Alternative Front End Analysis for Automated Complex Systems

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ABSTRACT

A growing body of literature reports that task-based analyses alone are not sufficient for determining training requirements for highly automated, complex systems that rely upon multilevel command and control integration. This has spurred concerns among Army leaders that the traditional Systems Approach to Training (SAT) Front End Analysis (FEA) strategy may not sufficiently identify training requirements for some emerging systems, and provided impetus for our research effort to develop an alternative FEA strategy better suited for these types of systems. The first phase of our effort focused on the research and design of potential alternative FEA strategies. The second phase provided a use case application of an alternative FEA to existing air and missile defense system training to validate and refine the strategy. During the third phase of our effort, we applied the alternative FEA to an emerging integrated air and missile defense architecture. The refined alternative FEA strategy supplements traditional SAT analyses with team-based and expertise-based analyses and was used to successfully identify requirements beyond those found through traditional SAT methods alone.

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INTRODUCTION

There is growing concern among U.S. Army unit leaders that task-based analyses alone are no longer sufficient for determining the full range of training requirements associated with highly automated systems, particularly when these systems are incorporated into multilevel, networked Command and Control (C2) chains. The integration of multilevel C2 information and decision requirements adds complexity to processes, communications, and decision-making. Traditional front end analysis (FEA) have often focused on individual tasks and roles with little regard for critical decision and coordination points, interpersonal interactive skills and requirements, or the full range of collective activities inherent in complex, networked systems. These complex systems collect information from multiple sources, process it, and output recommendations for action.

As technological advances deliver an ever increasing amount of information to Soldiers in the field, they must quickly interpret, assess, decide and act on this information to successfully perform their mission, while using automated systems to do so. Complicating matters further, the use of highly automated systems may actually impair decision-making due to an over-reliance on system outputs (see Hawley & Mares, 2006; Hawley, Mares, & Giammanco, 2005), an effect called automation bias. According to Hawley (2007) automation bias occurs when operators, overly reliant on system data and automated responses for decision-making, fail to recognize errors in system identification or faulty data and defer to the automated outcomes for decisions. These considerations coupled with a desire of Army leadership to keep abreast of emerging requirements, provided the impetus for our effort to develop a viable alternative FEA strategy.

In an effort to develop, validate, and refine an alternative FEA strategy, we conducted a three phase effort, from October 2013 to March 2015, focusing on the requirements of an existing air and missile defense (AMD) system and an emerging integrated AMD architecture. During Phase I, we explored and developed potential alternative FEA strategies, based on the team's past FEA applications, current U.S. Army Training and Doctrine Command (TRADOC) manuals and directives, and published literature (see Cobb, Brent, Buehner, Drzymala, & Nelson, 2014). This phase concluded with the recommendation of an alternative FEA strategy for use case applications in the subsequent phases. During Phase II, the alternative strategy was applied to an existing AMD system's air battle management training program in order to determine if it could identify requirements previously not identified by traditional task-based strategies (see Buehner, Drzymala, Brent, Cobb, & Nelson, 2015). Finally, in Phase III, it was applied to an emerging integrated AMD architecture's fire control requirements still under development (see Drzymala, Buehner, Brent, Cobb, & Nelson, 2015). Data for each of these applications was collected through the conduct of interviews and observations, as well as a review of government training materials that included course documentation and evaluation data for the existing system and drafted task lists, planned function/role configurations and designs, and capability documentation for the emerging multisystem architecture.

The Nature of Front End Analyses

U.S. Army training developers typically use a task or topic centered approach to conduct FEAs called Analysis, Design, Development, Implementation, and Evaluation (ADDIE). The ADDIE process is embedded within the Army's larger Instructional Systems Design (ISD) and Systems Approach to Training (SAT) strategies prescribed by TRADOC (U.S. Department of the Army, 2004; U.S. Department of the Army, 2013). These traditional FEAs focus on individual tasks and duties, and treat collective tasks as individual tasks that must be performed in concert with other individually defined tasks. A growing body of literature makes the case that task-based analysis methods seem increasingly ill-suited for progressively more complex, multisystem environments (see Hawley, 2011; Hawley & Mares, 2006; Mayfield & Boehm-Davis, 2009). This is because the process typically falls short in regard to analyses of critical decision and coordination points, interpersonal interactive skills and requirements, and the full range of collective activities inherent in complex, networked systems.

