Augmenting Team Cognition in Human-Automation Teams Performing in Complex Operational Environments

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There is a growing reliance on automation (e.g., intelligent agents, semi-autonomous robotic systems) to effectively execute increasingly cognitively complex tasks. Successful team performance for such tasks has become even more dependent on team cognition, addressing both human-human and human-automation teams. Team cognition can be viewed as the binding mechanism that produces coordinated behavior within experienced teams, emerging from the interplay between each team member's individual cognition and team process behaviors (e.g., coordination, communication). In order to better understand team cognition in human-automation teams, team performance models need to address issues surrounding the effect of human-agent and human-robot interaction on critical team processes such as coordination and communication. Toward this end, we present a preliminary theoretical framework illustrating how the design and implementation of automation technology may influence team cognition and team coordination in complex operational environments. Integrating constructs from organizational and cognitive science, our proposed framework outlines how information exchange and updating between humans and automation technology may affect lower-level (e.g., working memory) and higher-level (e.g., sense making) cognitive processes as well as teams' higher-order "metacognitive" processes (e.g., performance monitoring). Issues surrounding human-automation interaction are discussed and implications are presented within the context of designing automation technology to improve task performance in human-automation teams.

Keywords: automation technology, human-automation interaction, intelligent agents, semi-autonomous robots, team coordination, cognitive processes, metacognitive processes.

TECHNOLOGICAL advances have significantly intensified the challenges facing teams performing in today's complex operational environments (e.g., nuclear power plants, military battlefield, long-duration spaceflight). This has led to a growing reliance on automation (including intelligent agents and semi-autonomous robotic systems) to support and enhance performance of increasingly complex cognitive tasks. Successful team performance requires a focus on team cognition, addressing the contexts of both human-human and human-automation teams. Team cognition can be viewed as the binding mechanism that produces coordinated behavior within experienced teams, emerging from the interplay between each team member's individual cognition and team process behaviors (e.g., communication, coordination) (3,6,14). Team cognition supports both team processes (e.g., communication exchange of team-relevant knowledge) and team products (e.g., shared mental models, task completion outcomes) (14). Past research has emphasized the importance of enhancing human-human interaction to improve team coordination and communication. More recently, issues surrounding the effect of human-agent and human-robot interaction on team performance have generated a great deal of interest. Thus, any comprehensive model of team cognition needs to support human-automation as well as human-human team dynamics.

Integrating constructs from organizational and cognitive science, we present a preliminary theoretical framework illustrating how the design and implementation of automation technology may influence team cognition and team coordination in complex operational environments. Specifically, our framework outlines how information exchange and updating between humans and automation technology may affect a team's lower-level (e.g., attention) and higher-level (e.g., shared situation awareness) cognitive processes, as well as the team's higher-order "metacognitive" processes (e.g., performance regulation). In this paper, we first distinguish our framework from existing team performance models. We then discuss issues and implications surrounding human-automation interaction, followed by recommendations for designing automation technology to promote coordination in human-automation teams.

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Theoretical Approaches to Team Performance

Several models and theories have been proposed over the last few decades to describe the underlying mechanisms for effective team performance. We argue that our theoretical framework adds a unique contribution to this body of research in that we propose a more integrative approach with respect to human-automation collaborative processes. Rather than attending to only team processes or considering only certain cognitive processes, we suggest how design can better focus on team cognition, that is, the manifestation of cognition during the collaborative process. For example, the Team Effectiveness Model (TEM) is a widely cited descriptive model used to characterize a set of team related inputs, processes, and outcomes (29). Although this model attends to task characteristics and, to some degree, individual characteristics, TEM does not adequately capture the types of cognitive processes occurring in complex teamwork that we suggest may be supported with automation.

