Increasing Robot Autonomy Effectively Using the Science of Teams

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Abstract. Even as future robots grow in intelligence and autonomy, they may continue to face uncertainty in their decision making and sensing. A critical issue, then, is designing future robots so that humans can work with them collaboratively, thereby creating effective human-robot teams. Operators of robot systems can mitigate the problems of robot uncertainty by maintaining awareness of the relevant elements within the mission and their interrelationships, a cognitive state known as situation awareness (SA). However, as evidenced in other complex systems, such as aircraft, this is a difficult task for humans. In this paper, we consider how application of the science of human teaming, specifically task design and task interdependence in human teams, can be applied to human-robot teams and how it may improve human-robot interaction by maximizing situation awareness and performance of the human team member.

Keywords: Human-robot interaction, system design, situation awareness.

1 Introduction

Even as future robots grow in intelligence and autonomy, they may continue to face uncertainty in their decision making and sensing. A critical issue, then, is designing future robots so that humans can work with them collaboratively, thereby creating effective human-robot teams. Operators of robot systems can mitigate the problems of robot uncertainty by maintaining awareness of the relevant elements within the mission and their interrelationships, a cognitive state known as situation awareness (SA). However, as evidenced in other complex systems, such as aircraft, this is a difficult task for humans. Often, when automated systems fail, the result is a lack of situation awareness. This problem has come to be known as the out-of-the-loop performance problem [1].

To achieve high SA in the human-robot team, robots should supplement the knowledge held by their human team mates, and human team members, in turn, should be able to aid the robot(s) without sacrificing their own knowledge or experiencing high workload. We believe that the most efficient and effective way for designers to facilitate collaborative work with robots is by applying principles of human teamwork to human-robot systems.

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While teaming can inform human-robot interaction, it is only one angle from which to approach this problem. In our other paper [2], we examine how robot design can mitigate or exacerbate the effects of the out-of-the-loop performance problem. In this paper, we specifically consider how the application of the science of human teaming, and, in particular, of task design for human teams, can improve human-robot interaction by maximizing situation awareness (SA) and performance of the human team members. Specifically, we propose that structuring a task to promote task interdependence between human and robot is a potential solution to improve SA in future human-robot teams.

2 Background

2.1 Situation Awareness and Human-Robot Interaction

Situation awareness (SA) describes the relevant knowledge held by an operator while performing a task. Endsley [3] created a model in which SA is a high-level, goal-directed information processing function as part of a sensation-decision-action cycle. Generally, SA is goal-directed, high-level knowledge that comes as a result of an individual's information processing within an environment [4].

In a team context, Salas and colleagues' suggested that SA is an individual-level process that takes place in the context of team process [5]. In human-robot interaction, this model is useful for explaining how heterogeneous agents (e.g., a robot and a human) may develop SA as part of a team. Robots differ from humans in how they acquire, process, and structure information. By investigating SA as an individual-level process, researchers and practitioners can focus on maintaining a sufficient level of SA in the human without asserting that the robot performs human information processing. This model also allows consideration of robots at any level of autonomy. Robots have been traditionally thought of as tools, and in this model, the SA of the human is independent of the information processing of the robot. The robot participates in the human's development of SA through its communication and coordination with humans. One way to assess the effectiveness of the human team member within the system is, therefore, to measure SA.

Researchers have aimed to increase SA when working with automated systems by strategically altering the level of automation. Two categories of solutions have come from this approach: intermediate levels of automation and adaptive automation. The former is characterized by utilizing a lower level of automation than may be technically feasible as a means of avoiding the effect [6]. Another solution is to employ adaptive automation [7]. Adaptive automation encompasses a number of methods aimed at optimally dividing tasks between humans or automated agents based on the state of the environment, system, or behavior of the human.

Both intermediate levels of automation and adaptive automation can effectively change the task assignments between automation (here: robot) and human, but they often do so at the task level: Task A is performed either by the human or the robot, and its assignment may be switched as the situation changes.

2.2 Task Interdependence

Recently, Johnson and colleagues [8] put forth a number of criticisms of solutions based on selecting the appropriate level of autonomy. Rather, they argued, “it is more productive to think about autonomy in terms of multiple task-specific dimensions rather than in terms of a single, uni-dimensional scale.” We aim to expand upon existing solutions to the creating and maintaining SA specific to robotic systems by including task/mission factors as a moderator of the relationship between autonomy and SA.

