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Orchestrating Humans and Non-Human Teammates to Counter Security Threats: Human-Autonomy Teaming in High and Low Environmental Complexity and Dynamism

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ABSTRACT

The changes in the security environment run parallel to changes in humans and artificial cognitive systems to meet these challenges. In a military setting, this is exemplified by novel technologies of adversaries such as in high-speed and high-precision missiles that can be deployed to ensure anti-access area denial (A2AD) capabilities, i.e. ability to control access to and within an operating environment. While novel humans and artificial cognitive systems may be important to handle such situations, it is important to enable the use of the technologies so that they will actually have the effect of reducing threats. In this paper, we discuss some human-autonomy teaming (HAT) design approaches (mechanisms for coordination), specifically levels of automation (LOA), mixed-initiative (MI), and coactive design (COAD). We discuss how humans and artificial cognitive systems can be orchestrated to enable the handling of complexity and dynamics of an environment, e.g. handling military threats, and how different design are affecting mission solutions. Specifically we suggest that there are trade-offs between the HAT designs so that LOA and to some degree MI provide better coordination in low complexity and low dynamics environment, while COAD could support coordination in high complexity and high dynamics. LOA and MI would be less costly in low complexity and dynamics while the opposite holds for COAD. Ways of using these HAT designs in a complementary way are suggested to support coordination through both plan and feedback, such as by integrating external and internal feedback in prediction of future action. We illustrate our suggestions through a use case, which provide additional nuance to our theoretical discussion. Lastly we provide directions for future research and practical implications.

Keywords: Levels of automation, Mixed-initiative design, Co-active design, Human Systems Integration, Systems Engineering, Environmental characteristics, Coordination

INTRODUCTION

Handling an external environment is key to many types of human-machine teams: e.g. the use of unmanned surveillance drones in difficult rescue operations and the widespread use of such drones in a military setting to ensure endurance and reach. In these cases human-autonomy teaming is needed where human-autonomy teams (HATs) are defined as "at least one human working cooperatively with at least one autonomous agent (McNeese et al., 2018), where an autonomous agent is a computer entity with a partial or high degree of self-governance with respect to decision-making, adaptation, and communication (Demir et al., 2016; Mercado et al., 2016; Myers et al., 2019)." (O' Neill et al., 2022, p. 904). The problem is how to be able to adjust own actions taking into account environmental characteristics, in such a way that the HAT is continued and able to perform their tasks despite various environmental conditions. Prior research have suggested that when complexity of the environment is low more decisions may be delegated to the computer entity but when the complexity increases human control is needed (Abbink et al., 2018). Furthermore, prior research indicate that task resolution, of both human-to-human and human-machine teams, is impaired, in general, when complexity increases (O'Neill, 2022).

However the degree to which more complex situations can be handled by machine and humans may depend on the different designs of HATs ranging from planned levels of automation (LOA) via mixed-initiative (MI) to enacted coactive designs (COAD) (Jiang & Arkin, 2015; Kaber, 2018a). Some research is also more optimistic concerning the ability of technology to handle unforeseen situations (Goodrich, Adams & Scheutz, 2021; Lundberg et al., 2022). A concrete example is the development of drones that over time have developed to more adaptable entities. We suggest that environmental characteristics, specifically complexity and dynamics and their influence on coordination and performance (Mouloua et al., 2020) will vary according to HAT design used. In the face of environmental characteristics we suggest that the three HAT designs have strengths and weaknesses, and to overcome such tradeoffs one may use different HAT in concert, e.g. LOA may reduce communication costs, while COAD may increase synergies among human and computer entities. Thus, interfaces (Rico et al., 2018) need to be refined in parallel to advancements in the capabilities of autonomy, especially with the vision of a human operator and intelligent agent dynamically collaborating to solve problems and share task completion in a manner similar to effective human teams e.g. supporting peer-to-peer type communication between human-autonomy team members (Schraagen et al., 2022). We ground these suggestions on dynamic decision theory (DDM) and organization theory which points to the complementarity of feedforward (planned coordination), and feedback (coordination through adjustments) (Brehmer, 1992; Simon, 1957) as they handle different problems, e.g. problems of scheduling and problems of unforeseen events.