More recently, within the fields of cognitive engineering and collaborative problem solving, theories espousing what is termed 'macrocognition' have been proposed. For example, Klein et al. (19) argue that contextually bound cognitive processes (e.g., sense making, uncertainty management) must be studied in natural settings. According to this approach, these are the environments in which complex and emergent cognitive processes arise (i.e., macrocognitive processes), as opposed to what are termed "micro-cognitive processes", described as cognition investigated in laboratory studies of, for example, solving puzzles. The Klein et al. notion of macrocognition does not necessarily pertain to teams. Nonetheless, others have recently developed the concept of macrocognition as a term to capture cognition in collaborative contexts. In their theoretical analysis of collaborative problem solving, Warner, Letsky, and Cowen (32) argue that macrocognition encompasses both internalized and externalized processes occurring during team interaction. These processes include not only internalized individual processes such as mental model development, but also externalized processes such as goal definition and alternative solution negotiation. These are used by teams in complex environments where collaborative problem solving focuses on one-of-a-kind situations (e.g., noncombatant evacuation operations).

While acknowledging the value of these differing theoretical approaches, our framework integrates not only lower- and higher-level cognitive processes along with team process behaviors, it also considers the potential mitigating effects of task stressors. By taking this broader perspective, we are able to offer more prescriptive guidance to the specific areas of teamwork that are more readily targeted with automation technology. Before more fully specifying the essential elements of our theoretical framework, however, we first review several issues that influence the successful interaction between humans and automation.

Issues Surrounding Human-Automation Interaction

For the purposes of this paper, we define a human-automation team as the dynamic, interdependent coupling between one or more human operators and one or more automated systems requiring collaboration and coordination to achieve successful task completion. "Automation" and "agent" technology include a broad range of systems designed to support human operators during task performance. For example, aviation pilot performance is facilitated through the use of computer-based intelligent decision-support aids integrated within a larger system, such as the flight management system found on today's highly advanced aircraft. Similarly, the prevalence of unmanned radio-controlled robotic ground, air, and underwater vehicles has increased dramatically in recent years, particularly in military and rescue operations. The purpose of such unmanned vehicles is not human transportation, but rather risk mitigation, allowing operators to execute complex or dangerous tasks by remotely controlling the actions of the robotic vehicles (11).

In complex task environments, levels of automation (i.e., the degree to which control is allocated to the human operator or the automation) vary considerably from full manual control of the system (no automation) to supervisory control (human operator monitors automation) to full automation (no operator input) (8). To illustrate, before the introduction of automation, the pilot fully controlled the aircraft through manipulation of the throttle, ailerons, elevator, and rudder to maintain the desired airspeed, altitude, and heading. With the transition from the traditional analogue "stick-and-rudder" cockpit to the highly automated digital "fly by-wire" flight deck, the pilot no longer flies the aircraft, but rather controls the aircraft indirectly through instructions to the automation. The role of the pilot has changed from active controller to passive system supervisor, intervening only during takeoff and landing or in the event of an automation failure (18). During the cruise phase of normal flight operations, the pilot often transfers full control of the aircraft to the auto-pilot, thereby transforming the automation into a vital nonhuman member of the flight crew.

The focus of this paper is on intermediate levels of automation, where one or more human operators work to control and coordinate the efforts of multiple autonomous systems. These intermediate levels of automation include human-computer interaction technologies such as operator decision support systems and human-monitored artificial intelligence agents. Human supervisory control of semi-autonomous robotic systems, such as unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs), are additional examples of this intermediate level of automation. Although the use of automation offers several unique advantages for safe and effective task performance, numerous issues still remain regarding how to promote optimal human-automation interaction.

The interaction between human operators and advanced automation technology is influenced by a wide range of psychological, cognitive, social, affective, situational, and system design factors (12,16). Automation characteristics such as level of automation, automation reliability (both actual and perceived), automation consistency, automation processing transparency (i.e., providing the rationale behind automation judgments), and feedback on performance all influence automation usage decisions. From a socio-cognitive perspective, human operators' trust in automation dictates their subsequent reliance on automated systems, ranging from the extremes of over-reliance and complacency to under-reliance and mistrust of automated systems (20,23). Appropriate calibration of trust in automation can be addressed through adequate training regarding the automation's functional capabilities (e.g., reliability) and limitations (e.g., effects of contextual factors) as well as through appropriate system display design (i.e., information presentation in terms of content and format) (20).