An FEA should define the context framing the training needs and answer a series of questions that inform subsequent training design, development, and delivery. Figure 1 (Cobb, et al., 2014) illustrates a generic FEA process and the questions it typically addresses. Regardless of the types of analyses used, or the specific questions asked, a consistent feature of an FEA is that the results are entirely dependent on what is included and the types of questions asked. As we considered potential alternative FEA strategies, we focused on the types of operational issues faced by system operators in the field, especially known training and/or operational shortcomings.

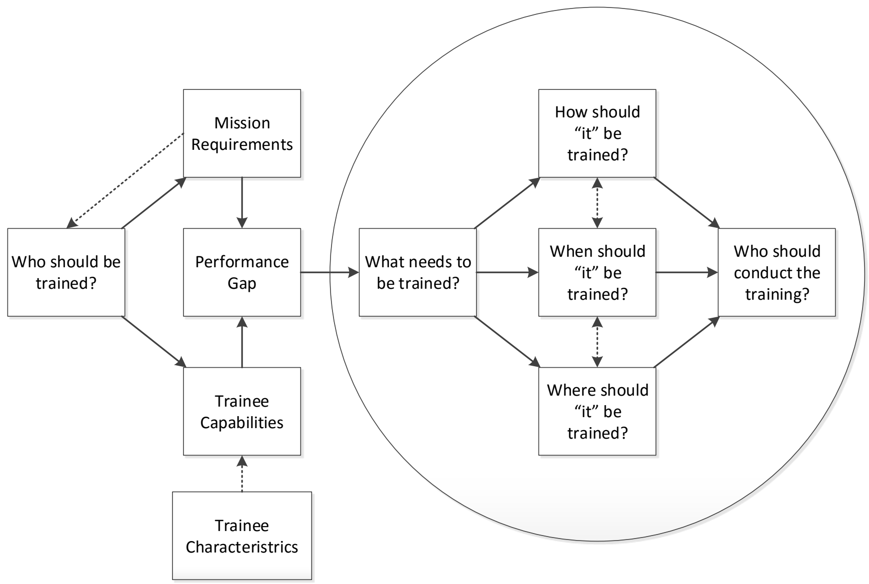

FIGURE 1. FEA CORE CONSTRUCTS

Research Questions

This research was an applied effort to design and refine an alternative FEA strategy. While the use case applications of the alternative FEA produced system specific findings and recommendations, the purpose of this paper is to focus on an alternative FEA design and summarize findings regarding the utility of the approach. Three questions guided the overall three-phase research effort.

1. First, could an alternative FEA strategy identify requirements beyond those established for a current system using the traditional SAT approach to FEAs (i.e., already being trained)?
2. Second, could an alternative FEA strategy render recommendations for adjusting training progression to enhance expertise development?
3. Third, could the FEA prove flexible enough for analysis of both established and emerging systems?

AN ALTERNATIVE FRONT END ANALYSIS STRATEGY

The alternative FEA strategy injects additional analyses into the Army's standard SAT, and uses the information in conjunction with that produced by the standard SAT analyses to supplement rather than replace the SAT. In Figure 2 (Drzymala, et al., 2015), shaded boxes contain major analyses of the traditional SAT and the bold outlined boxes depict the alternative complementary analyses. We wanted to retain the SAT strengths and familiarity while offering an additional capability to capture non-task based training requirements. SAT compatibility was deemed desirable because of: a) practitioners' familiarity with the SAT model; b) standalone analytic compatibility for established systems designed using SAT; and c) complementary capability within the SAT framework for emerging systems.

