Enhancing Training of Supervisory Control Skills for Automated Systems

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ABSTRACT

Contemporary warfighters operate in fast-paced and complex domains that, without assistance from automated technologies, would overwhelm their information-processing and decision-making capabilities. These warfighters must exercise supervisory control, learning to monitor, initiate, change, and stop processes in automated systems. Several challenges to supervisory control are identified in scientific literature, but there is little information concerning how supervisory control is exercised for air battle management in air defense systems. One system requiring supervisory control is the Army's Phased-Array Tracking Radar to Intercept on Target (Patriot) missile defense system. Our research collected data about Patriot crewmembers' performance of supervisory control to inform the compilation of a supervisory control skillset and identification of training interventions to enhance its training. Twenty-nine (N = 29) Patriot crewmembers, trainers, and evaluators were interviewed about the general supervisory control issues and challenges presented in the literature, their prioritization of those for supervisory control performance in air battle management, and the skills and training required to perform supervisory control effectively. Problems with understanding how the system works, comprehending and integrating critical information to maintain situational awareness, understanding one's role within the tactical situation, and attentional tunneling were identified as potentially being most detrimental to mission performance. We identified crew resource management, decision-making, interpretation, situational awareness, system operation, and vigilance as key complex skills for effective supervisory control in this environment. We proposed seven training interventions to enhance development of those key skills and the training of supervisory control. While the U.S. Army's Patriot system was the focus of this research, supervisory control training is applicable to other Department of Defense applications, particularly those that require exercise of supervisory control over individual networked systems (such as integrated air and missile defense) or multiple grouped systems (such as multiple unmanned vehicles) by single operators or teams.

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INTRODUCTION

There is a growing need for skill definition, exploration, and information regarding supervisory control in military environments to inform training. As the systems used in warfare become increasingly complex and automated, more warfighters will be required to exercise supervisory control, monitoring automated systems and stepping in to initiate, change, or stop processes and functions. Though the supervisory control concept has been around since the 1960s, it remains largely unaddressed with respect to air and missile defense. The majority of supervisory control research relevant to air and missile defense focuses on human factor design considerations to facilitate supervisory control, or on issues related to supervisory control performance. A gap remains in our understanding of how to train and evaluate supervisory control skills. In particular, military trainers require an in-depth understanding of the cognitive skills defining supervisory control, and how to train and evaluate them most effectively. The research described in this paper adds to our knowledge of how supervisory control skills are applied with automated systems used in military contexts, supports an increased understanding of the psychological requirements for effective supervisory control, and identifies potential opportunities to improve training. This information may be useful in training supervisory control for other automated or semi-automated systems.

Supervisory control concerns the relationship of human control and interaction with automated systems. Dr. Thomas Sheridan, the term's progenitor, defined supervisory control based on how operators interact with automated systems, and it refers to the type of human to machine interaction required for operating and monitoring semi-automated systems during task execution (Sheridan, 1992). From this perspective, supervisory control lies between fully manual and fully automatic system control, and it can apply to a broad array of systems with varying levels of automation (Sheridan & Verplank, 1978; Mitchell, Cummings, & Sheridan, 2004). Cognitive and psychomotor task requirements exist for humans interacting with systems at all levels of automation, including those performing supervisory control of semi-automated systems (Endsley & Kaber, 1999).

Patriot provides a system-specific case of supervisory control.[1] Patriot is a ground-based missile defense system used by the U.S. Army. Each individual Army Patriot system is comprised of an Engagement Control Station (ECS), a Radar Set (RS), an Antenna Mast Group (AMG), an Electronic Power Plant (EPP), and a complement of missile Launching Stations (LSs). The U.S. Army organizes multiple individual systems under a single command and control (C2) architecture. At the battery level, each ECS is manned by a three-person crew comprised of Tactical Control Officer (TCO), a Tactical Control Assistant (TCA), and a Network Switch Operator (i.e., a communications operator). The Information and Coordination Central (ICC), a battalion-level component, coordinates multiple ECSs and has limited capability to remotely affect individual systems. The ECS's TCO and TCA directly interface with the automated system to perform supervisory control. Supervisory control as exercised in U.S. military Patriot operations is performed as a part of a collective of actions constituting the overarching task of air battle management.

In applying this concept to air defense, we defined supervisory control in the context of air battle management, defined a key skillset for it, and explored supervisory control requirements, skills, and training and evaluation using data collected from U.S. Army Patriot Soldiers. We used these data to identify potential training opportunities to enhance supervisory control training for U.S. Army Patriot and emerging systems, specifically looking toward the Army Integrated Air and Missile Defense (AIAMD) System, which will integrate Patriot with other sensor and missile systems into an integrated system of systems (U.S. Army Program Executive Office Missiles & Space, 2018).