However, accurate mental models that lie at the base of the trust equation take time to develop. These models have a lagged influence from operators' background, prior experience with automated systems, operator biases (e.g., automation bias, self-serving bias), and their naive beliefs about automation. This problem is compounded by system design factors resulting in opaque indications of the automation's status and behavior, in that the system provides limited feedback to operators on its past, current, and future actions. System designers may make assumptions about the capabilities of either the human or automated system that are incorporated into the automation design, and do not reflect the actual interaction processes that occur during execution of critical task scenarios. As a result, automation processing can continue without providing operators with useful information about how design assumptions are affecting system status, or what responses are available to the operator. Such barriers to automation processing transparency may potentially result in an "out-of-the-loop performance problem". Automation surprises, poor situation awareness, and leaving operators ill-equipped to assume manual control in the event of an automation failure are frequent outcomes of out-of-the-loop operators (9,12,26). Automation opaqueness, in fact, increases the operator's development of inaccurate or naive system models, increasing the disconnect between the operator and automation.

In addition, as robotic systems have become more complex, increasing levels of computing sophistication and human-robot interaction information flow are required to enable task performance. Especially in the development of unmanned vehicles (UV), complexity has resulted in systems with multiple operators required to coordinate the control of a single vehicle. Interface design improvements can reduce the number of operators per UV, but at significant cognitive costs to the operator(s). Even with simpler UVs, operators are called on to individually control larger numbers of autonomous UVs in swarms, and coordinate their swarms with those of other human operators. In both cases (group control of UV and coordinated control of UV swarms), a lack of attention for group-level interface design and human-human information flow can lead to degradations in required coordination between operators managing multiple robotic devices. Changes in both the function allocation model and the nature of task differentiation between human operators and UAV/UGV systems could significantly alter the cognitive loads of the humans called on to manage these teams. For instance, as operator control extends to a number of vehicles, their role may shift from controlling specific subsystems of a number of vehicles (e.g., forward-looking visuals and radar) to controlling a specific function of the whole swarm (e.g., managing neighbor awareness for all vehicles).

The introduction of "adaptive" automation, involving dynamic task allocation in response to operator workload and task demands, has further increased the complexity of automated systems and, therefore, led to greater complexity in the operators' formation of accurate mental models (27). The relationship between the operator and the automated system has become truly interdependent, and can in fact increase (rather than decrease) the situation awareness demands on the human operator. Not only do operators need to understand how the automated system operates, but now they must also have a complete understanding of their own behavior, how their behavior affects the system, and how the system reacts to their own and other operators' inputs.

Requirements for Supporting Human-Automation Teams

Fig. 1 illustrates how augmenting human-automation team cognition involves understanding how task-related factors interact with team members' cognitive and metacognitive processes to influence critical team behaviors. In defining the relation among the concepts within our framework, our first goal is to illustrate the mitigating effects of stressors on cognitive processes (first arrow linking task stressors to cognitive processes). Although a long line of research has documented how stress affects performance, we more specifically articulate particular cognitive processes attenuated by stress and which are well-suited for agent-based aiding. These range from human memory limitations to higher-level monitoring processes (metacognition). Our second goal is to illustrate the relation of these team cognitive processes to team behaviors (second arrow linking cognitive and metacognitive processes to critical team behaviors). The cognitive processes we identify directly support the team interaction behaviors we suggest are most critical in complex environments. Thus, unlike models such as the TEM (29), we link cognitive processes to team processes such as adaptability. In short, by specifying a practical set of cognitive processes emerging within complex teamwork environments and showing their relation to team behaviors, we illustrate where automation may most efficaciously support team cognition.

When designed appropriately, human-centered automation technology can effectively mitigate the detrimental effects of operational stressors (including time pressure, workload, and task ambiguity) by supporting the critical cognitive constructs underlying team cognition. Potential cognitive enhancements include, but are

