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Automation, Alarm Management, and Human-Computer Interaction in Space Operations Environments

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Abstract— Data from an online human factors survey of 59 remote operations professionals was analyzed to understand how automation, alarm management, and human-computer interaction affect dynamic shift work pattern workers. This research found a need for increased vigilance when working with automated systems, specifically in space operations. Subsequently, the study suggests that training and crew resource management are critical components of an effective operations center. Informed crews who work efficiently as a team are better able to mitigate automation bias, ineffective alarm management, and less than optimal human-computer interaction implementation. Furthermore, incorporating lessons learned in space operations programs could help decrease overall risk to individual on-orbit assets if leaders invest in proper documentation and continuity concepts while also prioritizing incorporating outside lessons learned into their programs.

Index Terms— Automation, Alarm Management, Human-Computer Interaction

1. Introduction

This study is the third segment of work revolving around mitigating complacency-induced human error in space operations environments. After a review of remote operations literature and associated human-computer interaction (HCI) technologies was accomplished [1], the authors conducted a 58-question human factors study which led to a second peer-reviewed publication on attention, concentration, and fatigue in space operations environments [2]. The survey and methodology referenced in this paper are the same as described in [2]. The survey analysis was deemed too large for just one research paper; thus, this publication details the remaining points of interest to increase the body of knowledge within the space operations human factors discipline. This qualitative research paper analyzes the human factors associated with automation, alarm management, training, and HCI in space operations environments using a comprehensive online survey of 59 remote operations professionals.

Automation of a system entails limiting or completely removing the human from a highly complex equation [1]. Automation is a process that performs a series of well-defined tasks with minimal or no human interaction according to a set of predefined parameters under human supervision [3]. Space operations environments consist of highly automated systems with satellite operators at the helm, ensuring their mission continues as planned. Parasuraman, Sheridan, and Wickens proposed four classes of automation: "1) information acquisition; 2) information analysis; 3) decision and action selection; and 4) action implementation" [4, p. 286]. Depending on the specific satellite system, varying levels of the four classes of automation may be employed, affecting the degree to which human interaction is required when decisions and actions are executed [4]. While limiting the role of the human-in-the-loop (HITL) may lead to efficiencies, " 'clumsy' automation" [4, p. 290] may bring about negative human factors associated with situational awareness (SA), complacency, and a potential decrease in the professional skillset of the HITL [4].

Ineffective alarm management has been cited as a contributing factor in many human factors-related incidents [5, 6]. Poor prioritization and ineffective alerting mechanisms have caused operators to incorrectly respond to critical indications indicative of a potential problem [1]. The topic of alarms has been substantially highlighted in the medical literature due to the life and death nature associated with alarm prioritization and management [7]. Medical alarm issues are similar to those seen in other sectors where nuisance and nonactionable alarms have hindered time-sensitive operations. In the space operations environment, developers must first figure out the importance of each unit within a satellite system of systems and then prioritize their importance to create internal redundancies and failure responses to keep the spacecraft operational [8]. This methodology is similar to how healthcare professionals use medical device alarming mechanisms when caring for patients. A best practice of prioritizing alarms has been developed through the use of emergency, high, and low priority alarm categories within the oil refinery industry, where 5% of alarms are reserved for an emergency, 15% for high priority alarms, and the remaining 80% are reserved for the lowest priorities [9, 10].

Alarms are usually conveyed to the operator through a user interface, which ties the computer system and the human together [11]. Developers of the computer portion of the system must account for the planned average operator skill level, accessibility effectiveness, usability, and satisfaction when working to ensure remote operations centers are equipped to meet mission requirements [12]. Within remote operations centers, operators are responsible for the command and control (C2) of their specific assets using HCI systems. These HCI systems enable the HITL to set up and manage various automation modes and alarm management tools to ensure the system executes the mission as planned.

Furthermore, without properly thought-out HCI systems, the operator may experience increased cognitive loads when attempting to simultaneously process alarm screens, respond to C2 issues, and maintain the health and safety of their remote system [13]. Increased cognitive loads may drive an overload of information, resulting in "change blindness" or a diminished

SA of the entire operating picture [14, p. 3]. This decreased SA could create the possibility of the operator missing critical visual cues, thus hindering overall alarm management and control of the system. Due to the potential severity of complications within human factors associated with automation, alarm management, and HCI, this paper will discuss the results of a study on shift work in remote operations environments.

