “a carrier-based Airborne Early Warning (AEW) platform with a 24-foot diameter saucer-shaped radome housing radar for tracking over 250 targets (Department of the Navy, CNATRA P-825, 2017), as seen in Figure 3.

Figure 3. E-2D Advanced Hawkeye

The NFOs sit sideways in the back of the aircraft, as seen in the simulator shown in Figure 4. They manage five radios providing control for more than 30 separate airborne intercepts simultaneously (Picken & Rogoway, 2018). In this project, the AICs sat at a desktop simulator monitoring the battle using Next Generation Threat System (NGTS) software.

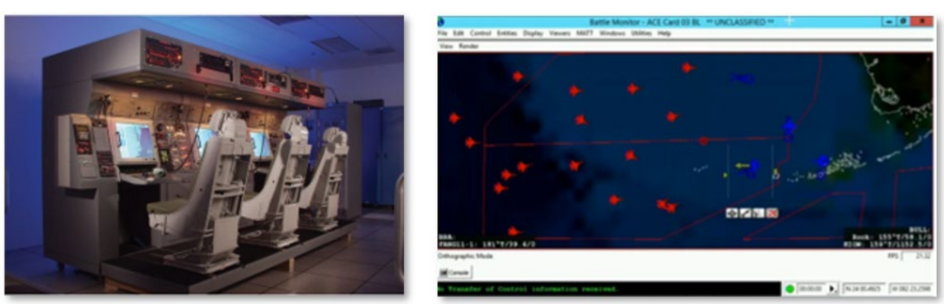

Figure 4. NFO Crew Seating (left) and NGTS (right)

Fighter Pilots

A fighter pilot is seated in a single-seat military jet, such as an F-16 Fighting Falcon (shown in Figure 5). These jets can "carry up to six air-to-air missiles, conventional air-to-air and air-to-surface munitions and electronic countermeasure pods" to be used against air or surface threats (Military.com Network, 2021). A canopy covering the cockpit has a bubble design to provide pilots with an unobstructed forward and upward visual out the window.

Figure 5. F-16 Fighting Falcon

This project used an Aero Vodochody L-29 experimental aircraft where an Artificial Intelligent (AI) agent controlled the pilot's ownship while the pilot focused on controlling unmanned aerial vehicles (UAVs) to attack adversaries in Cruise Missile Defense (CMD) scenarios (Defense Advanced Research Projects Agency, 2021). They were equipped with six air-to-air missiles for each mission. Figure 6 shows a pilot seated in the L-29 and NGTS integrated with the avionics.

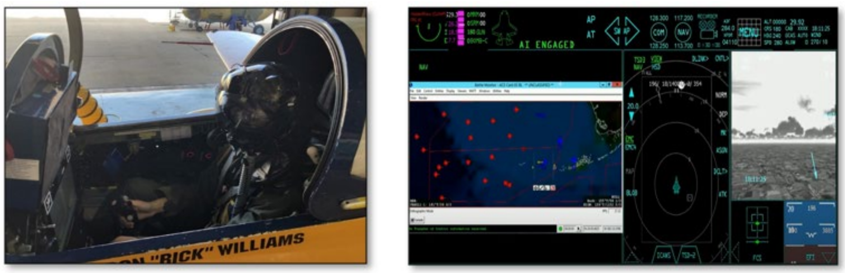

Figure 6. Pilot in L-29 (left) and NGTS Integrated with Avionics (right)

COGNITIVE ENGINEERING

To fully understand the constraints in the air warfare domain, an ecological interface design (EID) approach was applied. Ecological design refers to the perceptual constraints of the operational battlespace or environment (Burns & Hajdukiewicz, 2004). The EID approach is a systematic analysis of the work to be performed in a specific domain and provides a framework for developing real-time, HMI solutions that allow for adaptation in a dynamic, complex, and sociotechnical environment.

Figure 7 illustrates the process that was used for this project. The process began with a task workflow, which was used to define the functional purpose of the work domain analysis. The air warfare domain was depicted in an abstraction hierarchy. Variables and parameters were identified for each element, as objective, quantifiable measures were needed for data analysis. A functional information profile was used to identify gaps of information in existing interfaces, which were mapped to a cognitive processing model to guide the development of widgets for the HMI.