[1] *Patriot* is the standard referent for the Phased-Array Tracking Radar to Intercept on Target system.

METHODOLOGY

We merged the results of an extensive review of the scientific literature with input from U.S. Army Air Defense Artillery subject matter experts to identify an initial key skillset for supervisory control. Following this, we conducted individual and group interviews as well as observations of Patriot training, air battle management exercises, and evaluation and after-action reviews to cross-check the key skillset identified. Analysis of observation data and an examination of historical evaluation data and instruments used in the training program were also performed but are not detailed in this paper.

Literature Review

We reviewed published scientific literature relevant to supervisory control, Patriot, and the AIAMD system; many studies highlighted common cognitive requirements and issues.[2] To focus on supervisory control from a performance perspective, we developed a definition for it specific to air and missile defense systems. We defined supervisory control, in this context, as an operator's performance capacity to: (a) understand the relationships between mission requirements, system parameters, and operators' roles and responsibilities; (b) initialize or modify system settings to reflect mission requirements; (c) monitor and correctly interpret system and operational data and cues; (d) respond appropriately to these data and cues; and (e) adapt system inputs and operations to changing or novel conditions.

Hawley and Mares (2007), in the context of an examination of Patriot, referred to effective supervisory control as "a situation in which Soldiers and not the automated system are the ultimate decision makers in air and missile defense firing decisions" (p. 2). The importance of firing decisions cannot be argued for systems like Patriot. However, supervisory control also involves other important functions. For example, the human operator must monitor system data and cues. The functions in our definition of supervisory control for air battle management imply complex associated skills for supervisory control including crew resource management (CRM), decision-making, interpretation, situational awareness (SA), system operation, and vigilance.

We found issues most relevant to our subject by examining information related to supervisory control in unmanned aerial systems (UASs), network centric warfare, and Patriot operations. Parallels exist between systems. For example, supervisory control in the Patriot system is similar to UAS operations in terms of the need to intervene in firing decisions, address system malfunctions, and monitor the system (see Chen, 2010; Chen & Barnes, 2012). Mitchell, Cummings, and Sheridan (2004) identified issues that challenged supervisory control in the context of network centric warfare, including decision bias, attention allocation, and information overload. Based on our review of the literature, the following eight issues were identified and then reviewed by Army stakeholders[3] as viable targets for our research:

1. *Attentional tunneling*: focusing one's attention on a single piece of information while ignoring other information or responsibilities, i.e., tunnel vision;
2. *Automation bias*: accepting system recommendations without critical thought;
3. *Double-hatting*: when an operator must both manage system settings and perform fire control while operating the system;
4. *An inability to comprehend and integrate critical information to maintain SA:* relating to an operator's inability to identify, understand, and use critical information to maintain or update SA;
5. *An incomplete understanding of how the system works*: a lack of understanding about how the system operates, particularly how operator actions affect system operations, how system settings and functions relate to the feedback operators receive from the system, and what limitations the system has;
6. *Insufficient mode awareness*: failing to maintain awareness of what the system is currently doing and being unable to anticipate what it should do next;
7. *Insufficient understanding of one's own role within the tactical situation:* a lack of understanding of the relationships of operator roles, system behaviors, and the tactical situation; and
8. *Track identification (ID)*: problems with ID and confirmation in the presence of conflicting information.

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[2] See, for example, Adelman, Tolcott, and Bresnick (199l); Hawley and Mares (2006); Hawley, Mares, and Giammanco (2005, 2006); Hew, Lewis, Radunz, and Rendell (2010); Macmillan, Entin, and Serfaty (2004); McKendrick and associates (2014); Sarter, Woods, and Billings (1997); and Shaw and associates (2010).
[3] Group discussions with United States Army Air Defense Artillery School personnel on Oct. 27, 2016.

Interviews

Interview data were collected from twenty-nine (N=29) Patriot Soldiers, including operational ECS and ICC crewmembers, trainers, and evaluators, as well as instructors and students. Our interviews focused on: (a) how an identified issue may manifest during air battle management tasks; (b) what possible antecedent conditions or factors could contribute to challenges; (c) what could happen as a result of these challenges; (d) what current training and/or evaluation strategies could potentially mitigate the challenges; and (e) ideas for additional training to address the issues discussed. When analyzing the interview data, responses were marked with codes representing each theme; additional codes were used for emerging factors such as associated skills or secondary effects. We constructed diagrams for each issue, aligning data elements to each theme. Relationships were indicated in the diagrams to understand potential issue factors, relationships, and processes. This allowed us to visualize the data in the context of each issue.