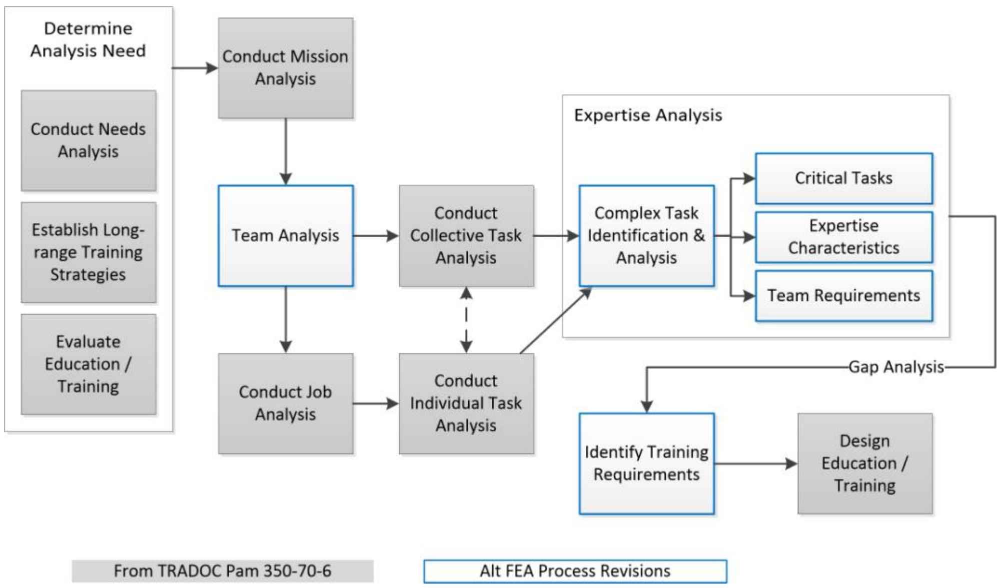

FIGURE 2. ALTERNATIVE FEA STRATEGY

The Team Analysis

One basic FEA question is "Who needs to be trained?" This question is often answered before the analysis is begun, as most FEAs typically align with personnel designations, which are then used to further define associated missions, jobs, and duties. A shortcoming of this approach is that it often removes the individual Soldier from the context of the overall operation. In other words, a Soldier's individual mission, job, duties, and tasks are prioritized above or without consistent consideration of their role in the unit's mission. Thus, collective tasks are conceptualized in the context of an individual's task performance. In answering "Who should be trained?", our alternative FEA postulates that the team should be considered as the proper unit of analysis in complex systems requiring the interaction of multiple individuals and agencies, rather than a simple aggregation of individually defined tasks and responsibilities.

Team Analysis Background

Building on work by Cooke, Salas, and Cannon-Bowers (2000), and Weaver, Rosen, Salas, Baum, and King (2010) further refined three dimensions of team competencies defined by team member interactions rather than individual performance (see Table 1, following). For example, "accurate/shared mental models," a competency within cognition, reflects the mental organizational structure or model that an individual has relative to his or her role and the degree to which it is shared or common across team members. Thus, this competency includes an individual level requirement (i.e., accuracy) and a collective requirement (i.e., shared and accurate across the team). Other competencies, such as mutual trust, backup behavior, and conflict management, are relevant only in a collective or team environment. This distinction illustrates how team-based competencies can inform collective training requirements that may not be identified from a solely task-based analytic model. While some competencies may be identified through a task-based analysis (e.g., cue-strategy associations) other competencies (e.g., mutual trust, shared mental models, and mutual performance monitoring) may go unnoticed.