2. Methodology

A comprehensive online survey was distributed to research human factors within remote operations environments. The researcher's professional network and the "snowball" method were used to distribute the survey to as many people as possible within a two-week period between October and November 2021. The target audience consisted of adults aged 18 and older who worked in remote operations for at least six months within the last five years. Additionally, the survey specifically targeted the following professions: air traffic control, launch operations, remotely piloted aircraft operations, and satellite operations [2]. Potential participants were asked to initially answer five entrance questions before they were permitted to continue with the survey. 59 out of 77 participants successfully progressed past the qualification questions to complete the survey. Three reasons presented themselves as to why 18 participants could not complete the entire 58-question survey successfully: less than six months of experience, they did not work in remote operations within the last five years, or they had never worked in remote operations [2].

After the participants completed the entrance questions, they were asked to answer 53 multiple choice and 5-point Likert scale questions about their experience in remote operations. The topics covered alarm management, attention and boredom, automation, fatigue, HCI, lessons learned, shift work, training, and work-life experience [2]. The topics covered were chosen to gather data on the human factors of shift work while working in remote operations environments. The researchers split the data into two topics: 1) attention, concentration, and fatigue [2]; and 2) automation, alarm management, and HCI. This paper focuses on the latter and seeks to answer the following research questions: Can ineffective automation, alarm management, and HCI design lead to complacency-induced errors in remote operations environments, and if mitigation methods from other sectors could help mitigate human error in remote operations environments?

3. Demographics and Training

This demographic of this study consisted of 59 adult participants within the remote operations workforce [2]. The education level of those surveyed spanned from high-school graduates to master's degree holders, with the majority holding a Baccalaureate degree or higher (86%) [2]. Most operators (92%) worked in their field for at least two years, and almost 14% had worked for over nine years at the time the survey was conducted. Satellite operations professionals accounted for 80% of those surveyed, while the remainder consisted of "Other (14%), uncrewed aerial operations (3%), missile crew operations (2%), and launch operations (2%)" [2, p. 2].

Figure 1 reflects the results of the training section of the survey. Military technical training followed by on-the-job training (OJT) was accomplished by 88% of participants in this study, while the rest either completed only OJT or civilian trade school followed by OJT. The length of qualification training for the majority of those surveyed was 12 months or less (88%) to become an operator. Communication and teamwork skills or Crew Resource Management (CRM) were taught to 73% of study participants. Seventy-one percent of participants answered that they attended a realistic training environment, and 81% agreed that their training adequately prepared them for the operations floor.

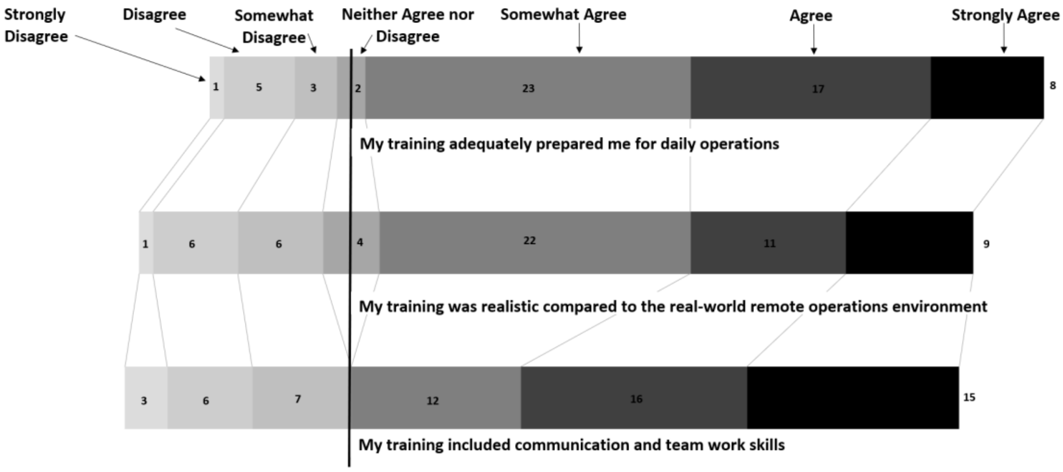

Fig. 1. Results of the Training section of the survey (n=59)