We used an issue-based approach to interview Soldiers. These issues were found through the conduct of an extensive literature review prior to data collection with Patriot crews. The identified issues provided a targeted way to collect information specifically about supervisory control within the larger context of air battle management, and a relatively well-defined set of behavioral constructs to assess skills. This approach also provided a basis for discussing supervisory control with Soldiers, a term often misunderstood outside of the research community. Supplemental data was simultaneously obtained through nine (9) observations of Patriot training and after actions reviews. Separately, we observed three days of AIAMD system operational testing events and debriefs.

Data Collection

Data collections were conducted with active duty Patriot Soldiers. We conducted four types of interviews. The same basic questions were asked during the Evaluator, Operator, and Trainer interviews, from the Soldier's perspective as an evaluator, operator, or trainer. The Air Battle Management Process interview was used to place issues within the context of an air battle. Table 1 provides interviewees' average Patriot experience by type of interview. Though some Soldiers performed multiple roles in their respective organizations, they were administered only one type of interview. For example, some operators also served as trainers but were only administered a Trainer interview.

Table 1. Patriot Interviewee Experience in Years by Type of Interview

Interview Type	Current Roles of Interviewees and Military Occupational Specialty (MOS)	Number Subjects	Mean Experience (Years)
Evaluator	Air Defense Artillery Fire Control Officer (ADAFCO), Brigade and Battalion Standardization Officers (all 140E); Master Gunner (14T)	4	10.2
Operator	ECS crews: TCO (14A); TCA (14E); Network Switch Operator (25N) ICC crews: Tactical Director (TD) (14A); TD Assistant (TDA) (14E)	15	2.9
Trainer	Advanced Leadership Course (ALC) Instructor (14E); Battalion Trainer (14A); Warrant Officer Basic Course (WOBC) instructor, Battery Trainer, Standardization Officer, TCO, and TD (all 140E)	8	13.0
Air Battle Management Process	Battery and Battalion trainers (both 140E)	2	6.5

Note: Interviewee MOSs included 140E Air and Missile Defense Tactician/Technician, 14T Launching Station Enhanced Operator/Maintainer, 14A Air Defense Artillery Officer, 14E Fire Control Enhanced Operator/Maintainer, and 25N Nodal Network Systems Operator-Maintainer.

At the beginning of each interview, we asked each Soldier to rank order the above identified issues using a card sort activity. Soldiers sorted the issue cards, prioritizing the issues according to how detrimental they believed each could be to successful mission performance. We then asked each Soldier to explain the rationale guiding their prioritization of the issues. Following this activity, we interviewed Soldiers about the skills, training, and evaluation related to each issue. Interview questions focused on: (a) how the issue might manifest during air battle management; (b) possible antecedent conditions or factors that might contribute to issue occurrence; (c) performance consequences of issue manifestation; (d) indications of current training and/or evaluation strategies thought to mitigate the issue; and (e) ideas for other training that might address the issue.

RESULTS

Table 2 presents measures of central tendency for all Soldiers' rankings. Figure 1, following, compares issue rankings by MOS and the Soldiers' primary roles in their units. Data is excluded data from three (3) participants (25N and 14T). Higher scores indicate Soldiers perceived the issue could have a relatively greater negative impact on mission success. In other words, a higher score means the issue is potentially more problematic in comparison with the other issues in the ranked set; a lower score, less problematic.

Table 2. Issue Rank Order Scores, Measures of Central Tendency

Supervisory Control Issue	Median	Mean	Min[a]	Max[b]	Mode	SD[c]
Incomplete understanding of how the system works	8	6.9	2	8	8	1.6
Inability to comprehend and integrate critical information to maintain SA	6	5.6	2	8	6	1.5
Insufficient understanding of one's own role within the tactical situation	6	5.1	1	8	7	2.1
Attentional tunneling	5	4.8	1	8	6	2.1
Insufficient mode awareness	4	4.3	1	8	5	1.8
Track identification	4	3.8	1	7	4	2.0
Automation bias	2	3.0	1	8	1	2.2
Double-hatting	2	2.8	1	8	1	2.0