On this background the purpose of this article is to elucidate the following research question: How do different HAT designs contribute to support the coordination of task under various environmental characteristics? In this article, we thus discuss how HAT designs, specifically levels of automation, mixed-initiative and coactive design, may support changes to the workflow between man and machine (Fitts, 1947; Sherdian, 1978; Parasuraman, Sheridan & Wickens, 2000), due to different environmental characteristics. This article thus explores some parts of a research gap identified by O'Neill et al. (2022) who call for investigating the role of different task conditions for HAT designs. We do so by focusing on certain characteristics of the task environment. We also build on and extend the prior work that we have done on HAT designs. In a 2021 paper we discussed the prospect of HAT teaming in the context of unmanned combat aircrafts collaborating with fighter jets. Stensrud et al. (2021) indicated that the dynamic of tasks would influence the type of coordination between human and non-human entities requiring a mix of formal and informal mechanisms, but here we add the influence of environmental complexity and look upon a less controllable empirical setting. We discuss a use case building on prior empirical and conceptual work that we and others, have done regarding F-35 and loyal wingman (e.g. Stensrud, Mikkelsen & Valaker, 2020; Stensrud, Betten, Mikkelsen & Valaker, 2021; Bjerke & Valaker, 2022). Finally we discuss future research and practical implications.

EFFECTS OF DIFFERENT SYSTEM DESIGN APPROACHES ON COORDINATION UNDER DIFFERENT ENVIRONMENTAL CHARACTERISTICS

We now discuss how LOA, MI and COAD may support coordination in two types of environmental characteristics: complexity and dynamism. Coordination we define as the integration of interests, understanding and activities to reach a common goal (Mathieu et al., 2018; Van de Ven, Delbeq & Koenig, 1976; Kouchaki et al., 2012; Grote et al., 2018). We also discuss some potential costs of using the designs, e.g. communication cost. Complexity we define as the number of elements and number of relations among elements in an environment (Schneider et al., 2017) and dynamics as the rate of change in elements in the environment (Dess and Beard, 1984). On this background we briefly present some key assumptions regarding the designs and the external environment, and then discuss the influence of complexity and dynamics specifically.

LOA concern prescribed “levels” where the human does “everything to a level where the computer does everything” (Verplank & Sheridan, 1978, p. 8-5) and the research have been concerned with how LOA changes the working conditions for human operators (Fitts, 1947; Sherdian, 1978; Parasuraman, Sheridan & Wickens, 2000). Several extensions and modifications to the original framework have been made (Vagia, Transeth & Fjerdingen, 2016) a recent example is Cabrall et al. (2018), and it has been used in several practical applications (Hopkins & Schwanen, 2021). One key observation is that automation may hamper visibility and as a consequence situation awareness of humans if used extensively. Miller and Parasuraman (2007) for example suggest that LOA could be changed if the environment demanded, and that automating decision-making functions “may reduce human operators’ awareness of system and environmental dynamics” (Miller & Parasuraman, 2007). On the other hand, extensive automation and delegation may help perform tasks in difficult environments and when speed is essential (Kaber, 2018 b). The research to date indicates that flexible use of LOA could be used to handle environmental demands.

The MI approach distinguishes itself from LOA by positing a more equal role for the machine and has been described as "a flexible interaction strategy in which each agent (human or computer) contributes what it is best suited at the most appropriate time." (Hearst, 1999, p. 14). Later on Jiang and Arkin (2015) have developed this definition to encompass robots. Jiang and Arkin (2015) suggests that feedback from an external environment or inferred state of environment can trigger initiative in a reactive or deliberate way, however uncertainties of the environment can make initiative reasoning challenging (Kirlik, 1993).

One of the key components of COAD is to emphasize collaboration rather than delegation as principles of man-machine interaction, it emphasizes the observation of and sharing of knowledge of own status and knowledge of internal interdependencies and external environment, as well as the predictability of own actions in order for others to rely on them and directing behavior and be directed (Johnson, Bradshar & Feltovich, 2014). Johnson and Bradshaw (2021) explain the problem of people becoming unaware of changing in environment and system states when changes are under control by other agents, by the idea that the system is opaque to the users. They claim that support for interdependence could mitigate such issues.

On the basis of this short summary of the three HAT designs we now suggests ways in which they may support coordination under complexity and dynamics (Brehmer, 2010). Detailed indications of the potential outcomes of the HAT designs are shown in table 1 below.

In less complex situations LOA may be preferred because less feedback is required. A dominant feedforward (command based) coordination mechanism based on a high degree of pre-programmed and role-based assignment of authority. On the other hand it requires that formal roles and capabilities (of human and machine) must be defined prior to task resolution, something that could be increasingly difficult to foresee when complexity and dynamics increase. MI and to an even larger extent COAD may be (at least initially) to reactive to fully function in time critical tasks.