4. Automation

Table I illustrates the results of the automation portion of the survey. The automation portion of the survey gathered data about the level of automation used on the operations floor, if the worker ever had to take control of the system, and if autonomy, automation, and internal redundancy give operators a false sense of security. All 59 operators surveyed indicated they were subjected to varying levels of workload while on shift; specifically, 12% stated they had to control everything, and 76% cumulatively indicated they had to intervene at least half the time due to the limits of the automation present within the system. Two satellite operators (3%) indicated that automation was highly reliable, while the remaining 57 participants indicated they needed to intervene at some point while on shift. When asked if autonomy, automation, and internal redundancy give the operator a false sense of security, 58% disagreed or were neutral, while 42% agreed.

TABLE I. AUTOMATION (N=59)

How would you describe your workload while on shift?	Frequency	Percentage	Cumulative
I had to control everything (No Automation)	7	11.86	7

I was engaged MOST of the shift	20	33.90	27
I was engaged about HALF the shift	18	30.51	45
I was not very engaged during the shift	14	23.73	59
I just sat back and relaxed (Fully Automated)	0	0.00	59

I have had to take control of the system.	Frequency	Percentage	Cumulative
Never (automation was highly reliable)	2	3.39	2
Rarely	3	5.08	5
Sometimes	22	37.29	27
Often	19	32.20	46
All the time (automation was NOT reliable, or there was NO automation present	13	22.03	59

Autonomy, automation, and internal redundancy give operators a false sense of security.	Frequency	Percentage	Cumulative
Strongly disagree	4	6.78	4
Disagree	10	16.95	14

Neutral	20	33.90	34
Agree	14	23.73	48
Strongly agree	11	18.64	59

5. Alarm management

The results of the alarm management portion of the survey are presented in Table II. Questions about alarm management were asked to gather data about distractions and gauge operator knowledge about alarm response. Ninety-three percent of those surveyed indicated they were trained on alarm priorities. Eighty-three percent said they had to contend with 20 or fewer alarms while on shift, while the remainder of those surveyed indicated they had worked with upwards of over 41 alarms at any given time while on a nominal shift. When asked how many alarms were considered HIGH or emergency priority, 88% answered 25% or fewer. Missed alarms were rarely or sometimes an issue 64% of the time, while important alarms were "often" missed 5% of the time. Finally, erroneous alarms were identified (greater than "rarely") as a nuisance 73% of the time.

TABLE II. ALARM MANAGEMENT (N=59)

I was taught which system alarms are considered emergency, high priority, and low priority.	Frequency	Percentage	Cumulative
True	55	93.22	55
False	4	6.78	59
Approximate how many alarms you may encounter on a normal shift?	**Frequency**	**Percentage**	**Cumulative**
0-10	38	64.41	38
11-20	11	18.64	49
21-30	5	8.47	54
31-40	0	0.00	54
41 or more	5	8.47	59

Using the last question's response, approximately how many of the alarms are considered HIGH and/or emergency priority?	Frequency	Percentage	Cumulative
0-25%	52	88.14	52
25-50%	4	6.78	56
50-75%	0	0.00	56
75-100%	1	1.69	57
I don't know	2	3.39	59
Important alarms are missed on shift	**Frequency**	**Percentage**	**Cumulative**
Never	18	30.51	18
Rarely	28	47.46	46
Sometimes	10	19.95	56
Often	3	5.08	59
All the time	0	0.00	59
Erroneous alarms become a nuisance while on shift	**Frequency**	**Percentage**	**Cumulative**
Never	6	10.17	6
Rarely	10	16.95	16
Sometimes	22	37.29	38
Often	18	30.51	56
All the time	3	5.08	59