The presence of distinct team competencies (vice individual competencies) highlights the fact that collective training within a team context is not a simple matter of joining or adding individual tasks at the proper time and place. Team training is subject to different processes, attributes, requirements, and goals than individual training. Knowledge construction, in particular, is tied to team performance with multiple researchers pointing to the importance of shared cognition (Salas, Cooke, & Rosen, 2008) as a precursor to successful team performance. In their review of fifty years of team performance research, Salas and his associates concluded that shared cognition is a critical driver of team performance (Salas & Fiore, 2004, as cited in Salas, et al., 2008). Shared cognition is particularly important in developing shared mental models, team situation awareness, effective team communication, and team decision-making, all of which are critical components of mission performance using highly automated systems within multilevel C2 mission environments.

TABLE 1. TEAM TRAINING COMPETENCIES

Competency Category	Competency	Descriptor
Attitude	Mutual trust	Trust across and between team members
	Team / collective efficacy	How well the team works together effectively
	Team / collective orientation	Common focus of the team
	Psychology safety	Feeling of security in team and decision
Cognition	Accurate / shared mental models	Common cognitive model for mission activities
	Cue-strategy associations	Triggers that provide cues to associate action
Behavior	Closed-loop communication	Communications within the team
	Team leadership	Leadership roles for each crew member
	Mutual performance monitoring	Individual monitoring of team performance
	Backup / supportive behavior	Performance of the individual that benefits the team
	Conflict management	Management of disputes within team
	Mission analysis	Individual, collective analysis of desired outcomes
	Team adaptation	Ability of team unit to adapt to any change

Cobb, et al. (2014), adapted from Weaver, Rosen, Salas, Baum, and King (2010)

Team Analysis Design

The Team Analysis component of our alternative FEA strategy can be conceptualized as a top-down analysis – the operational environment, crew configuration, and mission requirements are identified early in the process, followed by a deconstruction of roles, tasks, and processes that constitute mission performance. While this approach is similar to a Mission Analysis conducted with traditional task analyses, it differs in that the primary unit of analysis is team performance, rather than individual performance. This top-down approach required that a conceptual framework be established to organize and bound the information for our analyses. Based largely on information provided by AMD subject matter experts; our framework was bounded by a focus on Air Battle Management (ABM) performance. Figure 3, following, is a detail of the Team Analysis shown previously in Figure 2.

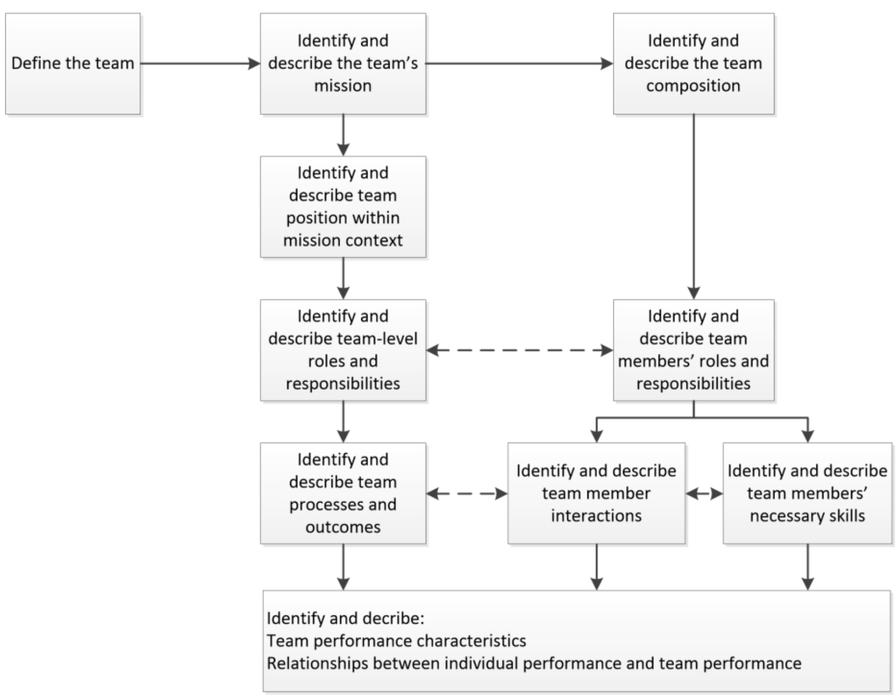

FIGURE 3. TEAM ANALYSIS COMPONENT OF ALTERNATIVE FEA

In our team analysis design illustrated in Figure 3 (Drzymala, et al., 2015), team analysis is process and function oriented, and examines the relationships between individual and team performance. In this research effort, the functions, inputs, and outputs of team requirements were identified, constructed, and compared to each crew role and interdependencies within the crew-based system. Interdependencies were examined to identify communication and coordination processes and requirements within the crew as well as between the crew and other command echelons.