[a] Min=minimum; [b] Max=maximum; [c] SD=standard deviation

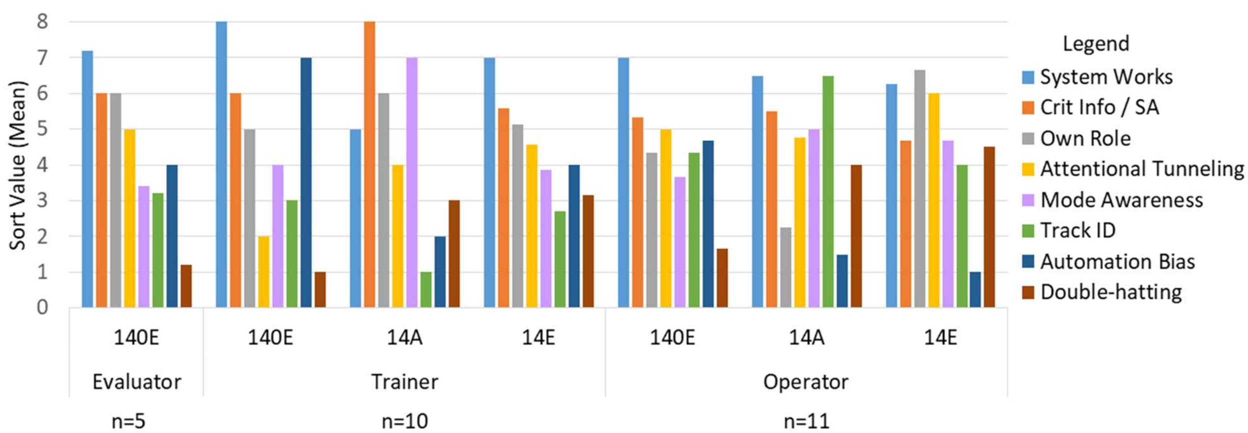

Figure 1. Soldier Rank Order Comparison of Issues by MOS and Primary Role in Unit

Overall Soldiers ranked an incomplete understanding of how the system works highest (Table 2), though 14A Trainers ranked an inability to comprehend and integrate critical information to maintain SA (Crit Info/SA, Figure 1) highest. Track identification and double-hatting were ranked on the lower end of the issue set (Table 2); concerns seemed to diminish with increased experience (Figure 1). An insufficient understanding of one's own role within the tactical situation was ranked high overall (Table 2) and rankings remained fairly steady across groups (Own Role, Figure 1). 140Es expressed more concern for automation bias than other MOSs (Figure 1).

Group sample sizes were too small for meaningful statistical comparisons, but future research may provide insight into the ranking tendencies we found. For example, it appeared to us that the more knowledgeable a Soldier was about the system itself, the more likely they were to understand the potential for automation bias, based on results for 140Es in all roles (Figure 1). More research would be required to definitively conclude if and why these particular groups believe automation bias may have a greater negative impact on mission success than other groups.

Additional Soldier Identified Skill Requirements

Soldiers were also asked to identify a single skill they believed would have the most positive impact on supervisory control performance. A few supplied two, resulting in thirty-one (31) responses. System knowledge, understanding and application accounted for eight (8) responses. Critical thinking, deductive reasoning, and adaptive thinking accounted for seven (7). Faster cognitive processing speed was stated four (4) times, and knowledge acquisition and retention and memorization were stated six (6) times; Soldiers related these responses to copious amounts of reading materials required to learn and maintain system currency. They wanted an increased ability to study and retain information, and a better understanding of how and where to find information within technical manuals. Time management, multitasking, resilience, motivation to learn, training ability, and knowing others' roles each received one response. While most of these responses were subsumed under the key skillset, some were not specific to supervisory control and therefore not included in the skillset.

DISCUSSION

Each issue discussed during data collection aligned with multiple key supervisory control skills. For brevity, findings for each issue are included in the following discussion under the key skill they align with most apparently. The key skills are CRM, decision-making, interpretation, SA, system operation, and vigilance.

Crew Resource Management (CRM)

A simple definition for CRM is the "effective utilization of all available resources…to achieve safe, efficient…operations" (Driskell & Adams, 1992, p. 8). CRM provides an organizing framework for understanding crew-level processes and performance necessary when Soldiers are performing supervisory control. Team structure, backup behavior, team communication, mutual performance monitoring, and task coordination influence crew resource management (Naylor & Dickinson, 1969; Gao, Cummings, & Solovey, 2014; Macmillan, Entin, & Serfaty, 2004; McKendrick et al., 2014; Salas, Sims, & Burke, 2005; Hawley & Mares, 2007).