6. Human-Computer Interaction

Figures 2 and 3 illustrate the HCI section of this study. Questions about HCI were asked to understand the relationship between the HITL and the computer console within a remote operations environment. Operators indicated that job guides or technical manuals were sufficient to operate the system most of the time (53%). In comparison, 97% said they had to perform a workaround or "hack" the system to accomplish their job. When asked if the system alerts the operator when there is inactivity, 49% indicated "never," while the remainder answered there was some sort of an alerting mechanism to warn of system inactivity. When removing the answer "neutral," 41% responded that they did not believe designers had the operator in mind during software development, while 37% believed designers thought about the operator during development. When removing the answer "neutral," 34% answered that not all alarms and essential information are always visible, while 51% agreed that all alarms and essential data were visible on the operations console.

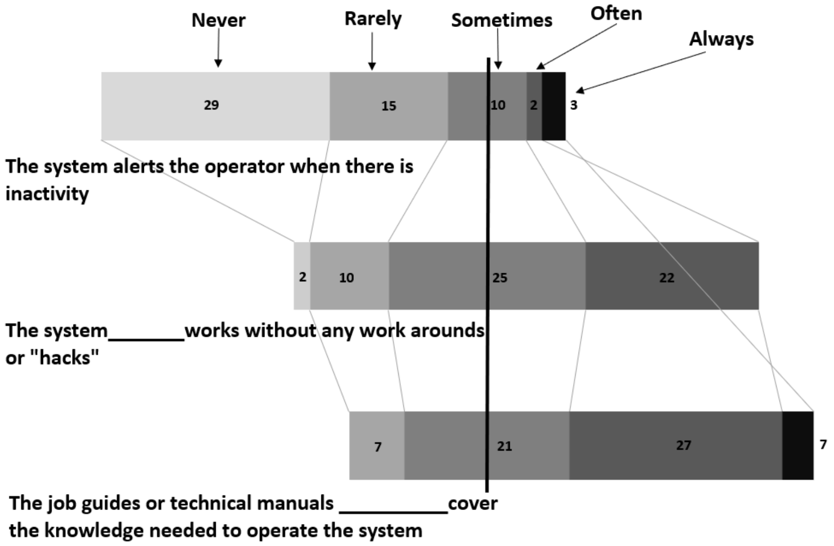

Fig. 2. Results of the HCI section of the survey (n=59)

The survey asked questions about methods of conveying alarms, popups, default operator screens, and two-party verifications for critical tasks. Auditory alarms were presented to 58% of operators. In comparison, visual alarms consisting of lights or colored displays were presented to 95% of operators. When asked if mistakes were easy to make while on console, the majority (54%) answered with "agree" or "strongly agree." Forty-four percent of operators indicated popups and system prompts are always visible when needed, while 32% disagreed. Availability of diagnostic or trending data from the default operator screens was believed to be easy by 32% of respondents, while 46% disagreed. On the subject of if defaulted operator screens have everything needed for the operator to operate the system successfully, 31% agreed, while 39% disagreed. Finally, the operators were asked if their operations HCI employed a two-party verification system for critical or sensitive tasks. Everyone surveyed indicated they understood the concept of a two-party verification. However, the concept was only utilized in the operations centers of 81% of survey participants. Of those that use a two-party system, the majority (51%) indicated the verification happens at a separate crew members console.