On the other hand: In highly complex situations, more elements need to be observed, processed and potentially communicated about in order to coordinate between man and machine. There may be a likelihood that the tasks cannot be as easily divided in high complexity and high dynamic situations as in low complex and low dynamic situations. We may posit that increased interdependence among coordinating elements in an extended socio-technical multiteam (Luciano et al., 2020) that includes non-human actors, leads to increased coordination requirements on the boundary of this arrangement. As the degree of interdependence between entities increases, the need to process more information increases. In such situations HAT designs that rely on feedback should function better and MI and perhaps even more COAD could be chosen rather than LOA. A dominant feedback (e.g. threat based model) coordination mechanism based on a high degree of reactive feedback and operator-based assignment of authority, will promote this type of arrangement (informal control).

In other words our brief analysis indicate that there are trade-offs between the HAT designs. To compensate for the trade-offs using the different HAT

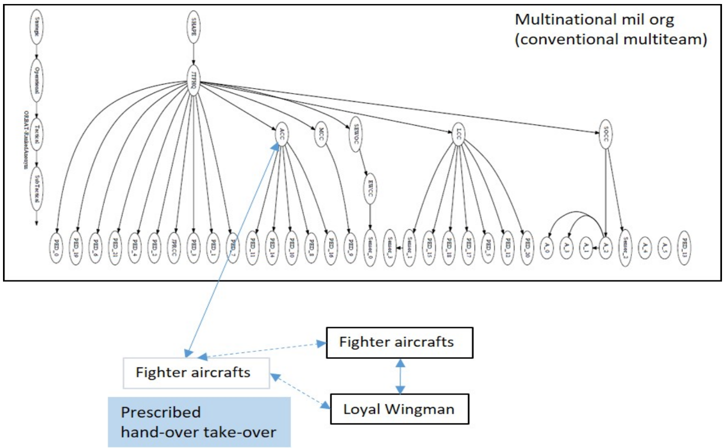

Figure 1a: Pre-scribed socio-technical multiteam that includes non-human actors. (Adapted from Stensrud et al., 2020).

designs in concert could be a solution. A feedback and feedforward integrated model fully integrating feedforward and feedback will promote this evolution (formal and informal) adjusting who coordinates based on both (pre-programmed) role and (individually and situated selection of) operator most suitable to mitigate any gap of authority. (Johnson 2018). For example MI (and/or COAD) could be used together with dynamic LOA levels (Petousakis et al, 2020; Schmitt et al., 2018; Lindner et al., 2022). Playbooks such as suggested by Miller and Parasuranam could be used to ensure predictability in a COAD design. In this way planned and emergent activities could be joined.

USE CASE

We are now illustrating and discussing the suggestions made in the theory section in a use case. We focus on fighter aircraft (e.g. F-35) that collaborate with loyal wingmen (e.g. surveillance drones) to solve missions (Rebensky et al., 2022). There is a need for an Interaction mechanisms, i.e. HAT design, in order to ensure coordination. These tactical man-machine systems is embedded in a larger organization (Multinational military organization) which directs the activities of the fighter aircraft and loyal wingmen, illustrated in figure 1a and 1b. Figure 1a illustrate a pre-scribed socio human capability that includes non-human actors and limitations are considered, and figure 1b illustrate an emergent and dynamic handover take-over event with a changed socio human capability that expand ability to include non-human actors. The lower part of the Figure 1 a and b illustrates the fighter aircraft and loyal wingman system.

We draw on prior unclassified reports by RAND to form a use case:

"(…) low-observable, multirole F-35 Lightning II Joint Strike fighter could be used as both a sensor and a shooter in a SEAD campaign.[7] *Still, air planners will likely want to reduce the amount of time that F-35 aircraft spend in*

Table 1. Evaluation of coordination through HAT designs under different environmental characteristics.