As shown in Figure 3, the first step is to define the team. While this may seem obvious, consider that the team definition establishes the scope of the analysis, and in turn, frames its results. The team can be as small as a two-person crew that must work in concert, or as large as a multi-theater group of agencies that are required to perform collectively and collaboratively. The defined team should directly reflect the purpose and scope of the analysis.

Questions guiding the team analysis were oriented around teamwork and team performance during ABM mission performance, including operational context, environment, team composition and processes, and individual and collective task management, and coordination requirements. The following questions were organized to begin with larger issues, such as describing the mission, then subsequently followed with more specific questions to gather information about specific interactions during performance and details about what defined those interactions.

1. Describe the team's mission.
2. Identify and describe the crew composition.
3. Describe the team's position and mission relationships in respect to higher and lower echelons.
4. Describe the team's mission requirements and processes. (Use follow-up questions).
    a. Identify and describe key events/moments (e.g., milestones) during each phase.
    b. Using the defined mission requirements, identify crew member tasks and responsibilities. (Use more follow-up questions to gather details with greater specificity).
        i. Describe each crew member's responsibilities during each mission phase.
        ii. Describe what each crew member does to accomplish/reach each milestone.
        iii. What are the knowledge, skills, and abilities each crew member needs to accomplish their job?
        iv. What are the crew leaders' responsibilities during each mission phase?

Crew level processes were distinguished from individual tasks and requirements using team-focused questions, such as:

1. Describe what the crew does to accomplish each milestone.
2. Describe how the crew interacts during each phase.
3. Who coordinates crew interactions?
4. Does another team member step in to assist or question what is happening?

Additionally, more focused questions were asked to gather information pertaining to specific topics or issues, such as:

1. What are the risks during each mission phase?
2. How are risks mitigated?
3. How are errors detected?
4. How are errors corrected?

As described earlier, in the use case application of our FEA strategy to an existing AMD system, we focused on crews predominately responsible for air battle management. Subsequently, fire control crews were the subject of our use case application to an emerging multisystem architecture to set boundary conditions that paralleled those in the previous use case application. Our design employed open-ended questions to allow interviewees to describe functions and processes from their own mission experiences. This approach allowed the subject matter experts to use their experience to provide detailed information about the mission, the requirements, and their performance, without being limited by our team's preconceived ideas or performance expectations.

The Expertise Analysis

Training to expert performance has a long history in performance-based activities (e.g., sports, dance), and is applied increasingly to other domains (see Erikson, 2006, for a comprehensive discussion). Chi (2006) proposed a proficiency scale (novice, initiate, apprentice, journeyman, expert, and master) directly relevant to military training. Expertise can be viewed as a learning process characterized as an active problem solving process in a specific context (Valkeavaara, 1999). Expertise is not related to the amount of experience in the domain, but rather the amount of deliberate effort and practice applied to improve performance (van Gog, Erikson, Rikers, & Paas, 2005).

Expertise Analysis Background

Kozlowski (1998) identified different types of expertise and differentiated routine expertise from adaptive expertise. According to Kozlowski, routine expertise is effective in well-defined predictable situations, and can be achieved through the learning and rehearsal of routine tasks. Adaptive expertise, on the other hand, is necessary for more ambiguous, unpredictable situations. Adaptive expertise requires problem solving and adaptation of previously learned skills, knowledge, and experiences to achieve successful task outcomes. Following this model, expertise, situation predictability, and task requirements all lie in a corresponding continuum, as illustrated in Figure 4.