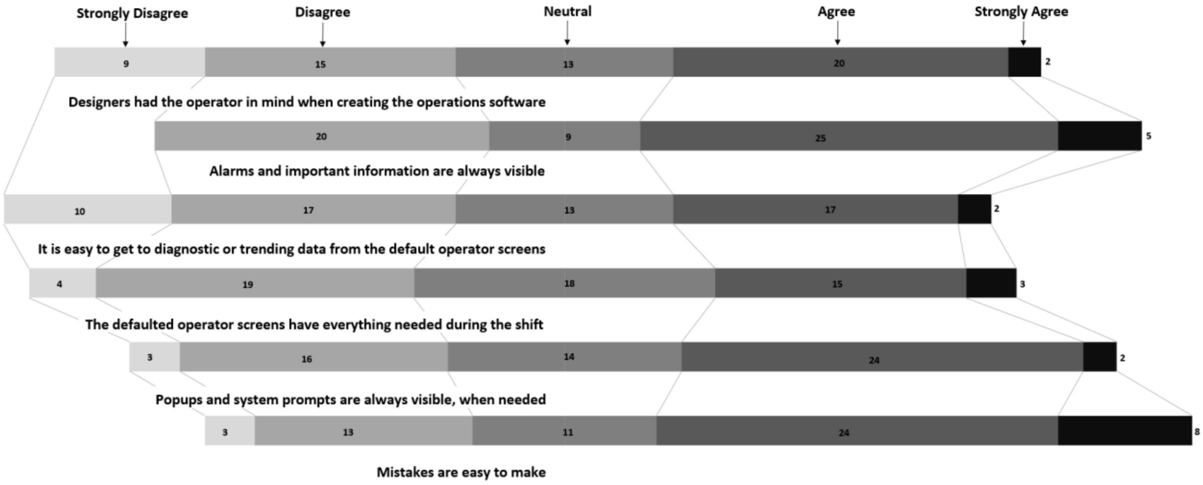

Fig. 3. Results of the HCI section of the survey (n=59)

7. Lessons Learned

Figure 4 shows the results of the lessons learned section of the study. Questions about the incorporation of a lessons learned program within the survey taker's unit were asked to understand how lessons learned are viewed within the remote operations community. Most respondents (71%) indicated their operations program had an established lessons learned program, but only 25% agreed that their program incorporated lessons learned from other programs to enhance operations crew life. Sixty-six percent indicated their leadership believed in using lessons learned to better prepare operators, yet 75% answered "neutral" or "disagree" when asked if their program had a robust lessons learned program. Finally, with the answer "neutral" removed, 17% agreed the process for correcting incorrect job aids or technical manual data was easy, while 63% disagreed.

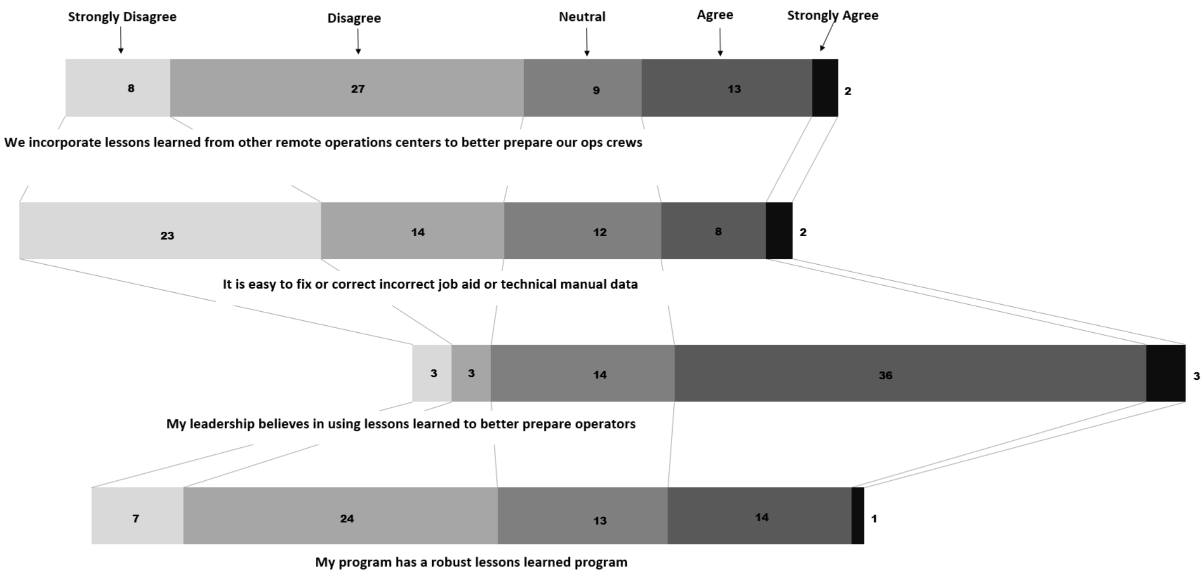

Fig. 4. Results of the Lessons Learned section of the survey (n=59)