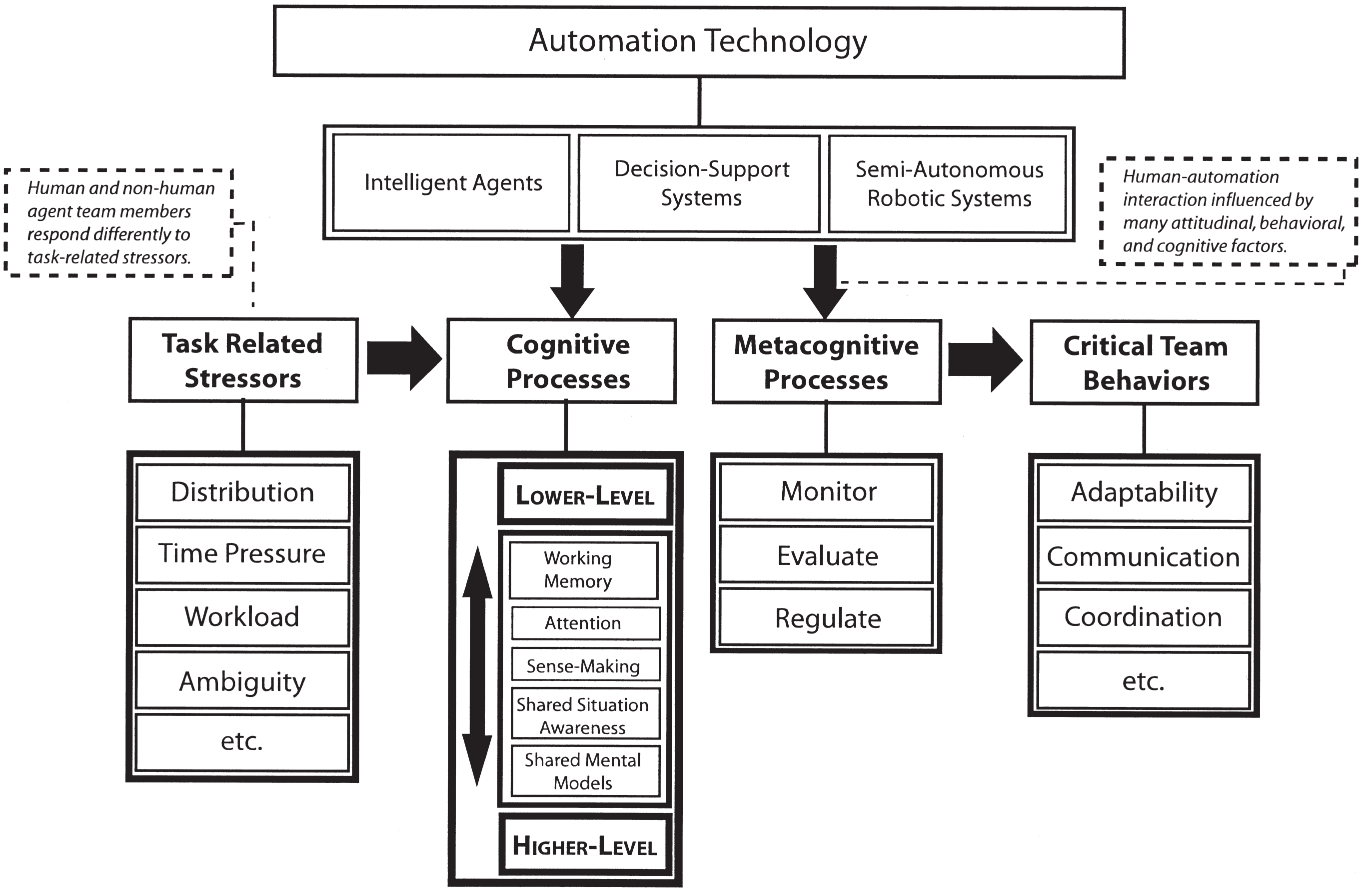

Fig. 1. Theoretical framework for augmenting team cognition with automation technology.

not limited to: increasing the scope and duration of attention and processing of the task environment; reducing the cognitive load on working memory and attention; supporting prospective and retrospective memory; and facilitating sense making and the development of shared mental models and shared situation awareness. Improving human-automation teams' ability to monitor, evaluate, and regulate their human and non-human team members' performance is especially valuable with respect to changing task requirements and goal states in complex task environments.