Double-hatting

Soldiers tended to view double-hatting as an inevitability of their jobs. Double-hatting challenges operators if they do not fully understand tasks for the roles they assume, or they are overwhelmed by additional tasks required for the assumed role. A lack of understanding of how to do other crew members' work and a lack of system understanding can lead to an operator's failure to perform weapons control procedures (i.e., reload, slew, and switch actions), can elicit automation bias in a firing decision. Even knowledgeable operators could become task saturated, however, if they have poor prioritization skills or if crew workload distributions fail to effectively redistribute the total workload.

Soldiers attributed the potential negative effects of double-hatting to a lack of system understanding, automation bias, and/or lack of understanding of the tactical role. System understanding and role understanding together enable the critical thinking that prevents automation bias. An understanding of the tactical role is required to perform weapons control and understand self-defense criteria while double-hatted. We associated CRM, system operation, and decision-making skills with double-hatting. Soldiers need to know the roles of other crewmembers in order to properly perform tasks they will inevitably assume, because operators may be required to different perform system tasks outside their normal roles while double-hatted. The assumption of an additional role may affect a Soldier's ability to prioritize SA information. An operator may be required to maintain communications while double-hatted, and apply their understanding of the situation and the system to make a decision.

Insufficient Understanding of One's Own Role Within the Tactical Situation

Soldiers viewed this issue from different perspectives. Less experienced Soldiers focused on the role aspect of this issue and related it to learning their new jobs, learning how to perform as a crewmember, and learning how to differentiate the TCO and TCA roles. This issue was also described as a precursor to negative double-hatting situations, since the TCO must assume the tasks of the TCA at some point. Therefore, we related this issue to CRM, but also associated it with an incomplete understanding of how the system works and automation bias.

Problems associated with lack of crewmember role understanding may arise due to a poorly distributed workload; an operator may become overwhelmed by taking on too many tasks, or taking on tasks for roles they do not understand. Experienced operators may have this issue if they habitually take on tasks for other crewmembers. This issue could negatively impact CRM, system operation, and decision-making skills. Communication quality, reporting timeliness, and the crew's ability to complete tasks on time could be affected. Operators must understand how to perform weapons control, fix faults, send reports, process orders, and distribute the workload to prevent negative effects of this issue.

Decision-making

Hawley and Mares (2006) reported that conscious problem solving and discernment form the basis for firing decisions in effective supervisory control, and accordingly a decision is a conclusion reached after deliberation. There are numerous other decisions made by operators and crews; some are extended across multiple actors.

Automation Bias

There was a high degree of awareness of this issue as it related to a firing decision. Most Soldiers ranked the issue of automation bias low, and asserted that Army emphasis on the severe consequences of automation bias in firing decisions throughout training had ensured they would not simply acquiesce to the system. Highly experienced Soldiers asserted that operators may still over rely on the system in other ways, and maintained that effective training must continuously guard against complacency. For example, operators cannot just memorize system procedures, they must also understand how the system works.

Other issues can contribute to automation bias and render complex situations where operators fail to recognize an issue and assume the system is correct. For example, poor threat briefs result in poor SA and a reduced understanding of the tactical environment; an operator may not know that there are certain threats in the environment that can change their SA by affecting their system. Or, an operator with poor system understanding may not understand how maintenance issues affect the system, negatively impacting their capability to identify threats and degrading their SA accuracy. Our data indicated that automation bias can be caused by a lack of underlying knowledge and the abilities associated with performance rather than a simple failure to perform procedures and an operator's uncritical acquiescence to system recommendations.

We related other issues to automation bias including a lack of tactical role understanding, lack of system understanding, problems with SA, and inaccurate track identification. Skills associated were system operation, SA, decision-making, and CRM. System operation and SA are critical key skills that mitigate this issue because they enable the operator to recognize system faults. They also enable operators to, recognize how aspects of the environment may be affecting the system thereby changing SA, and ultimately enable operators to negate the impact of environmental threats on the system.

Interpretation

Interpretive processes rely on an individual's and/or crew's ability to observe, understand, evaluate, and communicate relevant information. To correctly classify threats, operators must comprehend data, apply SA, communicate with crew members, communicate with other actors in the C2 chain, communicate system data, and reach conclusions through active consideration. Interpretation is a critical aspect of effective supervisory control in this context.

