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Team Cognition as a Mechanism for Developing Collaborative and Proactive Decision Support in Remotely Piloted Aircraft Systems

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Abstract. Remotely piloted aircraft systems (RPAS) are steadily increasing in their presence and role in the Military's overall strategic operational picture. The benefits of RPAS are apparent, ranging from saving time, money, and lives. Yet, the utilization of RPAS is still very challenging in many different aspects. Teams have become a central focus of RPAS due to their many benefits. Yet, teamwork is challenging and the RPAS community must continue to attempt to understand how to support it. A specific aspect of teamwork that has proven over the years to be of paramount importance is *team cognition*. In this paper, we discuss how team cognition needs to be considered during the development of collaborative and proactive RPAS decision support. We highlight the concept of team cognition accounting for multiple perspectives, outline an integrative perspective of team cognition for the RPAS domain, and conclude by outlining multiple design objectives for utilizing team cognition as a mechanism for RPAS decision support.

Keywords: Remotely piloted aircraft systems · Teamwork · Team cognition · Collaboration · Decision support · System design

1 The Growing Importance of Teamwork Within RPAS

Over the past decade, multiple military entities have adapted their overall strategic operational picture from fighting wars with "boots on the ground" to a more technologically innovative means of utilizing Remotely Piloted Aircraft Systems (RPAS). RPAS allow the Military to conduct a wide range of activities ranging from intelligence gathering to real time operational weapons deployment. The increasing usage of RPAS has been steady, and in recent years has become a standard within multiple sectors of the Military.

The reasons for the increased presence of RPAS are abundant and often well documented. When compared to a traditional boots on the ground approach, the utilization of RPAS often saves, time, money, and lives [1]. For these reasons, we have seen the many successes owing directly to RPAS usage.

Yet, while RPAS have shown to be effective in many situations, there are still many research questions that need to be addressed. Historically speaking RPAS are relatively new. This relative newness has resulted in a myriad of challenging issues and problems throughout the growth of the platform. Specifically, in recent years, the RPAS domain

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has become increasingly collaborative. Collaboration within and across multiple RPAS teams is a beneficial aspect of recent RPAS work but with it comes significant challenges. Communication and coordination challenges, a lack of team level situational awareness, and information overload are just a few of the many potential problems stemming from increased collaboration in RPAS.

Teams are a central and critical focus and function of RPAS operations, often directing multiple different components of the overall RPAS system. The specific operation of an RPAS is dependent on interdependent and heterogeneous roles within the teams working together to provide information critical to the deployment, flight, and operational needs of the mission. Not only are teams collaborating to operate the vehicle and carry out mission objectives, they are also collaborating within a larger set of teams who may or may not be working on a similar strategic goal. The RPAS domain is a system that consists of multiple sub-systems. Often, these sub-systems are teams, and if one team or even one individual fails to perform effectively, the entire system is jeopardized.

For these reasons, we must consider how to facilitate effective teamwork within the domain of RPAS. If we fail to promote, train, and apply effective teamwork principles, the pending results can be deadly. There is a science of teamwork that can be applied to enhance team performance and teamwork occurring within the specific context of RPAS. In general, across multiple domains of work, teamwork is viewed as beneficial as long as the team members understand how to work together in an efficient, accurate, and meaningful way. These assumptions are no different in the context of RPAS. Yet, in order to produce effective teamwork, multiple considerations must be made. A specific aspect of teamwork that has proven over the years to be of paramount importance is *team cognition*. Team cognition is cognition that occurs at the team level [2]. The development of team cognition occurs during real time team level interactions where team members share relevant teamwork and taskwork knowledge resulting in a shared understanding. Team cognition is typically associated with concepts such as shared mental models, interactive team cognition, situational awareness, and transactive memory. More than 20 years of team cognition research has demonstrated that the development of team cognition has the potential to improve team effectiveness [3].

The role of team cognition within the domain of RPAS needs to be further explored and articulated. We see team cognition as being applicable to many of the collaborative problems that RPAS is currently facing. By considering team cognition as a form of interaction, as we do within the theory of Interactive Team Cognition (ITC), we can begin to postulate how to better manifest and develop it through rich meaningful team level interactions. Teamwork within the context of RPAS must instill communication and coordination at the team level. Disparate interactions that occur at the individual level and are then abstracted up the chain of command do not represent effective teamwork and fail to allow for team cognition.