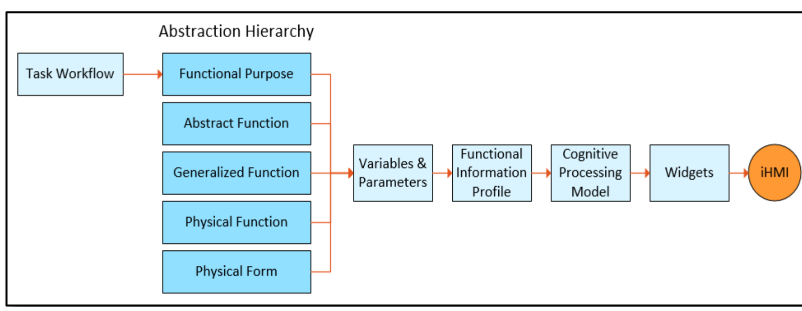

Figure 7. EID Process

Task Workflow

The task workflow identified the tasks that were performed by each of the warfighters involved in air-to-air intercept operations. The United States military follows a kill chain model for air warfare that includes Find, Fix, Track, Target, Engage, and Assess, or F2T2EA (Hutchins et al., 2011). The task workflow for NFOs and fighter pilots is illustrated in Figure 8.

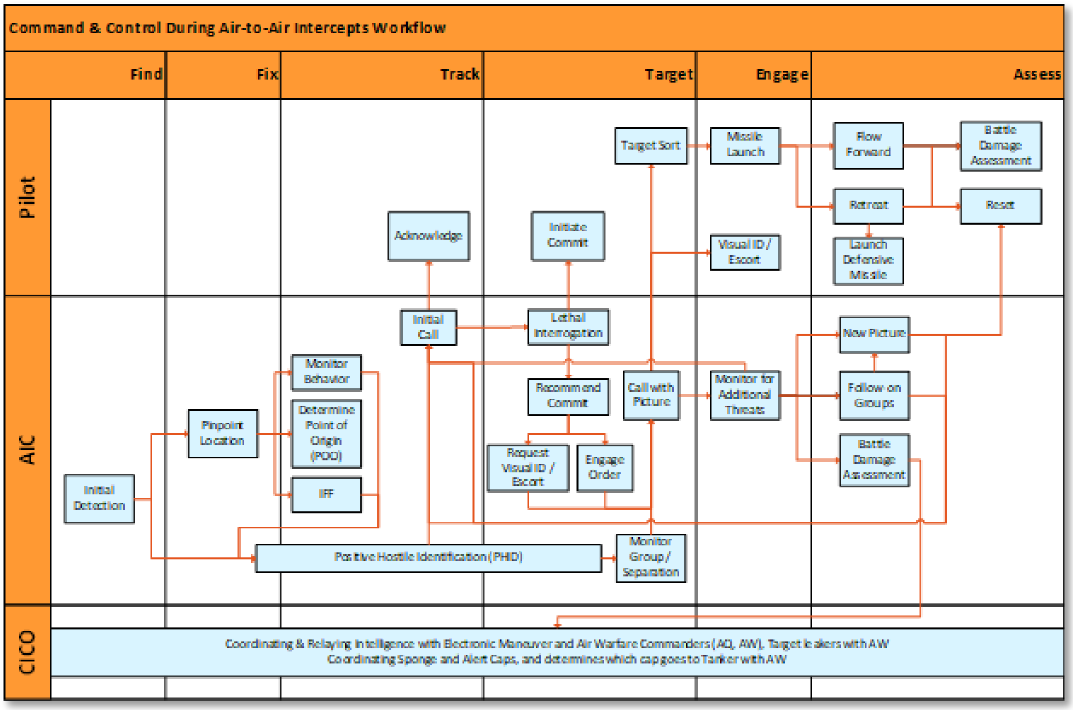

Figure 8. F2T2EA Task Workflow

This workflow was developed through interviews with AIC and military pilot subject matter experts and DoD publications. The workflow begins with the AIC detecting an entity in the battlespace in the Find phase and determining if the entity is friendly or adversarial with the exact location in the Fix phase. The AIC determines the point of origin while continuing to determine if there is a threat and notifies the pilot of the entity location in the Track phase. In the Target phase, if the entity is unknown, the AIC will conduct a lethal interrogation and ask the pilot to commit. If the entity is determined as adversarial, the AIC will provide a tactical picture and might direct the pilot to escort the entity for visual identification or target the aircraft. In the Engage phase, the pilot directs UAVs to attack the entity, while the AI agent attacks and defends his ownship. The AIC continues to monitor for additional threats. The process completes with the Assess phase that includes a battle damage assessment after the attack. This is a generic task workflow that may become more complex with unexpected adversaries, friendly and unknown aircraft entering the battlespace at different times and frequencies during the operation. Teams that can accomplish their mission while quickly adapting to the changing environmental dynamics have more successful performance results (Goodwin & Coats, 2018).

Abstraction Hierarchy

The work domain analysis is represented in an abstraction hierarchy that describes the constraints that govern the purpose and function of the work domain. This analysis includes various elements of the domain at five different levels as described by Burns & Hajdukiewicz (2004):

- *Functional Purpose*: describes the purpose for the entire work domain
- *Abstract Function*: describes laws and priorities
- *Generalized Function:* describes the processes
- *Physical Function*: describes the equipment or components needed
- *Physical Form*: describes the equipment or component attributes needed for the mission.

To identify the functional purposes, the tasks from the task workflow were grouped into categories with purpose labels for the air warfare domain. Once the functional purposes had been identified, the elements for the other four levels were identified. For the project use case, humans were included as an element. The human-machine and human-AI team should be considered as one system. The Abstraction Hierarchy for the Air Warfare domain with the project use case is illustrated in Figure 9.