Adaptive intelligent agents and decision support systems can alleviate problems of information overload in several ways. These systems (when well designed) enable implicit and explicit knowledge sharing and improve information visualization by increasing the saliency of important information while decreasing the distractions caused by irrelevant information (30). Well-designed automation technology facilitates awareness of shared workspaces and provides access to distributed expertise (17,19,30), thus improving distributed collaborative task performance. Specifically, distributed team members share knowledge and understanding of the world based on varying levels of expertise in a variety of specialized domains, interactions with distinct or overlapping system components, and availability of shared as well as individual information. These distinct capabilities can be thought of as multiple dimensions of expertise, and not simply different levels of expertise in a single subject matter area (4). Thus, automation technology can support knowledge management and information flow to ensure that team members have timely and ready access to the distributed expertise of their team (11).

Intelligent agents can also be used to augment team members' memory processes with regard to retrospective memory (recalling information already stored) and prospective memory (cues to enhance remembering to engage in a certain activity in the future) (13). Most members of organizations already use basic aspects of agent features through "to do" lists and calendar alerts. Task and calendar agents mitigate prospective memory failures (forgetting to do something) by monitoring task execution and providing alerts, as needed, to remind operators to perform a scheduled task at the appropriate time. Similarly, retrospective memory failures (forgetting something one knows) are reduced by using journals and documentation that provides easier access to critical task-relevant information. Sharing these document artifacts with team members ensures improved knowledge management and information sharing.

A broader goal of human-centered automation technology is to formulate higher-level cognitive processes such as shared mental models, sense making, and shared situation awareness. Shared mental models refer to the knowledge structures teams possess about team member functions and the task environment (5). Teams draw on their shared mental models to coordinate their actions and adapt their behaviors to changing demands of the task and other team members. This coordination and sharing enables them to shift from explicit to implicit coordination, as needed, to decrease communication and coordination overhead (5,10,21). Sense making involves the process of information gathering, transformation, analysis, interpretation, and recognition of the implications of the information or query received (33). Sense making thus serves as a transformation from data to knowledge about task requirements, and is a necessary precursor to effective task performance (3). Similarly, shared situation awareness involves the degree to which team members perceive, comprehend, and interpret the information requirements of the situation and criteria for successful performance (1).

Automation technology can also enrich a team's ability to monitor, evaluate, and regulate the actions taken by both their human and non-human team members. Effective performance monitoring, such as for semi-autonomous robotic systems (24), has direct implications for adaptive function allocation of tasks between humans and automated systems. Adaptive function allocation, in its most general form, would allow the automated system to provide more or less information and decision control to the human operator(s) based on the current cognitive state and task load of the operator(s). The decision as to when, for example, a robot independently executes a task or waits for the human to exert direct control over task performance would be a function of the adequacy of the human and automation models of the operator's and robot's previous, current, and future task performance. Thus, an important role of these non-human team members is to aid their human counterparts by:

- maintaining awareness of member actions and status;
- updating team members regarding important changes in within-team and external information (without diverting their attention away from the central tasks);
- monitoring intra- and inter-team communications;
- tracking task execution and completion and progress toward achievement of the team's goals; and
- providing timely feedback on performance and guidance on correcting team errors (2,16,17,28).

As suggested by our theoretical framework, design considerations to ensure that automation technology effectively supports team performance will be discussed in more detail in the next section.

Design Considerations for Augmenting Human-Automation Team Performance

A critical question during the design process involves determining which information human-automation teams use to perform a given task or how the presence of non-human team members may hinder coordination efforts. Coordination may be impaired because of the difficulty associated with conveying and processing critical task-relevant information due to a lack of understanding of automation team members' roles and functional capabilities and limitations (11). Human operators use different criteria to evaluate incoming information depending on whether the source of the information is a human operator or an automated agent. Incomplete information from a sensor may be perceived as unreliable, but incomplete information from a human may still be perceived as credible.