In addition to specifically outlining and highlighting how team cognition can be used for better collaborative RPAS work, we will also articulate the role of team cognition in collaborative and proactive decision support for RPAS. As RPAS have become more collaborative in nature, a myriad of collaborative technologies and tools have been developed to support the increased collaboration. These technologies have often been meet with inconclusive results, with many failing to actually support the most essential collaborative activities within the RPAS mission set. In addition, many of the decision support systems that are currently being utilized are dependent on individualistic notions. RPAS decision support systems should support the individual user, but also the team as a whole (through team level interactions).

Knowing the benefits and importance of team cognition, decision support systems need to account for the role of team cognition. Similarly, we need to develop collaborative technologies that support team cognition during RPAS activities. Yet, to develop these systems and technologies we need to know what design features and objectives are critical to team cognition within the domain of RPAS. Later in the paper, we outline specific affordances that should be built within RPAS decision support to better develop team cognition. First, we begin the paper by conceptually outlining team cognition.

2 Team Cognition Within the Context of RPAS

Team cognition has long been studied within the context of teamwork and team decision-making. As teams were identified as an important facet of society, scientific research investigating them became common. Through years of research, knowledge regarding the importance of a shared understanding of both team and task related issues were acknowledged. Initially, team cognition was viewed through the psychological viewpoint of input, processing, output, where teams were viewed as actual information processing units [4]. In this sense, team cognition was the result of each individuals' cognition as it was combined together. So, the input was each individuals' cognition, the processing was the aggregation of each individuals' cognition, and the output was often referred to as a shared mental model. As the concept of team cognition has grown, an alternative perspective has developed that has moved away from team cognition being the aggregation of individuals' cognition, and rather surmises that team cognition is the actual interaction that occurs at the team level. The theory of Interactive Team Cognition (ITC) [2] further postulates that the communication and coordination occurring amongst the team is team cognition.

As the concept of team cognition has grown, multiple other conceptual areas of interest have been studied within the corpus of team cognition. Concepts such as the shared mental model [5], team situational awareness [6], and transactive memory [7] have all been directly linked to team cognition. The concept of a shared mental model will further be explained in the next section, as it is the main outlet for the shared knowledge perspective of team cognition.

2.1 The Shared Knowledge Perspective of Team Cognition

As previously noted, team cognition was initially viewed as the aggregation of individual team members' cognition. Throughout the team's life span, relevant individual knowledge is shared amongst the team resulting in shared knowledge. To this day, the shared knowledge approach is held in high regard and often what people consider when team cognition is brought up.

The primary concept aligned with the shared knowledge perspective is shared mental models. The shared mental model concept stems from the mental model concept, an individual cognitive construct that helps to explain situations and environments. More specifically, Rouse and Morris [8: pg. 96], define a mental model as a *"mechanism whereby humans generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states"*. As research on mental models expanded and teams become increasingly important, the mental model was extended to the team level, conceptualizing the *shared (or team)* mental model [9]. Shared mental models are defined as *"team members' shared understandings and mental representations of knowledge about key elements of the team's relevant environment"* [10, 11].

Initially, the shared mental model was articulated into multiple sub-models: *equipment, task, team interaction,* and *team* [12]. Each separate sub-model contained specific cognitive aspects of the overall shared mental model. Yet, these separate models brought forth unnecessary convolution, and they were eventually collapsed into a *taskwork* and *teamwork* model [13]. With this new delineation, the taskwork model encompasses much of the procedural aspects of the work the team conducts, whereas the teamwork model includes aspects of interpersonal relationship, emotion, and understanding who team members are beyond a taskwork perspective [14, 15].

In addition to being defined by the content of the model (taskwork and teamwork), shared mental models are associated by two properties: accuracy and similarity. Accuracy is defined by how close the shared mental model is to the real world, consisting of properties accurate to human behavior and complex environments [16]. Whereas, similarity is how close or similar a team members' knowledge structure is to an experts' structure [17]. Support for both accuracy and similarity have been empirically mixed in predicting an increase in team performance [5].

2.2 The Ecological Perspective of Team Cognition

Another perspective on team cognition follows from ecological psychology that positions much of cognition in the world [18, 19]. Interactive Team Cognition (ITC) [2] is one ecologically based theory of team cognition that holds that team cognition can be observed in the interactions among teammates. These interactions occur in the world and are therefore observable and are analogous to cognitive processing that occurs at the individual level, though not as observable. The think aloud procedure is, in fact, an attempt to reveal individual cognitive processes. Teams often communicate as part of their everyday work.