8. Analysis

Mission success requires an effective initial and recurring training program to build a comprehensive understanding of the overall job and skillset required for daily operations [15]. In theory, training to work in a team setting should consist of communication and teamwork skills [16]. The training questions asked at the beginning of this survey lay the foundation for which the rest of this research is based. Forty-two operators (72%) indicated their training was realistic compared to real-world operations. Nearly all 42 operators agreed their training adequately prepared them, while two operators selected "neither agree nor disagree." This realistic training enabled 40 out of 42 members (95%) to understand the difference between emergency, high priority, and low priority alarms. Furthermore, realistic training enabled the 42 operators to ensure critical alarms were either "rarely" or "never" missed about 74% of the time.

The automation portion of the survey suggests that most systems within the purview of this study were automated yet still required occasional operator intervention. The data suggests the operators did not believe their respective systems were considered "highly reliable." HCI trust researchers have assigned five core concepts when assessing overall user trust of a computer system: "perceived understandability, perceived technical competence, perceived reliability, personal attachment, and faith" [17, 18, p. 9]. These core concepts of HCI trust can be highly subjective; in remote operations, this trust may stem from the number of alarms they encounter while on shift, the overall attitude toward alarm management, and the training they received during their qualification and certification. Only two participants (3%) indicated their system was "highly reliable," while the remainder of the operators answered that taking control of the system was necessary at least rarely.

The HCI may play a key role in how operators view overall system reliability. Job guides or technical manuals tend to cover required knowledge in about 53% of the responses, and 97% of operators indicated they needed to perform a workaround or "hack" of the system at some point to make the system work. There was no clear indication if auditory, visual, haptic, or some combination of the three would lead to increased success in catching all alarms. Including neutral responses, 63% indicated HCI designers did not have the operator in mind when designing the system. This could be partly due to diagnostic or trending data being complex or challenging for the operator to access (68% of the time), or defaulted operator screens may not present everything needed during shift (84% of responses).

9. Discussion

Automation can be an invaluable tool to ensure the system works through a process with minimal effort imparted by a HITL. Nevertheless, automation does not equal autonomy. When automation deviations occur, there must be a HITL present to catch and correct deviations [19]. Conversely, automation should not be confused with autonomy, which enables the system to act independently from the operator due to self-governance [20]. The fundamental difference between automation and autonomy is that autonomy requires the ability for the system to self-direct to achieve an objective and act in a self-sufficient manner to operate independently of a HITL [20, 21]. Human-system integration, including HCI integration, is a critical component of any space-based system. This survey indicated that 76% of participants had to intervene at some point while on shift due to the limitations of automation. Almost everyone agreed that their system's automation was not considered "highly reliable." Without active operator vigilance and intervention, a recurrence of related human factors failures could manifest due to "sub-optimal monitoring of automation performance" [22, p. 1].

Autonomy, automation, and internal redundancy within the system may create the potential for a false sense of security in an operations environment. The survey found that 42% agreed or strongly agreed that operators may feel a false sense of security due to perceived complexity and intelligence built into the system. This false sense of security may lead to an automation bias complacency. An over-reliance on automation, automation, or internal redundancy could lead to an operator becoming less vigilant because they may feel inclined to defer to the "more intelligent" system to handle potentially complex issues [23-25]. The concepts of a false sense of security and automation bias have been explored in the medical literature, where overworked healthcare workers, physically and cognitively, often have difficulty monitoring and interpreting automated aids in dynamic medical shift work environments [1, 26]. As a result of shift work fatigue, both health care workers and space operations professionals may need help maintaining vigilance through increased training on the risks and implications of automation bias, vigilance, and fatigue.

Most operators (93%) were taught about alarm management when working with their respective systems and were given an understanding of the difference between emergency, high priority, and low priority alarms. The survey found that 64% encountered ten or fewer alarms, and 83% encountered 20 or fewer alarms while on shift. Additionally, 88% indicated that up to 25% of those alarms were considered high or emergency priority. This data complements existing literature outlining best practices for prioritizing alarms by reserving 5% for an emergency, 15% for high priority, and 80% for the lowest priority alarms [1, 9, 10]. The data suggests the participants' system's alarms were accurately prioritized, which has helped 78% of the participants rarely or never miss critical alarms while on shift.