An additional challenge when combining human and non-human team members is that humans develop a variety of responses to time pressure, including both "macrostrategy" and "microstrategy" responses. Macrostrategies include developing shifting cost/benefit ratios, quicker rejection of options that fail to meet critical performance criteria, or interim task solutions. Microstrategies can be linked to more fundamental cognitive processes, including filtering, omission, and acceleration responses to information overload (22). Among the skills attributed to experts when dealing with such stressors are improved capacities to recognize and prioritize tasks within time constraints, and recognize which tasks are most critical to complete based on shifting performance demands and situation constraints. For example, in complex, evolving task scenarios such as space mission operations, flight controllers learn to adapt to multiple time scales affecting current operations and strategic goals, and even incorporate time delays from multiple sources (3). Current generations of robotic and software agents do not commonly adopt shifting strategies for dealing with time constraints, and, therefore, can induce performance asymmetries or breakdowns when attempting to coordinate with humans. Research indicates that human operators do shift their expectations for acceptable delays based on task difficulty and urgency, regardless of whether the coordination partner is believed to be a human or software agent (31).

Similarly, when operators are faced with a high criticality, short time line task, they may decide to stabilize the situation in order to resolve it later, rather than try to solve it all at once. In other words, task performance is focused on spending resources now to extend the deadline. In responding to a time critical task, an operator evaluating available resources may decide to only slow down the rate of situation degradation (and thus extend the time available for performance), rather than complete the task. In most cases, software agents are extremely poor at recognizing that some tasks do not need to be solved immediately and that one can instead work toward stabilizing the situation so that tasks can be resolved later.

Further, advances in automation technology have increased the level of complexity in human-automation interactions such that human operators can now interact with automated systems, such as intelligent agents and semi-autonomous robots, in a distributed manner, separated by both space and time. In a number of contexts, the human and automated system (e.g., unmanned vehicle) are geographically separated, but share a common operating picture through the use of technology. Successful performance of these human-automation teams are significantly influenced by numerous factors including task characteristics (time pressure, workload, number of vehicles controlled), vehicle characteristics (air, ground, underwater), environmental characteristics (terrain quality, obstacles, time of day, weather), and technological constraints (available bandwidth, communication delays, visual display characteristics). Overall system capabilities must be maintained to provide team members information, using available information pathways, relevant to team members (human or agent) activities, ongoing task projects, required resources, and task outputs (16). A related issue involves the influence of the scale of team and task variables that the automation must support. Specifically, automation design considerations for supporting individual level and small team (e.g., aircraft cockpit crew) performance differ from the more complex requirements of large teams (e.g., space mission control).

At the individual level, the focus of automation includes enhancing display design to support information presentation and integration as well as monitoring the performance of the automation. Within the context of unmanned robotic systems, for example, design considerations differ depending on whether a human operator is managing one function across multiple robotic vehicles or managing multiple functions across a smaller set of robots. In the first case, the focus is on maintaining awareness of the status and location of different vehicles. The second case critically depends on dynamic task switching among different functions, and inherently may result in greater cognitive workload for the operator. Thus, the design specifications of automated decision support aids will differ according to the unique needs of the human operator in each situation.

At the small team level, team members each have different information requirements, but must also be supported by automation that helps maintain effective communication and sharing of this information across the different positions. For example, in previous work, we generated design concepts for developing an integrated decision support display suite (Synergy) to support shared situation awareness and collaborative planning and execution processes in Army Brigade Command and Control operations (7,25). The Synergy display suite, at present, is aimed at supporting three command staff positions: intelligence, operations, and logistics, with multiple displays for each officer. However, the Synergy display suite is also designed to explicitly support the transmission of critical situation awareness requirements across positions within distributed command and control operations in a mobile battlefield (7,25). The specific design goals for the Synergy displays included:

- facilitating direct presentation of high level situation awareness elements to support situation assessment, comprehension, and projection;
- supporting dynamic switching between goal-driven and data-driven processing;
- managing data overload and avoiding the inclusion of extraneous information;
- providing mechanisms for gaining a historical perspective;
- providing features that support the global situation awareness of Army battle planners; and
- supporting team communications and shared situation awareness among the dispersed planners.

In large teams often consisting of teams of teams, team members are typically separated by space and time, making the need for effective collaboration even more critical. For example, given the task demands and system dynamics of NASA Mission Control Center operations, it is impossible for a unitary centralized command and control structure to effectively perform the required tasks to achieve mission success (3). Multiple ground personnel (e.g., mission control operators, research scientists, and other space mission support personnel) must communicate information and coordinate their efforts, not only among each other but with the astronaut crewmembers in space. Thus, automation design considerations for such complex distributed communication and coordination operations include the implementation of automated information and communication technology to support effective information flow. “Effective” is defined not only in terms of the accurate exchange of data, but more importantly, the appropriate interpretation, integration, and action based on the data being exchanged (3).