Positioning team cognition in the world not only makes it easier to observe, but also allows observation of dynamics in team cognition as opposed to a static knowledge structure. Another advantage of the ecological perspective is that the focus is on interaction which is inherently a team variable. Shared knowledge perspectives tend to measure team cognition at the level of the individual.

2.3 Relevant Team Cognition Work Within RPAS

The theory of Interactive Team Cognition (ITC) was developed through multiple empirical teamwork studies that occurred within the UAV-STE (Uninhibited Aerial Vehicle-Synthetic Task Environment) [20]. Below, we will briefly highlight some of the teamwork studies that have occurred within the UAV-STE.

The metric of experience has been studied within the UAV-STE setting. An experiment that brought both novice and experienced command and control teams into the lab found that the experienced teams performed better than the novice teams [21]. The interesting finding of this study is that teams that were experienced in command and control surpassed novice teams in performance but were not superior in regard to individual or shared knowledge. The performance differences between teams depended on how the team interacted.

Over multiple experiments in the UAV-STE, we have found that team skill acquisition (reflected by changes in a team performance score) follows the log-law of skill acquisition [18, 22, 23]. Essentially, as a team gains experience with the UAV-STE, their performance increases in a log-linear fashion. Team performance is typically associated with better communication and coordination, and not individual or shared knowledge. If shared knowledge does occur, it occurs early in the mission set.

In addition, the UAV-STE setting has shown the value of team training for retention and skill acquisition. Gorman et al. [24] compared three types of training, procedural (training followed a script), cross-training (team members given training of all roles-increased shared knowledge), and perturbation training (team presented with brief disruptions forcing adaptation) to better understand each training types impact on skill retention and transfer of cognitive skill. The findings indicate that the perturbation-trained teams performed better in missions that consisted of conditions requiring adaptation. In addition, the procedural trained teams were the least adaptive. Finally, the teams that were cross-trained failed to perform as the task became non-routine.

3 An Integrative Framework of Team Cognition Within RPAS

The shared knowledge perspective and ecological perspective on team cognition are both fundamentally important to defining team cognition. Yet, as identified in the previous section, most scholars subscribe to one or the other, with more adhering to the traditional shared knowledge approach. In this paper, we recommend that the ecological approach would be beneficial for the context of RPAS. The often fast-paced and dynamic tasks found within RPAS teams are better aligned to the theoretical positioning of the ecological approach. Yet, we also suggest that while utilizing the ecological approach, it would be most appropriate to also integrate and consider aspects of the shared knowledge approach. Although, we subscribe to the notion that team cognition is team level interaction, we also acknowledge that individual cognition is being shared, albeit through team interaction.

In the UAV-STE we started looking for evidence of shared mental models as relevant to performance. We found early on that taskwork and teamwork knowledge developed by Mission 1 and remained stable throughout the experiment, not further differentiating effective from ineffective teams. At the same time, we noticed that our various process measures (communication and coordination) continued to show improvement as performance improved. This general pattern of findings led to Interactive Team Cognition (ITC). The UAV-STE task is a command-and-control task as opposed to a knowledge building task and seems suited for ITC over shared mental models. We feel that the findings from the UAV-STE task are ecologically valid to real RPAS operations, hence why we recommend utilizing the ecological approach with aspects of shared knowledge being also integrated depending on the specific task.

4 Team Cognition as a Mechanism for Developing Collaborative and Proactive Decision Support in RPAS

The tasks of both AVOs (air vehicle operator) and sensor operators are becoming increasingly complex due to mission goals, but also due to collaborative responsibilities. It is simply not enough to individually perform the tasks of both jobs, rather collaboration consistent with high levels of both communication and coordination are needed. Not only must the UAV team steadily communicate amongst each other, but they often are forced to communicate with members outside the direct team to provide status updates. In response to increased collaborative efforts in this domain, the community has, in many instances, sought to develop decision support or aids that are oriented towards supporting collaborative work. This is certainly a step in right direction, but many of the collaborative decision support tools are not adequate to support the collaboration occurring within context. Much of these tools are not representative of supporting *real time* interaction via *multiple* team dynamics. In addition, decision support within RPAS takes on an individualistic flavor. The tool itself is often marketed as being collaborative, yet only provides specific support for the individual *within* the team, and rather not support of team level functions or interactions. In other words, collaborative and proactive decision support in RPAS should support the *team* at the true team level, and not the *team* as the sum of the addition of each individual's roles or actions.