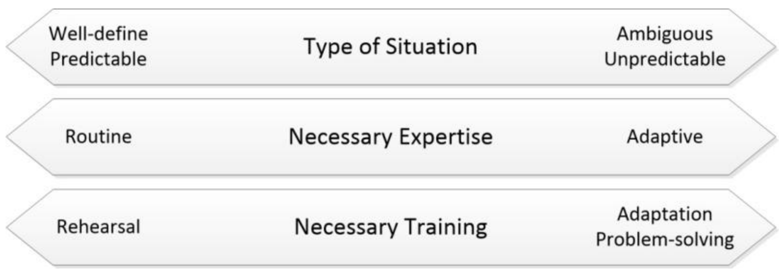

FIGURE 4. SITUATION PREDICTABILITY, EXPERTISE, AND TRAINING CONTINUUM

According to Valkeavaara (1999), a better understanding of expertise in the field can be achieved by taking a closer look at problematic situations encountered by experts in the field, or those lying toward the right side of the continuum illustrated in Figure 4. Considered within the FEA context, these are the situations most dependent on decision-making and problem solving, where established (and trained) performance requirements may not be sufficient for mission success. With this in mind, the expertise portion of our alternative FEA focused on the type of knowledge gained from problematic encounters, the knowledge base needed to place operators in a position to resolve and learn from those situations, and how that knowledge translates to performance.

Expertise Analysis Design

A lack of attention to expertise requirements in traditional FEAs may be due to the expectation that expertise is achieved through field experience and on-the-job training, two things that do not often fall within the realm of a training requirements analysis. Our intent by incorporating expertise analysis within an FEA is not to determine how to train to expert levels, but rather how training can be used to enable faster or more efficient expertise development.

The expertise analysis component of our alternative FEA strategy identified characteristics of expert performance and provided an understanding of how expertise was developed (e.g. through training, experience, or other means). Research questions that drove our expertise analyses included:

1. What differentiates expert performance from qualified performance?
2. What are characteristics of experts?
   i. What are the skills that experts demonstrate?
   ii. What are the capabilities that an expert possesses?
   iii. How would you describe an expert's understanding of (the particular aspect of the system)?
3. How did you develop your expertise?
   i. How would you describe what you did to develop expertise in (the particular aspect of the system)?
4. How does expertise decline?
   i. What aspects decline and at what rate relative to others?

Expert operators were sought out to inform our expertise analysis. Experts, for this research effort, were defined as operators with experience in deployed and/or mission theaters. In addition to providing first hand data based on their own experiences and performance, these experts are also able to reflect on the progression of their experience and identify salient aspects of training or experience that transitioned them from novice to qualified operator to expert operator.

Somewhat unexpectedly, we found data from non-experts (operators with limited operational experience) to also be valuable in identifying expertise requirements. While non-experts could not comment on their own expertise, they provided detailed information about their own performance and learning challenges. Non-experts typically identified skills and characteristics of experts to emulate for their own development, and indicated that expert performance demonstrations had highlighted areas that they were struggling to develop. Non-expert data, on its own, would not have been sufficient for our expertise analysis. Combined with experts' data, however, it provided an opportunity to triangulate data from multiple perspectives as illustrated in Figure 5.