HCI development has been cited in the literature as being inadequately developed in various systems, including healthcare, remotely piloted aircraft (RPA), and uncrewed ariel vehicle (UAV) systems [11, 27]. Instances of poor development of HCI systems in RPA and UAV operations centers have aided in more resultant Class A mishaps than in crewed aviation [28, 29]. In space operations, alarms and critical information must be visible to the operator because the HCI is the only method by which the operator can monitor a satellite on orbit. There is an expectation that the system will work without hacks or workarounds and that all available job guides and technical manuals contain the requisite knowledge to operate the system within the operator's training and certification skill level. Only 37% agreed their system worked without workarounds or "hacks," while the majority (58%) answered "often" or "always" when asked if their job aids covered the knowledge required to operate the system. The data suggests it may be easier to fix or alter job guides than to correct a fully operational HCI system, further validating the need for HCI systems to have more significant developmental testing before the system enters operations. Furthermore, 51% indicated alarms and essential information were always available. While there was a consensus on the importance of alarm visibility and prioritization, not all systems present readily visible alarms and mission-essential information, potentially increasing risk to the mission and operational assets.

Research participants stated their upper management tend to agree on the importance of lessons learned, yet implementing lessons learned programs may not be fully realized and implemented within space operations environments. Data from this study suggests that even though 66% agree their leadership believes in using lessons learned, only 25% answered with an often or always answer that their operations center had a robust lessons learned program. Moreover, when asked if their operations center incorporated lessons learned from other remote operations centers to prepare operations crews better, only 25% answered favorably, with an "often" or "always" answer. Lessons learned programs help document where the program did well and where the program needs work. Proper implementation of these programs can lead to best practices and highlight practices to avoid, which can only benefit the overall mission. In addition, when lessons learned are shared between various sectors or operations centers, common knowledge and efficiencies may be gained to help reduce the overall programmatic risk [1, 16]. As with all lessons learned, issues should be documented as they arise, including issues with job aids and technical manual data. According to this study, only 17% favorably answered that it was easy to fix or correct incorrect job aids or technical manual data. Lessons learned should be efficient enough that operators can quickly identify and submit change requests to update job guides and technical data. Without a proactive and efficient process, operators may be left to guess or use unvalidated tribal knowledge to accomplish their mission which could lead to increased risk on the operations floor.

10. Limitations

The demographics section did not provide clarifying questions for the eight (14%) participants who answered "Other (not specified)" to answer what specific remote operations job they worked. Furthermore, the survey did not ask the participants to indicate which assets they operated within their specific remote operations center. In the section about alarms, the question "Using the last question's response, approximately how many of the alarms are considered HIGH and/or emergency priority?" provided a multiple-choice answer that does not accurately match the industry-standard prioritization of alarms: 5% for an emergency, 15% for high priority, and 80% for low priority [10]. The answers to the question could have been worded differently to help correlate data within the study by having the first answer as "0-20%," which would have combined the emergency and high priority.

11. Conclusion

The research presented in this paper was the second analysis of a survey of 59 remote operations professionals focusing on the effects of dynamic shift work patterns in remote operations centers concerning: automation, alarm management, and HCI. This research concludes that automation can be invaluable for creating efficiencies within the human-machine system. However, an overreliance on automation can lead to complacency if the HITL does not remain vigilant. Vigilance in a remote operations center consists of active participation by the operator to "trust but verify" using a well-thought-out HCI that effectively presents properly prioritized alarms to ensure the operator is not overwhelmed with information. Furthermore, to ensure the operator is best prepared for the mission: a fully developed initial and recurring training program consisting of CRM concepts should be instituted, as well as a robust lessons learned program could help ensure alarm management, documentation, and HCI issues are resolved as quickly as possible. Leaning on a CRM construct where the operators can rely on each other would help enhance the ability to avoid and mitigate risk to keep sensitive remote assets safe and on orbit.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mr. Heinrich conducted the research, analyzed the data, and authored the paper. Dr. McAndrew and Dr. Pretty provided expert oversight and helped to edit the research. All authors approved this final version.

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