Unfortunately, to this day, many decision support systems are developed with little direction from human factors. The classic tale of engineers developing a technology via their insular perspective of what they *think* is useful to the user is often still persistent in this context. Collaborative and proactive decision support systems represent a great deal of future potential, but if we ever want them to be useful to the real users, then we must continue to study the users, and in this context, the team. The teamwork that occurs during a RPAS mission is incredibly complex and it must be fully understood before we can attempt to develop support mechanisms for collaborative efforts.

One approach to attempting to help develop better collaborative and proactive RPAS decision support is to consider the theoretical distinctions of team cognition. The direct team members (AVO and sensor operator) need team cognition to effectively perform their jobs. We feel confident in saying that most RPAS decision support systems never consider the impact or benefits of team cognition. Taking into account the theory of Interactive Team Cognition, we should be able to design decision support systems, tools, and aids that allow for team level support via interaction and decision-making.

In many ways, current RPAS collaborative decision support systems take forth a shared knowledge approach of team cognition where the outputs of the system are simply an aggregate of individual team member information. This perspective to designing collaborative proactive decision support systems is simply lacking and has the potential to hinder real time teamwork. Below, we highlight specific objectives that should be considered when designing for bettering team cognition through collaborative and proactive decision support.

(1) ***Support team interaction: communication & coordination***

Team level interaction is the heart of team cognition, and our eyes into observing it take place. Through interaction we are able to see teams communicate and coordinate in real time, which is team cognition. Knowing the importance of team interaction, decision support systems that are inherently focused on collaboration must support these associated activities. These systems should support both the individual's roles and tasks, but also team level activities. Support at the team level means that all members of the team are able to observe and interact with the support in real time.

Specific examples supporting team level interaction are providing communication and coordination mechanisms that are available to be used and observed by all team members at the same time. In order for decision support to truly occur at the team level and be proactive, the support itself must become embedded within the team. Conceptually, one could even think of the support as a team member where the team member has the ability to help with communication and coordination efforts. In fact, this is what our research team is currently exploring. In recent years, we have looked at the role of a synthetic agent as a proactive member of an RPAS team [25–27]. Our most recent experiment examined the conditions of *control, synthetic,* and *experimenter*. In the control condition we investigated team performance of a three person RPAS team working on typical RPAS task problems. In the synthetic condition, the role of the AVO was taken over by a fully autonomous ACT-R based synthetic agent. Finally, in the experimenter condition, a wizard of oz study was utilized where a human experimenter acted as a synthetic agent. In this condition, the experimenter attempted to push and pull information through communication and coordination at various moments during teamwork. Essentially this condition set out to show how an expert synthetic agent (or proactive decision support tool) could help improve RPAS team performance through aiding in team level interactions.

Moving forward, more collaborative and proactive decision support RPAS systems should consider features that help the team complete activities during team level interactions, and not just the integration of separate individual team activities.

(2) ***Support individual and team work***

Designing for collaboration is tricky. The collaborative system must inherently afford the ability to collaborate in real time, but also allow for individual work to still be conducted in concert with team work. The give and take between collaborative and individual work in system design is even more important when one takes into account team cognition. As previously outlined, team cognition is dependent on team level interactions but individual cognition still plays a major role in articulating team level cognition. The implications of the relationship of team level interaction and individual cognition means that collaborative RPAS decision support systems must allow for both to simultaneously take place. From the perspective of system design and human computer interaction, this is a highly complex design due to multiple varying goals.

Historically when we have designed collaborative systems, the focus has been on collaboration with the perspective that each team member has separate tasks and the goal is to support those tasks and often abstract them to the team level. Moving forward, system design of collaborative and proactive RPAS support must support both team level interactions and also individual work and cognition. If we are to adequately help team members develop team cognition during RPAS operations, then we need systems that support team level interaction via specific team activities that are dependent on team wide communication and coordination mechanisms. Yet, we must be deft enough to also allow for the appropriate individual tasks to be supported within the larger collaborative system. If we push too much focus on collaboration of team level interactions, individual team members will not be able to complete the individual work that is important to the team's work, as well as not be able to develop the appropriate individual cognition that is relevant to team cognition.