Track Identification

Track identification was highly ranked by Soldiers because it represents a primary ECS crew responsibility, closely related to the TCO's primary job, friendly protect. In the context of supervisory control, most Soldiers did not find track identification problematic as long as they followed established procedures. Soldiers who tended to rank this issue lower did so on the basis that the redundancy built into the identification process eliminated the need for a single Soldier to identify a track on their own. Problems may emerge if: (a) operators are less knowledgeable about track kinematics; (b) primary communication is lost, forcing operators to use secondary methods; and (c) multiple tasks (e.g., multiple tracks, system faults, or incoming orders) require divided attention, quick decisions, or hand-offs of responsibilities. Indecision may arise as a consequence, increasing the time it takes to complete critical tasks.

We associated every key skill with track identification. For example, deciding a correct course of action depends on correct interpretation of track kinematics. Critical to this is effective CRM; operators must rapidly communicate, coordinate, prioritize and accomplish multiple tasks within their own ECS crew and across other crews to ensure all necessary tasks are accomplished while tracks are being identified and confirmed. An understanding of the tactical environment, SA, and system understanding is required to accomplish track identification, maintain SA, and make decisions. To monitor and correctly interpret system and operational data and cues, operators must be diligent in their attention to system displays, data feeds, and other system feedback mechanisms. Operators' correct understanding of mission events depends on an understanding of how the environment can impact data displayed by the system. Operators must also understand how system faults can affect track discrimination.

Situational Awareness (SA)

SA is a complex skill, merging information from the system, individual, crew, and external team to develop an understanding of the tactical situation. It is the basis for anticipating events, solving problems, and making decisions. Endsley (1995) defined SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (p. 36).

Inability to Comprehend and Integrate Critical Information to Maintain SA

This issue was ranked higher than most others overall, alluding to complexity and difficulty in operationalizing this broad spanning concept. When interviewed, Soldier responses were at times contradictory regarding SA. Some reported that SA was directly observed during evaluations while others said it was only inferred during evaluation. Similarly, in some cases SA was reported to be evident during an air battle, while in others SA, or the lack of SA, was not evident until an after action review.

Discussions allowed us to associate this issue with understanding both the system and the C2 environment. Examples include: (a) operator failure to recognize that something in the environment is impacting the system and altering SA accuracy; (b) operator failure to manage system hardware and software issues; (c) operator lack of understanding about critical information that contributes to SA; and (d) operator lack of knowledge about what piece of information is required at a particular time to maintain SA. To maintain SA, operators must understand the system, understand the impact of entries on the system, and relate this information to details about the operational environment. They must also understand the tactical advantages of other organizational components, specifically their capabilities for provision of different and more accurate information. Operators must be able to recognize and fix system faults that may impact their SA. Acquisition, maintenance, and accuracy of SA can suffer from errors and deficiencies related to system understanding, attentional tunneling, and understanding of one's tactical role. This issue can impact the validity of track identification and ultimately, firing. We associated this issue with all key supervisory control skills.

Insufficient Mode Awareness

The Patriot system can operate in different modes, each with different functions and different information presented to the operator. When an operator is unaware of which mode they are working in a system, they have failed to maintain SA. Some participants dismissed insufficient mode awareness because it was addressed during training. Other participants ranked it higher due to its potential negative effects on SA accuracy and because, if left unchecked, consequences could culminate in system damage or fratricide. Insufficient understanding of modes may be evidenced by operators turning off or ignoring alerts. When an operating mode is ignored, the operator may not understand how the defense plan, radar settings/signals, and engagement modes are related.

We associated this issue with SA, interpretation, and decision-making, and system operation. Mode awareness can affect SA if operators fail to return to the correct mode after adjusting system settings. Accurate interpretation depends on operator comprehension of system information in the correct mode—data needs to be available and interpreted in the correct context to inform decisions. Correct system inputs depend on the correct interpretation of available data.

Attentional Tunneling

Soldiers related this issue to spending excessive time and attention trying to comprehend information or determine a course of action, and reported that it is typically caused by indecisiveness about the meaning of system data, external information, or events. A cluttered scope, hectic environment, or lack of confidence can exacerbate the issue. Common signs of attentional tunneling include operator neglect of other tasks, loss of SA, and delay in required responses. CRM aspects may break down as a result, such as task distribution and communication.

Higher rankings for attentional tunneling reflected opinions that the issue was highly problematic, especially for inexperienced operators, while lower scores reflected opinions that air battle exercise repetition with high target saturation or task interruption scenarios mitigated the issue. Soldiers reported that mitigating attentional tunneling depends upon performing other skills well, including vigilance, SA, and system operation. It can also be mitigated by ensuring an operator has an understanding of the system, an understanding of mission characteristics, and can perform the correct operational procedures while maintaining SA. We associated CRM, SA, system operation, decision-making, and vigilance key skills with this issue.