Environmental characteristics	Levels of automation	Mixed-initative	Coactive-design
Low complexity	High coordination possible because it easy to define what can be done by man and machine respectively	High coordination, but may be an overly complex method of teaming since complementarity may be less needed.	High coordination, but may incur a cost as to much emphasis is put on feedback, when it is not realy needed to have feedback
High complexity	Difficult to coordinate because the number of elements and their interrelations are many and therefore it is hard to decompose and delegate tasks.	Good coordination, but relatively few mechanisms for feedback and adjustments may hamper operations.	Good coordination because feedback is processed concerning the interrelations. However, dependent on capability to observe and predict and handle concurrent tasks.
Low dynamics	Good coordination because it is easy to predict the upcoming tasks and hence to predict to whom to delegate to.	Good coordination and easy to predict the complementarity (e.g. sequencing of human and machine actions is easy)	Good coordination, but may incur a cost as to how much feedback is needed, because the environment is predictable and hence feedback is not needed frequently.
High dynamics	Difficult to coordinate because of the many changes in environment that makes it hard to predict what to delegate.	Good coordination, but few mechanisms to adjust for sudden changes in who do what.	Good coordination because ongoing feedback can aid prediction even in high dynamics.

highly contested airspace by leveraging space-based ISR to help locate adversary SAMs [surface-to-air-missiles].[8] *Using long-range precision ground fires would also increase the firepower available to strike targets, offer a redundant capability to strike SAMs if aircraft need to leave the area, and complicate an enemy's defense planning (…)*" (Priebe et al., 2021: p. 37). We extend this case to include loyal wingman (Stensrud et al., 2020) that augment and are complementary to the F-35. The loyal wingman are drones that could but

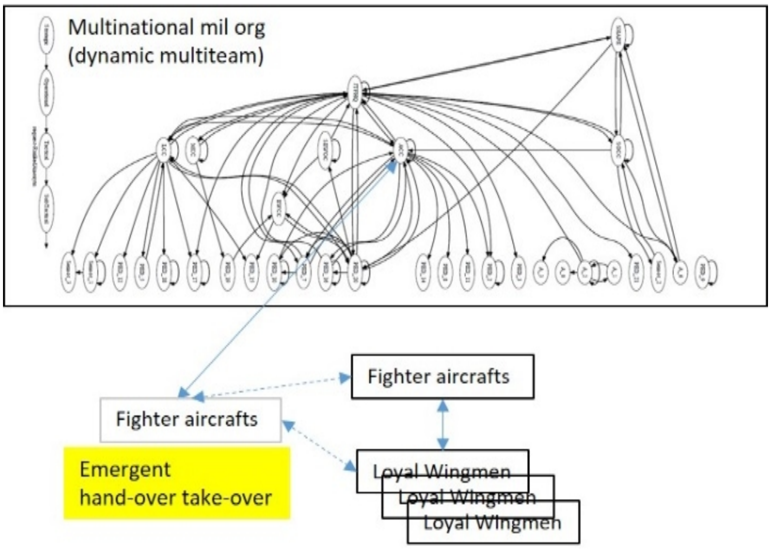

Figure 1b: Emergent socio-technical multiteam that includes non-human actors (Adapted from Stensrud et al., 2020).

used in a forward position both to surveil and attack an enemy air defence system. In this case we focus on a loyal wingman that can provide updated information about the enemy situation and that can be in a forward position and closer to the enemy than the fighter aircraft.

We simplify the environment to two environmental characteristics discussed above theoretically: the number of elements in the enemy integrated air defence (e.g. number of radars, missile launchers, C2 nodes etc), which is the complexity of the environment, and the variability of an additional air threat (e.g. number of incoming enemy fighter aircraft) which is the dynamic characteristic. We assume that in all conditions a set number of elements in the SAMs should be striked (eventhough the total number of SAMs increase) and we keep the number of friendly airframes constant. The low complexity low dynamic conditions are illustrated in the planned mode in figure 1a, while the high complexity and high dynamics are illustrated in the emergent mode in figure 1b.

We evaluate coordination, as in the theory section, but also add considerations of costs of coordination in the different HAT designs. The results of our analysis based on experience from workshops with military officers are presented in Table 2. We do not present results for the low dynamics as we focused on the critical issue of handling high dynamics. Largely our analysis of the empirical use case conformed to the theoretical discussions, although it provided some granularity to the theory. Overall, similar to theory the discussion of the case highlighted that LOA were preferred in less complex less dynamic situations and MI and COAD was preferred when complexity and dynamics increased. With respect to LOA it highlighted the relatively high cost of planning (i.e. deciding beforehand who do what and delegate) even in low complexity. With respect to MI the cost of making interfaces between man and machine to accommodate transactions was highlighted. In high dynamics situations it also suggested that the humans in the MI mode need to prioritize tasks on a high level rather than do detailed interaction with technology. Prioritizing tasks would require advanced technology. Regarding COAD the case illustrated a cost of using this method for low complexity low dynamics because of the lack of delegated and (initially) planned task allocation. It should be noted that these suggestions are preliminary and need further refinement through subject-matter expert input as well as experimentation.