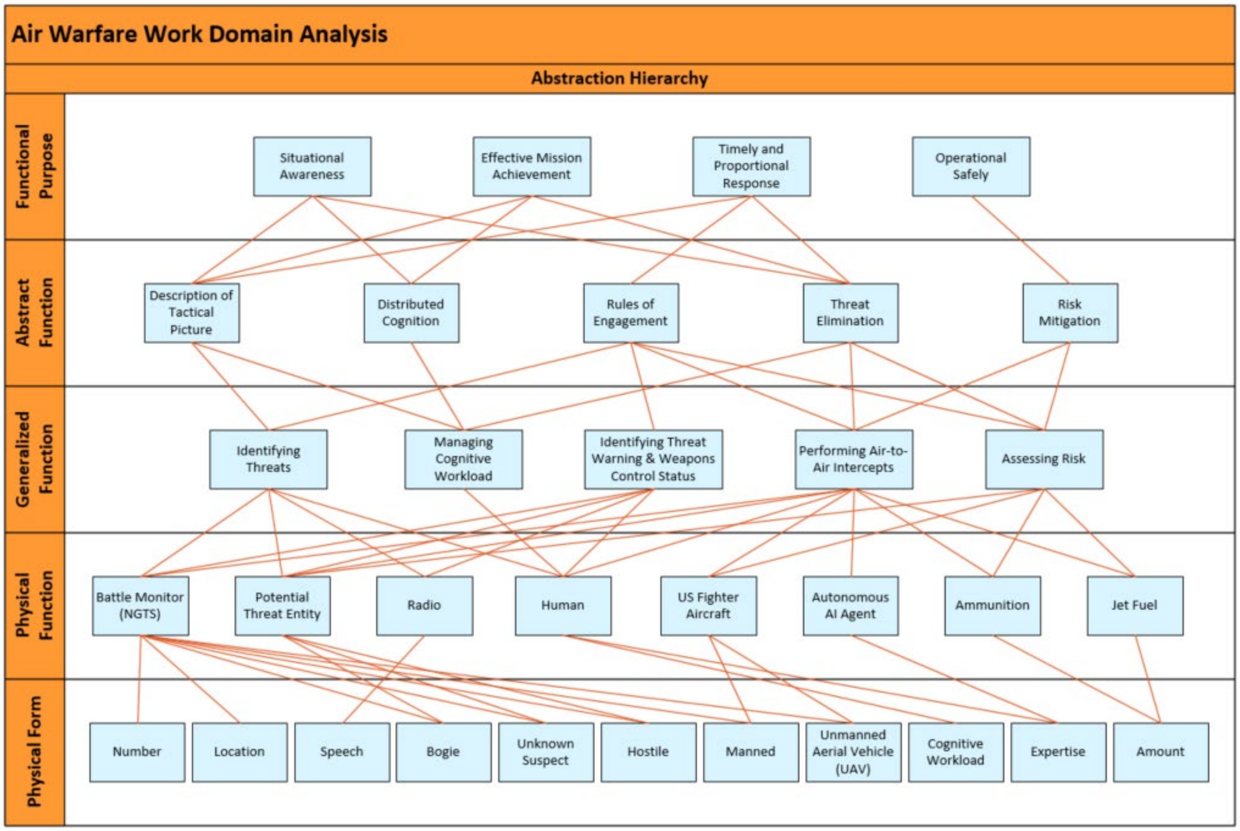

Figure 9. Air Warfare Domain Abstraction Hierarchy

The lines that connect elements are means/end links that indicate an impact on the value of each element. These data flows were used to supply data to the HMI designs. This abstraction hierarchy is a systematic approach, analogous to an electronics breadboard. By applying data analytics, it can be used to identify breakdowns in mission performance.

Variables

To apply the abstraction hierarchy to the design for HMI, variables were determined to measure each element. Some of these elements were collected directly from the system (machines and humans), and some measures were calculated. Table 1 describes the variables and parameters identified for each element of the air warfare domain.

Table 1. Variables for Air Warfare Domain

Level	Element	Variable	Calculations
Functional Purpose	Situational Awareness	Overall performance score, distribution of cognitive workload (CW)	* Future plan to develop a measure of Situational Awareness.
	Effective Mission Achievement	Average aggregate overall performance, average performance score, CW, and workload efficiency (WLE) for all subjects	Not/Applicable (N/A)
	Timely and Proportional Response	Rules of engagement (ROE) status and violation, kill chain response times	N/A
	Operational safely	Overall risk and missile accuracy	N/A
Abstract Function	Description of Tactical Picture	NGTS, Identifying Threats	AIC score, CW and workload efficiency = performance score +4 minus CW for each AIC
	Distributed Cognition	Cognitive workload	Recent average of mean, median and standard deviation for each individual. Distributed