(3) ***Support team level awareness***

Much like interaction, awareness is fundamental to team cognition. If team level awareness is not present, then the ability for team cognition to be present is significantly lessened. Yet, much like designing for the correct balance of individual vs. team work, it is also difficult to achieve a design that provides the correct amount of team level awareness. Similar to the issues outlined in the previous section, the system should allow for the correct amount of individual awareness to be supported in the system, while also affording the development of team level awareness. Developing team level awareness through system capabilities is challenging for two reasons: (1) the system must understand how much team level awareness is necessary to help develop team cognition and thus hopefully improve team performance, and (2) the system must acknowledge how to maintain awareness without disrupting both individual and team level work. It is imperative that decision support understands *when* to bring light of information to the entire team. If decision support is constantly bringing forth information that is not timely or relevant, the team's performance can be harmed. Team level awareness is helpful to developing team cognition if and only if the correct amount of awareness is acquired through the teams. Too much or too little awareness is counterproductive to teamwork and team cognition.

(4) ***Use visualizations appropriately***

Decision support is increasingly using data visualizations to aid in team level decision making. Although, these visualizations have the potential to be useful to team cognition, it is important that the visualization itself aids in team level interaction. Visualizations should be equally representative of important team level information and meaningful to all members on the team. Far too often, supposed team level visualizations are not equally helpful for the entire team, thus limiting team level understanding and cognition.

(5) ***Designing for heterogeneous and interdependent team member***

A team is a special group of people who all have interdependent and heterogeneous roles. These differing roles directly feed into the importance of team cognition. If team cognition is present, then team members have a better understanding of the scope and importance of each team members' individual role and how it aligns with the overall team's goals.

Yet, these specialized roles present a challenge to developing collaborative and proactive decision support for RPAS teams. The support must account for an equal balancing act between supporting team level interactions through various communication and coordination mechanisms (as highlighted above) and also catering to the individual team member's specific role. Thus, the decision support needs to be flexible in providing and aiding team level functions and individualized role based functions. This balancing act must be delineated on a situation by situation basis, depending on the goals and context that the decision support is oriented to.

(6) ***Account for cognitive load***

The tasks associated with RPAS teams are extremely complicated, requiring a great deal of individual and team level cognition. System design in this context must acknowledge the great deal of cognitive work required in RPAS. Systems should always account for cognitive load, but collaborative systems must pay closer attention to the additional cognitive load resulting from increased collaboration. Teamwork inherently brings forth a great deal of cognitive load as a result of having to manage both individual and team level work. The prevalence of too much cognitive load challenges the development of team cognition.

A human has limited cognitive bandwidth allowing them to process a certain amount of information within a specified amount of time. If that bandwidth is exceeded, performance drastically decreases. Unfortunately, many collaborative systems increase cognitive load through a myriad of unnecessary features. When RPAS collaborative systems are designed, they must not unnecessary stretch one's cognition- considering it is already stretched due to the dynamics of teamwork. Human factors analysis with the users must take place before, during, and after system development to fully understand what system features are necessary and actually help to aid team level interactions. If the system increases cognitive load through irrelevant and distracting features, individual team members will have trouble processing information, leading to team cognition not being present. The saying, "less is more" can be true in regard to designing for team cognition.

(7) ***Different tasks require differing team cognition perspectives***

Although we have introduced an integrative perspective of team cognition within RPAS that incorporates aspects of both the shared knowledge and ecological perspectives, it is important to understand that specific tasks may be suited better for one task than others. For this reason, it is of paramount importance to fully understand the task and context that the decision support is being used for. Careful consideration and understanding of the specific RPAS mission goals and tasks need to be taken into account when considering how team cognition plays a role in developing collaborative and proactive decision support. For example, a task that is highly interactive and dynamic should take an ecological approach where the system pushes team level interaction and information. Yet, in contrast, a task that occurs over many weeks, might be better suited in utilizing a shared knowledge approach where information can be shared in a longitudinal manner. And, finally, there may be many tasks that need both perspectives, which is the purpose of the integrated perspective. A system of collaborative decision support can and should be oriented to the task and the appropriate perspective of team cognition.

5 Concluding Thoughts

There is no question that RPAS is becoming more reliant on teamwork and collaborative activities. As the prevalence of RPAS missions continues to increase we will also see an increase in teamwork. As a community, we must work to understand how teamwork occurs within this context. More specifically, we also need to understand how to support RPAS teams in their collaborative activities.

In this paper, we highlighted a critical aspect of teamwork, team cognition, that needs to be accounted for when we attempt to support RPAS teams. When collaborative and proactive decision support systems are developed, they should directly account for multiple perspectives of team cognition depending on the task. The presence and development of team cognition in RPAS teams has the potential to increase team effectiveness. As the community moves forward, we need more team cognition research within this context. This research will then help further inform and build on the recommendations outlined in this paper on how to use team cognition as a mechanism for bettering future RPAS decision support systems.

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