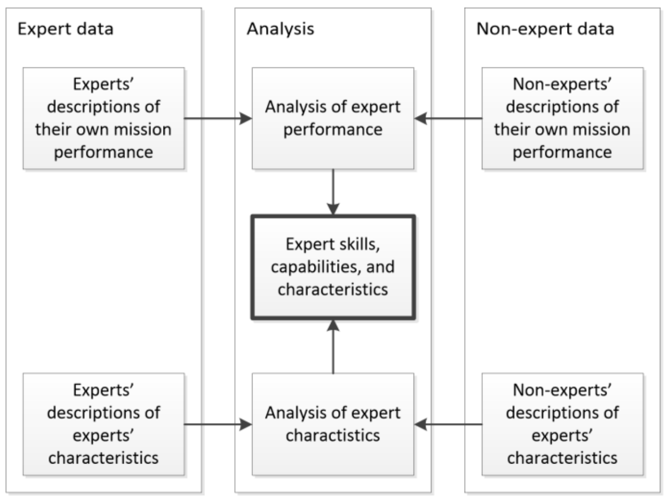

FIGURE 5. TRIANGULATING EXPERTISE ANALYSIS DATA

Our expertise analysis focused on data pertaining to complex, difficult, and/or ambiguous situations encountered in the mission or training environment. This orientation was taken in the expectation that adaptive, rather than routine, expertise would be most informative in differentiating expert and non-expert performance. The research team assumed there was little performance difference between qualified and expert performance during routine tasks. On the other hand, it was expected that expert operators would be more skilled at responding to ambiguous situations than their less accomplished counterparts. Our interview questions, then, were designed to understand the nature of such events and how individuals subsequently learned from them, as illustrated by the following sample questions.

- Identify and describe an unpredictable event you encountered during operations.
  - How was the event identified?
  - How was the event handled and resolved?
  - What knowledge and/or skill did you require to handle/resolve the event?
- If unpredictable events cannot be identified by the interviews, a similar line of questioning may be followed using events characterized as "difficult" or "unusual" rather than unpredictable.

This questioning yielded information about the types of situations, the types of solutions sought or attempted, and the type of knowledge and skills gained from these experiences. The type of knowledge gained from problematic encounters, and what knowledge base was needed to place operators in a position to resolve and learn from problematic situations is important to determine salient aspects of training or experience that facilitated the accumulation of new and advanced knowledge or skills.

RESULTS

The use case applications to an existing task-based designed AMD training program and the emerging requirements of a new multisystem architecture provided a number of insights into the utility of our alternative FEA strategy.

Research Question 1: Could an alternative FEA strategy identify requirements beyond those established for a current system using the traditional SAT approach to FEAs (i.e., already being trained)?

Given that the existing training system is the result of the defined and refined requirements for the qualification and certification of operators as determined through the application of traditional SAT methods, then any unique requirements emerging through the application of our alternative strategy could arguably be: 1) newly revealed because they were not captured by previous SAT applications; or 2) newly found because the SAT had been incorrectly/ineffectively applied previously and missed some requirements. The latter point seems unlikely since the existing training program is the result of several years of development and refinement through SAT applications.

Interestingly, the requirements we identified were not surprising to the community, rather, they were fairly well known and understood across the SMEs we interviewed. Yet, previous analyses provided no avenue to capture and define them in a manner readily translatable to actual training programs and requirements. Most significant in our findings was an apparent lack of formal training in key team skills, such as crew resource management and situational awareness. Teamwork training appeared to be a by-product of repeated exercise activities that required team members to work together to meet mission (and evaluation) goals. This is not to say that teamwork skills are not being developed (they are) but suggests they are not being developed as efficaciously as possible. Our alternative FEA indicated that these skills required focused, tailored training and measures in order to be sufficiently developed, evaluated, and refined across a wide range of crewmembers and instructors.

Research Question 2: Could an alternative FEA strategy render recommendations for adjusting training progression to enhance expertise development?

While indirectly inferred in previous SAT analyses with its reliance on well defined, easily measured task performance standards, our FEAs showed that greater consideration needed to be given to the mechanisms defining expertise earlier in operators' training progression. An in-depth understanding of and the ability to apply system knowledge in a wide range of contexts was seen by interviewed SMEs as some of the primary hallmarks of an expert. These findings relate to the previously cited work by Hawley (2007) regarding automation bias. Much as the SMEs in our FEA pointed out, Hawley points out that operators' lack of understanding about how the system works limits their ability to identify and react to faulty data. In other words, a lack of system knowledge contributes to automation bias which hinders effective decision making...one of the hallmarks of recognized expertise.