			cognition = add amount outside of 4-7, add standard deviation of 4.0. If < 4 add < 1, if >4 add > 1. Overall score is (10.0 – (average of 3 values))*10
	Rules of Engagement	Threat Warning & Weapon Control Status/violation and Kill chain status.	Communication keywords, violation (0.0- 0.1)
	Threat Elimination	Performing Air-to-Air Intercepts	Pilot score, CW and workload efficiency = performance score +4 minus CW for each pilot
	Risk Mitigation	Preserving life and aircraft/UAV	Risk assessment, missile hits and misses. Loss of life and loss of aircraft = reduction in score by 50%.
Generalized Function	Monitoring, Communicating & Coordinating	NGTS, Potential Threat Entity, Radio, Human	Compare accuracy of speech/text to NGTS
	Identifying Threats	NGTS, Potential Threat Entity, Radio, Human	AIC score, CW and workload efficiency = performance score +4 minus CW for each pilot
	Maintaining Optimal Cognitive State	Human	1-3 Undersaturated, 4-6 Optimal, 7-10 Oversaturated
	Identifying Weapons Control and Threat Warning Status	NGTS, Potential Threat Entity, Radio, Human	Keywords: Threat Warning = Hold, Tight, Free / Weapons Control = White, Yellow, Red
	Performing Air-to-Air Intercepts	NGTS, Location, Potential Threat Entity, Human, US Fighter Aircraft, Autonomous AI Agent, Ammunition, Jet Fuel	Pilot score = missile accuracy (launches/hits), risk imposed minus received, averaged with accuracy.
	Assessing Risk	Risk imposed and risk received based on position (threat is behind aircraft) and angle (threat is flying towards aircraft) scaled between 0.0-1.0 for each entity.	Total threat is an average between positional and angular advantage, scaled by distance (1-60 nautical miles for line-of-sight combat). Imposed positional and angular advantage = less than 45-degree cone = full 1.0 advantage), if greater than 90-degree cone, no advantage (0.0). All else we scale between 90- and 45-degree cones. Metrics are flipped for risk received.
Physical Function	Battle Monitor (NGTS)	Number, Location, Bogie, Unknown Suspect, Hostile, Manned, UAV	N/A
	Potential Threat Entity	Bogie, Unknown Suspect, Hostile	N/A
	Radio	Speech	N/A
	Human	Cognitive Workload, Expertise	N/A
	US Fighter Aircraft	Manned, Unmanned aircraft	N/A
	Autonomous AI Agent	Expertise	On or off
	Ammunition	Amount	Six missiles minus # launched
	Fuel	Amount	370 gallons minus fluid reduction over time
Physical Form	Number	Distributed Interactive Simulation) DIS Data from NGTS Entity Identifications (IDs)	N/A
	Location	DIS Data from NGTS (latitude, longitude, altitude, heading)	N/A
	Speech	Audio transcribed to text	90% accuracy non-VHF / 72% accuracy on noisy (oxygen mask, VHF)
	Bogie	DIS Data from NGTS Entity ID	N/A
	Unknown Suspect	DIS Data from NGTS Entity ID	N/A
	Hostile	DIS Data from NGTS Entity ID	N/A
	Manned	Flight state or DIS Entity ID data	2 jets (one sim, one live)
	Unmanned Aerial Vehicle (UAV)	DIS Data from NGTS Entity ID	4 per pilot

	Cognitive Workload	Electrocardiogram (ECG) Classified Cognitive State	Scale of 1-10
	Expertise	Novice, Competent, Expert	Flight hours (N<250, C=500-1500, E>1500)
	Amount	DIS Data from NGTS or Timer and Counter	N/A

Functional Information Profile

Before beginning HMI designs, a functional information profile was conducted to compare the elements in the abstraction hierarchy and legacy displays. If a display already existed and was in production, there was no need to create a new display. The goal of the project was to design new HMIs to address gaps in information that instructors need to monitor collective performance for joint operations and adapt training or mission strategies. The team focused on developing HMIs for the first two levels of the abstraction hierarchy (Functional Purpose and Abstract Function), as shown in Figure 9.

Cognitive Processing Model

As shown in Figure 10, when moving up the abstraction hierarchy, widgets need to be more abstract and provide less salient, detailed data (Vicente, 1999). This abstraction hierarchy is mapped to a cognitive processing model.

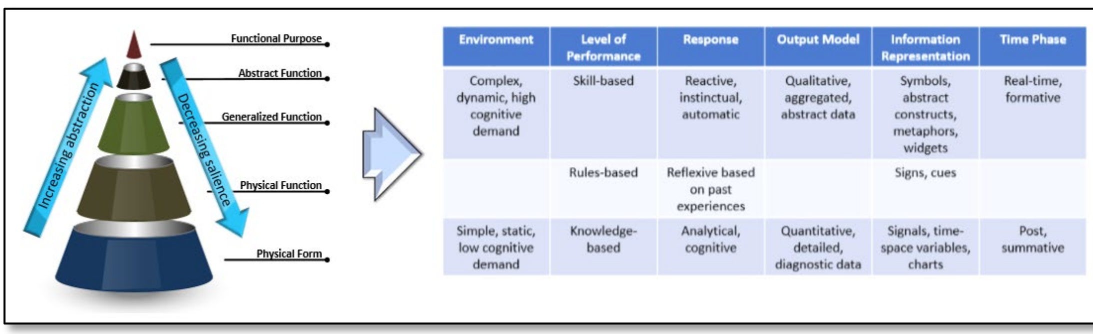

Figure 10. Cognitive Processing Model

The cognitive processing model includes variables to help determine the level of abstraction and detail needed in an HMI. These variables include:

- *Environment* – continuum from simple to complex
- *Level of Performance* – SRK model describing human behavior and decision making in human-AI environments (Rasmussen, 1983)
- *Response* – description of how humans process information to make decisions (Klein, 1998)
- *Output Model* – subjective or objective data
- *Information Representation* – types of communication (Rasmussen, 1983)
- *Time Phase* – when information is needed

For instructors or commanders to monitor and adapt mission strategies during the execution of the mission, HMI needs to be displayed in real-time with a high level of abstraction to reduce adding any additional cognitive load while performing their tasks. For instructors to debrief performance with warfighters after the mission, they have access to more detailed information. To understand the reason(s) a mission succeeded or failed, each HMI is designed to be flexible with interactive graphics that allow more detail to be provided as desired.

HUMAN-MACHINE INTERFACES

As outlined above, cognitive engineering and EID help to understand the tasks and objectives in a specific domain. Applying specific cognitive processes to the HMI design facilitates users to leverage cognitive processes supported by specific advanced interfaces. By aligning HMI design with EID, operators can reduce cognitive workload and increase situational awareness, resulting in more capable and ready warfighters.

From Graphical User Interfaces to Widgets

Since developments over five decades ago, the Graphical User Interface (GUI) has used iconography and pointers to realize metaphors and idioms to control elements of the software. Most computers, laptops, and software applications today are still engineered to be controlled by a GUI.

A widget is a system functioning as a small application to display data. Often it allows the user to interact and adapt. Human factors engineers and designers develop widgets by defining properties or events triggered by data or a series of algorithms. As opposed to icons or rigid interfaces, widgets can be easily integrated into applications to be accessible via multiple platforms.

Using the cognitive engineering models discussed, HMI designers were able to conceptualize widgets following user needs and created user journeys. Figure 11 is a widget designed to monitor the system's purposes for the air warfare domain. The widget provides average, collective scores in real-time for the mission performance.

Figure 11. Mission Performance

The design provides a high level of abstraction that allows commanders to glance at the display to monitor how the team is performing; requiring low cognitive demand so they can focus attention on other areas during the exercise. It is an interactive design allowing for navigation to additional information when each outer circle is selected. This additional detailed information is at the Abstract Function level of the hierarchy, so still requires a bit of abstraction, but not as much as the Functional Purpose level.

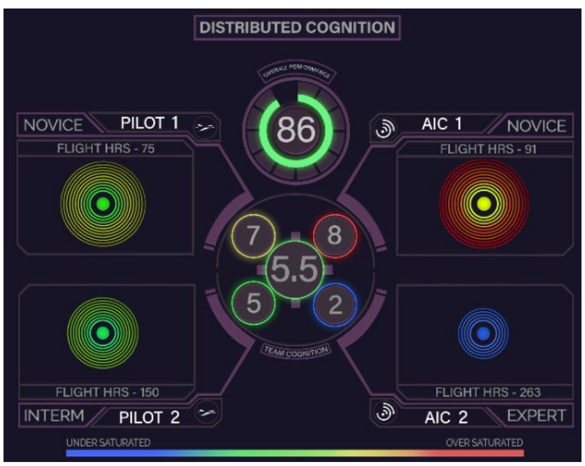

Figure 12. Situational Awareness

To improve instructor Situational Awareness, Figure 12 illustrates variables displaying the overall team performance score and the distribution of cognitive workload across the team.

Figure 13 illustrates the Effective Mission Achievement purpose and displays the average overall team performance score and average individual performance, cognitive workload, and workload efficiency measures. Performance for AICs is calculated through communication accuracy. Raytheon BBN's Cyrus, a natural language processing (NLP) software, transcribes speech to text with 95% accuracy, and the text is compared to what is being provided by NGTS. Pilot performance is measured through weapons accuracy, survivability, and measures of imposed and received risk.

Figure 13. Effectiveness

Figure 14. Responsiveness

Workload efficiency is a calculated measure that represents performance improvement and reduced cognitive workload. For a warfighter to reach optimal proficiency, performance increases, and cognitive workload decreases, (Dideriksen et al., 2018).