System Operation

System operation has both psychomotor and cognitive requirements for the operation and modification of the system interface to maintain positive supervisory control during air battles, and also the integration of complex knowledge to understand how mission, system, crew processes and specific operational environments affect supervisory control.

Incomplete Understanding of How the System Works

Soldiers reported that they acquired much of their system knowledge through self-directed learning, particularly during deployments when they had the time and access to the system to learn in depth. Deep system understanding is necessary to enable critical thinking about how to employ the system operationally, and Soldiers noted that learning to interpret the meaning of system information and behaviors, human actions, and mission context, particularly during adverse conditions, took a significant amount of training beyond achieving operation proficiency and certification. For example, a Soldier may know what tabs to adjust following specific communications, but may not be aware of how those adjustments impact system performance. Issue indicators may include delayed communication or the inability to verify the accuracy of system settings.

System understanding was identified as a bedrock of other supervisory control skills. For example, operators must be able to understand system settings and data in order to develop and maintain SA. Similarly, problem solving (decision making) is dependent on operators' understanding of corrective effects on system faults or errors. A comprehensive understanding of how the system works and of how operator actions affect system performance enable the multitasking, task redistribution, and backup behavior that comprise CRM. System understanding plays a key role in mitigating the negative effects of double-hatting and automation bias, because operators will understand the tasks required by other roles, and will be able to recognize oddities in system information and question them.

Insufficient Understanding of One's Own Role Within the Tactical Situation

Soldiers tended to have two perspectives concerning this issue. The first focused on individual operator roles and was discussed under CRM. As related to this issue, Soldiers focused on understanding the larger picture of the air battle, including how multilevel components (e.g., ICC) interact, and how C2 is implemented operationally for fire control. Soldiers reported that learning one's tactical role is an ongoing requirement, as each theater and mission is unique.

We associated this issue with system operation because effective supervisory control requires Soldiers to integrate knowledge about how the mission, system, crew processes and specific operational environments interact. As a general example of this issue, a crewmember might be unaware that another C2 component has additional information which could impact their decision-making. From a tactical perspective, the issue can also negatively impact other key skills including SA, interpretation, and decision-making. Other associated issues included an inability to comprehend and integrate critical information to maintain SA and track identification.

Vigilance

Vigilance concerns an operator's ability to attend to, monitor, and detect changes in the environment, and respond to those changes (Shaw et al., 2010; Nelson, McKinley, Golob, Warm, & Parasuraman, 2012; Warm, Parasuraman, & Matthews, 2008). With increasing levels of automation, operators must be effective system monitors, prepared to intervene when necessary in system operations (Shaw et al., 2010). Specific to our work, we summarized vigilance as an individual's ability to maintain attentional control over a length of time, monitoring and detecting changes in the environment, and responding to those changes. *Attentional control* concerns an operator's ability to be flexible in controlling how they attend to information (Derryberry & Reed, 2002), and being able to disregard or concentrate on different types of information purposefully (Wright, Chen, Quinn, & Barnes, 2013).

Vigilance is an essential part of Patriot supervisory control, yet it is not a skill that can be easily trained outside of deployed environments (Buehner, Drzymala, Brent, Cobb, & Nelson, 2015). This is because Soldiers require lengthy system monitoring periods to train this skill, but they do not typically engage in lengthy monitoring periods until they are in theater (Hawley & Mares, 2007). (Patriot operators typically perform for 12-24 hour periods while in theater.) Over time, vigilance is a skill that may diminish and lead Soldiers to rely more heavily on automated processes. Our data confirmed vigilance as a key skill, in that remaining vigilant was necessary to maintain SA and prevent attentional tunneling. Our findings suggested that more experienced personnel were sensitive to the relationship between diminishing vigilance and increased automation bias that can occur during long periods operating the system.

INTERVENTION RECOMMENDATIONS

The goal of this research was to identify ways to enhance training for supervisory control. This was accomplished by identifying and analyzing the contributing factors, performance manifestations, consequences, and training and evaluation practices associated with issues that affect the supervisory control performance, and defining a key skillset for operators. Based on this information, we identified seven interventions that may serve to enhance training for supervisory control. The interventions presented below are not organized by priority.