DISCUSSION

Our preliminary theoretical analysis and analysis of a use case indicate that LOA, MI and COAD could be complementary in terms of supporting coordination under high and low complexity and high and low dynamics. This largely confirm prior research, but our study may open up the discussion of how the different HAT designs could be used in concert to support difficult missions. We now point to some avenues for future research and practical implications.

Future Research

A key extension to this work is to define more clearly what the different HAT designs could offer in the particular case discussed and in other relevant cases. Such an analysis could for instance detail the communication requirements, the rules for delegation, and the mechanisms for updating among entities offered by the designs. More work is needed on defining how the trade-offs between HAT designs could be overcome, e.g. through developing COAD and its interface to LOA and MI. We did only a very general discussion of the costs of different designs in different situations. It is likely that the cost will also change over time as the actors learn how to operate in the environment.

Crucially other characteristics of environments need to be discussed in more detail such as the different interpretations that could arise regarding an environment. Related to this the filtering and transmission of environmental cues could impact the operation of both human and machine and thus determine their interdendencies and coordination. On a general note the interaction of different characteristics need to be spelled out in more detail, e.g.: what is the consequence of a situation with high complexity and low dynamics versus a situation with high complexity and high dynamics?

The technical interface that could support the different HAT designs under different environmental characteristics is also in need of discussion, and related to this the trust among entities. In particular how to achieve coordination in congested and contested environments is in need of more study.

Practical Implications

A suggested practical approach to implement different HAT designs is to use a supportive framework for design and modelling interfaces to evaluate the consequences of different HAT designs in a practical context (HSI 711th AFRL, 2022; Park et al., 2020). In development of the collaboration between man and machine it seems to be important to support different needs, and that not one HAT design (that we know of) seem to support all needs. Thus

Table 2. Preliminary evaluation of coordination and communication cost with different HAT designs under different environmental characteristics.

	F-35 with loyal wingman		
Environmental characteristics	**Levels of automation**	**Mixed-initiative**	**Coactive design**
Low complexity	**Coordination: High** **Cost: Medium** *Due to some planning needed to define task allocation and delegation authority throughout the mission in detail.*	**Coordination: Very high** **Cost: High** *because of requirement to interface during task resolution*	**Coordination: Medium.** *Require a supervisor role for the human.* **Cost: High** *Need to mitigate lack of planning through discover interdependencies.*
High complexity	**Coordination: High** **Cost: High** *Need to define in much detail what to delegate*	**Coordination: High** *But more likely to result in transaction overload.* **Cost: High** *Need to define "smart" interaction mechanisms to reduce transaction overload.*	**Coordination: Medium** *But better than in low complexity since the system is able to process the high number of elements* **Cost: Medium** *Scalability is challenging*
High dynamics	**Coordination: Medium** **Cost: High.** *Very detailed updating and definition of task allocation mechanisms needed*	**Coordination: High** **Cost: High.** *Requires detailed transaction mechanisms, and well-known procedures that allow the human operator to prioritize between tasks (in particular in low complexity and high dynamics)*	**Coordination: Medium** **Cost: Medium.** *Needed to have a repertoire of playbooks and select among these (in particular when high complexity is also present (Perkins, 2017)). Support team collaboration by modern technology (AI). (Seeber et al.,2020)*

in designing and supporting such collaboration one may need to orchestrate different designs, such as making elaborate ways of delegating to the machine, yet also be able to get feedback from the machine and its environment when needed to adjust and integrate on the fly.

CONCLUSION

While complexity may suggest that more control is to be held by the human, different HAT designs may ensure that control and goal achievement can be achieved also in complex and dynamic environments. A start point for integration of teammates (e.g. loyal wingmen) and existing human controlled capabilities (e.g. fighter aircraft) could be to levelling up automation (building adapters, and interfaces) in order to design approaches that utilize the best from LOA, MI and COAD. The article presented a set of environmental characteristics that could be important to consider e.g. complexity and dynamics, and pointed to tradeoffs between the designs in supporting human-machine coordination in varying environmental conditions. We hope that our preliminary discussion will enable teams to collaborate better by providing a common language and process to distribute models and share information about complementarities among the HAT designs.

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