Currently, operators gain knowledge and develop their expertise primarily through direct experience, peer (or near peer) coaching, and informal self-directed study and training. Employing expertise analysis methods showed that current evaluations are performance based without consistent assessment of the depth and scope of crewmembers' understanding. Consequently, operators can pass evaluations and certifications without truly knowing or understanding the "why's" behind their actions. Reconstructing training programs to emphasize system knowledge and understanding of how actions impact system operations provides a sounder foundation and context for subsequent training and expertise development. Our analyses also indicate that understanding how the system fits within and impacts the context of the larger mission will increase conceptualization of the system as a tool to perform the mission, rather than viewing successful system operations as the mission itself.

Research Question 3: Could the FEA prove flexible enough for analysis of both established and emerging systems?

One problem inherent in any emerging system is its lack of use in an operational environment. Consequently, operational procedures and documentation may not be fully tested and personnel experienced in using the system may not be available. Both situations were true of the selected emerging multisystem architecture, and we found ourselves lacking sufficient data sources to conduct a complete team or expertise analysis for the alternative FEA.

Consequently, research on the emerging system examined during the third and final phase of our effort relied heavily on system documentation, emerging test outcomes, and findings from the analyses conducted for Phase II of our effort. Phase II findings provided a baseline for like roles and functions and allowed us to extrapolate to the emerging systems. The system documentation we relied on included a user manual developed by the system developer, capability documentation, and evolving operational task lists. All were living documents and subject to revision during our research. The capability documentation contained proposed mission aspects, and functions and responsibility areas of the team members included in the analysis. For the most part, this information provided a framework for understanding the draft tasks provided by the operational task lists. Interviews with personnel familiar with and directly involved in the emerging system design and development were used to provide context for the information in the documentation and to address specific questions regarding evolving system implementation and projected task/role allocations.

To address the lack of experienced operators, we used archival data collected during the previous phase to leverage relevant findings on similar requirements between existing system air battle management requirements and issues and projected system fire control tasks and requirements. While actual relevance cannot be confirmed until Soldiers begin applying the emerging system to the air defense mission, during operations and in test simulations, this adjustment seemed to provide the flexibility needed to inform emerging system training requirements and designs.

FUTURE APPLICATIONS OF THE ALTERNATIVE FEA STRATEGY

The system context should be carefully considered when determining whether the alternative approach explored in this research effort should be used for a future FEA. It is important to remember that this alternative builds upon a traditional task-based analysis foundation. In the case of a new or evolving system, the FEA must remain flexible enough to adapt to changes in defined roles, tasks, and responsibilities. The utility of the team analysis component is self-evident – as it is only meaningful when a team, crew, or other defined collective is an appropriate unit of analysis and performance. However, a key consideration is not to underestimate the degree to which actual operational success depends upon collective interactions and collaborative efforts between multiple actors or agencies. In the case of the expertise analysis, one clear factor is the availability of subject matter experts to provide first-hand information and assessments based on their own proven experience or performance. Secondly, a focused, detailed expertise analysis is probably most useful in cases where adaptive expertise is required for successful performance. For routine expertise requirements, the necessary time investment for this type of analysis would probably not yield sufficient benefits (i.e., new information) to justify its use beyond relying on the outcomes from a well designed task analysis.

Consequently, our research demonstrated that much is to be gained by applying this alternative FEA strategy to existing systems and training programs. However, this approach is also recommended for emerging systems provided that:

a) a similar system can be used to inform the expertise and team analyses; OR
b) in the absence of a similar system, after a traditional task-based analysis has adequately defined critical positions, roles, functions, and performance standards and an initial pool of training experience has been developed among system designers and/or simulation and test outcomes; AND
c) the FEA focuses first on team dynamics and processes with the expertise analysis delayed until a foundational cadre of personnel have developed at least a functional expertise with the systems' requirements through simulators, operational tests, and functional assessments.

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