Task interdependence has been studied extensively as a performance factor in human teams. Task interdependence is the degree to which members must rely on each other to perform their tasks effectively given the design of their jobs [9]. An example of task interdependence is the necessity of sharing equipment or materials to achieve performance outcomes [10].

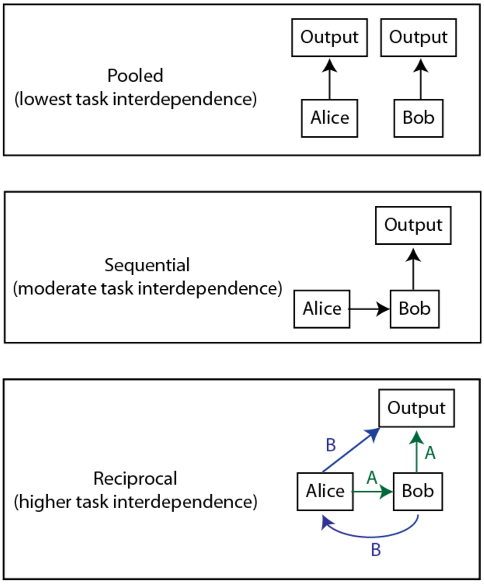

Fig. 1. Illustration of selected levels of Thompson's (1967) framework of task interdependence in human teams

Thompson’s [11] categorization of task interdependence has been widely cited. In this classification, discreet interdependence styles are ordered from least to most interdependent (Fig. 1). At the lowest level of task interdependence, each agent performs equivalent subtasks. Each pooled subtask generates a complete output, and the agents are not at all interdependent. An example would be the workshop of multiple craftsmen in which each individual produces a complete product. The number of completed products is the measure of work output. Sequential task interdependence requires performance of a subtask by each agent in order to produce an output. A key quality of this level is that the order in which the tasks are performed is not flexible. In the figure, Alice must always perform her task before Bob can complete his.

Only when Bob completes his second task has the output been created. Reciprocal interdependence adds flexibility in the order but not the specialization of role. In the diagram, Alice and Bob each perform a necessary step, but those steps can be performed in any order (either path A or path B). An example of this kind of work in a complex system is a surgical team.

Thompson's classification takes an information-processing approach and characterizes organizations as information processing systems working under conditions of limited capacity [12]. Although this is not the only taxonomy of task interdependence, and task interdependence is not the only driver of interdependence within a human team [13], Thompson's taxonomy offers provides a clear operationalization of the construct, which is complementary to Endsley's information processing approach to SA. Although it has been studied primarily in human teams, it has been applied it to automation as well.

Task Interdependence and Human Teams. Although task interdependence is an important construct in the team literature [14], there is limited support for a direct relationship between task interdependence and performance. Inconsistent findings of main effects suggest the presence of moderators of this relationship [15] [16] and the interaction of task interdependence with other determinants of performance [14] [17]. In a meta-analysis, LePine, Piccolo, Jackson, Mathieu, and Saul [18] found that task interdependence was a moderator of the relationship between teamwork (the coordinating behaviors amongst team members) and team effectiveness. Higher levels of task interdependence lead to stronger relationships between teamwork and effectiveness. In human teams, group control more positively impacted performance as task interdependence increased [19]. Although research on exclusively human teams does not have immediate implications for human-robot teams, it shows that task design interacts with other work factors in affecting the ability of humans to perform shared tasks.

Task Interdependence and Automation. As a task characteristic, task interdependence has been explored in human-automation interaction as well. Johnson and colleagues [20] suggested that lack of SA, such as in the out-of-the-loop performance problem, is the outcome of human-robot interaction under high autonomy, which they defined as a combination of self-directedness and self-sufficiency. They refer to the problem as opaqueness; the operator, disconnected from the behavior of the robot, cannot integrate or predict its actions, leading to reduced performance. Low levels of reliable autonomy lead to the robot being a burden on operator cognitive resources while the system becomes opaque at higher levels of reliable autonomy. Johnson et al. [20] presented the results of a study in which higher levels of autonomy, in the absence of task interdependence, lead to increased opaqueness and less subjective burden. In Johnson et al.'s work, task interdependence was described as an orthogonal third dimension that moderates this effect. Johnson et al. [20] argued that task allocation approaches do not allow agents to depend on each other and that increased levels of task interdependence are a means for operators to remain in the loop. By working in closer collaboration, operators may have more opportunities to communicate the status of shared tasks while focusing on their individual level outputs. This effect has been observed in human teams [21]. However, task interdependence may only show a benefit when the robot can contribute by performing an independent subtask.