1. Develop standardized evaluation metrics for supervisory control skills. The research findings suggested that supervisory control skill development could benefit from its own set of specific metrics. Such metrics would supplement the outcome-based measures frequently used in air battle management evaluations (e.g. destruction of incoming missile, protection of friendly asset, avoidance of a fratricide). Key supervisory control skills are predominantly cognitive in nature, yet there are observable behaviors that indicate their demonstration. Thus, the inclusion of metrics in performance evaluations would provide crew members with valuable feedback about performance of the underlying skills which enable effective supervisory control. This intervention would have the potential to impact multiple supervisory control skills. Standardization would ensure that each metric is consistently applied and evaluated.

2. Train operators to understand why something happens in the system, not just how to operate the system. While system operation is already a training focus for Patriot, it is trained and evaluated primarily as procedural performance in manipulation of system settings. Findings suggested that enabling operators to understand why something happens in the system would be more beneficial than adding more procedural-based training. Concurrently, training should emphasize system limitations and capabilities. This could help prevent automation bias by increasing operator understanding and by highlighting operators' responsibilities and contributions required to avoid it. Systematically improving system understanding among the force could also help programs handle the loss of available experienced personnel who possess system expertise and commonly provide training and informal coaching.

3. Facilitate operator development of a C2 mental model. Specific to our work, *mental model* is the operator's internal understanding of how the system, crew, and C2 processes work and fit together in air battle management (Mercado et al., 2015; Sarter & Woods, 1995). System operation requires using a mental model to predict how real-time changes impact the system, and revising the mental model to accommodate evolving mission conditions. Accuracy of mental models is also important for decision-making (Hawley and Mares, 2006). Findings indicated that operators may benefit from training to improve understanding of their role within the tactical environment, and of how individual operators relate to the broader C2 environment, particularly to address the need for understanding of one's own role within the tactical situation. Also, research has recommended that mental models be established early in training to facilitate knowledge acquisition (Norman, 1993; Hawley, Mares, & Giammanco, 2005). This prompted our recommendation for explicit mental model development as a component of training, developed early in training. Ideally, this training would focus on facilitating operator development of a C2 mental model, which would provide a framework for understanding and integrating communication requirements, duties and authorities, and processes to perform within each crew and in coordination with other command echelons. Promoting mental model development early in Soldiers' training would provide a mental framework personnel could use to build and maintain their system knowledge as training progresses.

4. Enable operator understanding of the third and fourth order effects of the system. Several Soldiers we interviewed stressed the need for training to enable critical thinking, problem solving, and understanding (in their words) the "third and fourth order effects" of both system actions and the air battle. In other words, Soldiers saw value in an operator's ability to project consequences of system actions beyond the immediate effects, and sought ways to build knowledge of the cause and effect networks of their interactions with the system. The use of scenario-based team training outside of actual system-based settings during air battle management training would allow Soldiers to practice critical thinking and decision-making and discuss their strategies and concerns over what might happen in real-time.

5. Facilitate the development of CRM-related skills and processes. Many air defense crews develop within crew performance strategies through trial and error during repeated air battle management exercise rehearsals. Crews work out coordination processes through discovery during training exercises. While repetition in training allows the crew, over time, to reach this goal, it also likely increases total training time due to the trial and error required to work out best practices. Training that is based on established CRM principals could provide: (a) guidance on factors that influence crew/team performance, (b) preferred strategies for delineating roles and responsibilities, and (c) tools to identify process choke points and strategies to address them. CRM training would provide knowledge and tools to crew members prior to practice in air battle management exercise training. Implementation of CRM training could have a positive impact on air battle management training efficacy and decrease time to certification because it may decrease the time taken up during exercises for newly constructed crews to work out their processes.

6. Crew process training should highlight the knowledge and skills to improve SA. This training should specify what data and communication elements contribute to SA, where they come from, and how shared SA is developed and maintained in the organization and in crews. SA is a challenging concept, and could be potentially be inconsistently understood and evaluated. It is obviously difficult to assess cognitive processes, but the development of supervisory control metrics may provide a more granular tool to indicate areas needing improvement related to SA. Training that improves system understanding, attention allocation, and understanding of the tactical environment could help operators maintain SA because it may mitigate the negative effects of other issues on SA and allows operators to concentrate on the inputs, outputs, and maintenance of it.

7. Cross-train specific supervisory control roles prior to deployment. Cross-training early in a training program could allow exercises and scenario based training events to prioritize development of other tasks and skills. It could mitigate negative effects of double-hatting and/or performance deficits related to task assumption outside of normal roles. This recommendation would be particularly relevant for systems where cross-training of lethal agent and supervising agent roles typically does not occur until after crews are deployed, but double-hatting is an inevitability.

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