Finally, it is also important to note that human-automation team performance is influenced not only by in-process interactions, but also by pre- and post-process interactions (15). Specifically, in-process interaction occurs during actual task execution and reflects aspects of the unfolding task. Pre-process interaction involves preparatory pre-task behaviors (e.g., mission analysis), where initial shared expectations and preliminary team dynamics are created in anticipation of task-focused team interaction. Post-process interactions would include post-task reflection on performance (e.g., after-action review) and consolidation of the completed experience for future reference.

Pre-process human-automation interactions affecting trust in automation involve considering human operators’ preconceived beliefs and prior experiences with automation as well as developing pre-task training programs that present operators with information about the automated system’s functional capabilities and limitations. These factors serve as the basis for the operator’s initial mental model of the system and his/her initial level of trust in the automation. In-process human-automation interactions would be influenced by human operators’ active use (or disuse) of the automation, and should be supported with appropriate system display design features that provide operators with information about the automated system’s current status and future actions. Of particular value during human-automation in-process interaction would be the implementation of useful tools designed to increase “other awareness” or “state projection” of the non-human team member, so that the human operator could understand what the future state of the system would be under various levels of automation. Post-process human-automation interactions would involve giving feedback on performance to human operators regarding the reliability and accuracy of both the human user and the automated system following task execution. This information would aid human operators in updating their mental model of the system and also in calibrating their trust in the automation.

Future Development of Theoretical Framework

Numerous other attitudinal, behavioral, and cognitive factors not discussed in this paper may also affect human-automation interaction. Such factors include human and non-human team members' ability to gauge the "intent" of their teammate, make accurate "inferences" to remedy gaps in their knowledge, and make "attributions" of their teammates' capabilities and competence (12). Further research in this area is clearly warranted to better understand the cognitive and metacognitive processes emerging within human-automation teams in order to develop the appropriate training and system design interventions for augmenting team cognition. Toward this end, our current and future work is aimed at empirically investigating the links specified in our preliminary theoretical framework. Our research objectives are: first, to identify the factors influencing automation usage decisions in complex operational environments; and second, to identify the potential for agent detection or assessment of human team members' attitudes and responses to automation.

In support of our first objective, we are investigating: how automation can help humans build reliability/trust models regarding non-human team members (e.g., intelligent agents, robotic systems); how variance in automation reliability (systematic vs. random failures) may differentially influence trust and subsequent reliance on automation; and the design of decision support tools that allow humans to establish an accurate mental model of the current state, functioning, and reliability of an agent assistant with dynamic role assignments. In support of our second objective, we are developing a metacognitive model that enables agents to adjust their automation policy based on humans' automation usage behavior and are also assessing the impact of agent attempts to alter performance parameters based on human team members' attitudes and responses to automation. This line of research will result in design recommendations to enhance human-automation team performance through effective calibration of human operators' trust and appropriate reliance on automation in complex task environments.

Conclusions

Synchronization of actions in human-automation teams during time-stressed, high-workload task performance is critically dependent on the seamless and efficient coupling between human operators and automation technology. We argue that team cognition provides the binding mechanism to support human-automation team members' ability to engage in these coordinated actions. In this paper, we presented a preliminary theoretical framework illustrating how automation technology may be effectively used to augment human-automation team cognition and promote team coordination in complex operational environments by supporting the cognitive and metacognitive processes underlying team cognition. We also discussed several factors potentially influencing human-automation team cognition, drawing attention to the importance of trust in automation, the effect of automation processing transparency on operators' mental models, and differences in human and non-human team members' response to incoming information and time pressure. Additionally, we looked at these issues across differing scales of human-automation interaction. When appropriately designed and employed, automation technology holds great promise for augmenting team cognition by supporting both low- and high-level information-processing activities, and facilitating team members' ability to monitor, evaluate, and regulate their human-automation team's performance.

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