Task Interdependence in Human-Robot Interaction. Since the problems with maintaining SA in complex systems are not limited to robots, much of the work in this area has examined human-automation interaction and not human-robot interaction. Robots are a unique form of automated system. As with human teaming, general approaches to task allocation of automation must be extended to address aspects of the problem unique to human-robot interaction.

Robots provide the most benefit when they perform tasks that are unsafe or undesirable. In both cases, increasing task interdependence may appear to conflict with the desire to physically separate the human from the work performed by the robot. We offer an extension to the theory and findings of Johnson and colleagues [20] by suggesting that the information requirements of the task can be interdependent even if the physical work is not. Tasks that require human and robot to continuously and seamlessly share information may provide similar benefits as tasks that require a human to hand off physical work with a robot. In this way, the robot and human will adapt the mission-relevant knowledge to each other and keep the human in the loop.

Prior investigations of the out-of-the-loop performance problem have been limited to system factors and have not considered the impact of task/mission factors. Both have been shown to independently affect SA in human-robot interaction [22]. However, it is not known how task/mission factors and system factors may interact to affect SA. While modifications to the task may be appropriately disregarded when mission goals are fixed and the relationship between human and automation is well defined (for example, in a nuclear power plant), the capability of robots is continually changing. Thus, it is important to not only investigate when a robot should operate autonomously and how tasks should be designed, but also the kinds of tasks for which robot autonomy is best suited.

3 Conclusions

3.1 Situation Awareness as a Metric for Human-Robot Interaction

Our first proposition is that robot system designers can understand the knowledge held by the human operator and, consequently, improve system performance through measurement and maximization of SA. The robot's contribution to SA is through the provision of information needed by the human operator who, in turn, builds SA. Given its importance in current robots and other complex, automated systems [23], SA should be considered as a metric for operator knowledge within the system.

3.2 Task Interdependence as a Framework for Task Design

Our second proposition is that task interdependence moderates the relationship between autonomy and SA such that high levels of autonomy do not lead to poor SA when task interdependence is high. That is, task interdependence is a potential solution to the out-of-the-loop performance problem. Further, the physical work of the task may not need to be interdependent if the knowledge needed to perform the task is interdependent, requiring collaboration between human and robot that does not conflict with individual-level goals. The success of human teams is impacted by task interdependence, although task interdependence does not directly affect performance. Rather, mediators suggest that task interdependence must be appropriate given other task factors.

In human-robot interaction, a critical need is to be aware of the robot while minimizing the time spent interacting with the robot. By employing robots in tasks that have reciprocal interdependence with the human team member, periodic sharing of information between human and robot team member takes place, and at the same time, advances mission goals. Consequently, the time spent interacting with the robot provides more efficient information sharing. An example of this would be a reconnaissance task in which the human and robot must monitor separate areas. This task becomes interdependent if individuals monitored by the robot affect or inform individuals monitored by the human. That is, monitoring separate rooms within a building could be reciprocal, whereas monitoring rooms in separate buildings would be pooled.

Our third proposition is an inverse of the first: Task interdependence moderates the relationship between autonomy and SA such that high levels of autonomy lead to poor SA when task interdependence is low. Tasks that are inadvertently designed with minimal task interdependence may exacerbate problems with maintaining SA. In this scenario, communication with the robot is not necessary for the accomplishment of mission goals, leading to a situation where the human team member must choose between accomplishing mission goals and interacting with the robot. Because interaction with the robot is burdensome, it will probably be minimized, decreasing SA as autonomy increases. Future research is needed to confirm these findings, and with empirical support, task interdependence could be a path towards increasingly autonomous robot systems.

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