Figure 14 depicts the Timely and Proportional Response purpose. This HMI displays Rules of Engagement (ROE) providing threat warning and weapon control status, along with response times for each phase of the air domain F2T2EA kill chain. Speeding up the military's kill chain is a top priority for the DoD (Williams, 2020).

Figure 15. Safety

Figure 15 represents the Operational Safety purpose. This design displays fuel levels, remaining ammunition, loss of life, and loss of aircraft or UAV.

Cognitive Engineering Mapping to User Journey

The abstraction hierarchy means-end links provided a map for navigating to all of the displays. As can be seen in Figure 16, all these designs include the elements of the first two levels of the abstraction hierarchy. This illustration is a user journey representation for an instructor or Mission Commander.

Building user journeys is a design methodology to help understand the user's mental model while interacting with a product or service. Hence, user journeys take into consideration user's needs, constraints, understanding, and emotional states. A multi-disciplinary team mapped the user needs with design metaphors that are congruent with the levels of the abstraction hierarchy. The team applied principles of cognitive engineering and a heuristic approach to develop unique user-specific HMI widget designs. Following real-time data capture from experiments, each of these displays are supplied with the data values from elements as you move down the abstraction hierarchy levels.

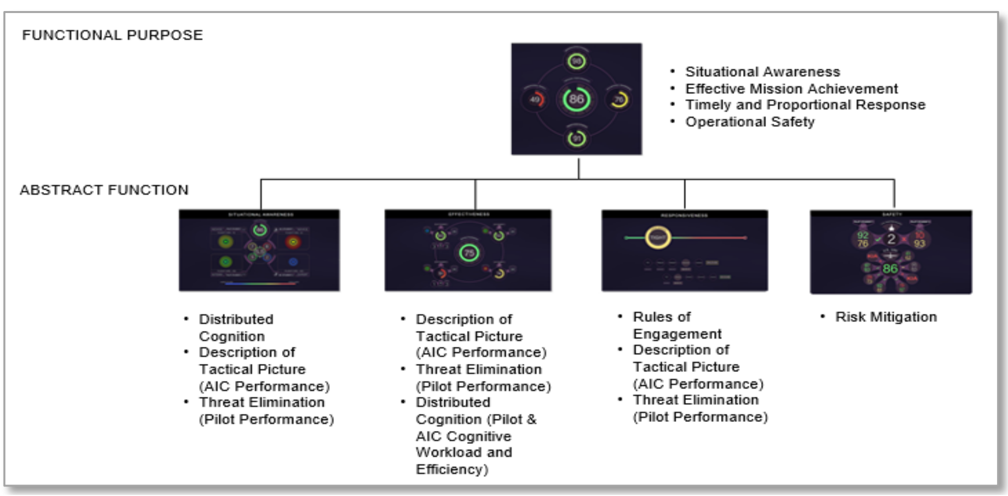

Figure 16. Navigational Mapping

CONCLUSION

Using the application of an EDI approach to design HMI, a performance assessment system was developed. This system was capable of assessing, tracking, displaying, and storing quantitative measures of mission performance. Instructors and commanders have a cognitively engineered display to monitor individual, collective, and distributed performance from a central location. This information can be used to adapt training or strategies during mission execution to improve performance.

The next steps are to evaluate its effectiveness through usability testing. There are two main areas of focus; (1) the value of HMI in monitoring mission performance, and (2) the use of the system as a diagnostic tool to identify points of failure in the mission. The hypotheses to evaluate include:

- HMIs provide a statistically significant increase in situational awareness for instructors and/or commanders during the exercise
- Real-time HMIs result in statistically significant performance improvement through effective adaptation
- HMIs allow for centralized control over distributed training and operational environments
- The system and supporting HMIs can be used as an accurate diagnostic tool to assess points of failure
- The HMIs do not significantly increase cognitive workload for users during the exercise/mission

If the system proves successful, more intelligent HMIs (iHMI) can be developed. This includes applying machine learning and AI to drive the content of the HMI being displayed to automate the adaptation of the mission strategies for learning and performance optimization.

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