



INSTITUTE FOR DEFENSE ANALYSES

**DATAWorks 2021:
Characterizing Human-Machine Teaming Metrics for
Test and Evaluation**

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April 2021

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Executive Summary

The Department of Defense and partner organizations are developing advanced machine systems that will work with humans to accomplish missions. Given that these human-machine teams (HMTs) have never undergone test and evaluation (T&E), this briefing helps guide evaluators through the new challenges HMTs bring. It defines human-machine teaming, describes challenges in evaluating HMTs, and provides a framework for categorizing metrics important to the T&E of HMTs.

Human-machine teaming is broader than the simple act of an individual using a system to accomplish a task. It involves extensive interactions between humans and systems as they work together to achieve a collective goal. Given the highly collaborative nature of HMT, measuring the machine and the human is insufficient. We also need to measure the team itself, and those measures need to be mission relevant, quantitative, and objective.

Several unique challenges arise when evaluating HMTs. These include how to address opaque mental models and situations in which machines direct communications, self-task, or task the human. For example, consider a human-machine search-and-rescue team in which an

autonomous drone flies overhead to locate survivors in a collapsed building, alerting a robot on the ground when it finds a survivor. The robot then pulls the survivor from the rubble and brings them to a human medic for treatment. How do you evaluate the drone's process for deciding where to search? Or how it communicates with the robot? What about the robot's responses to those communications? The medic's decisions about how to treat the survivors and in what order? How do the drone, robot, and medic cooperate and prioritize their efforts toward the most seriously injured survivors? How do they coordinate their other efforts? How do they handle the difficulties inherently associated with constantly changing circumstances? As is evident, team member interactions are key.

The framework outlines major categories of HMT evaluation, including capabilities (what abilities did the team have?), interactions (how did the team work together and coordinate their actions to achieve the goal?), and performance outcomes (what resulted from the team's efforts?). It emphasizes team metrics and the coordination of metrics across humans and machines. Thus, if you assess cognition for a human (i.e., attention and judgment), you

need to assess cognition for the machine (i.e., information-processing architecture and decision-making algorithms) as well.

The framework also provides a structure for identifying and selecting appropriate measures to evaluate team effectiveness. All such metrics are derived from prior scientific research.

First, look at the abilities of the human and of the machine, as any of these may underlie failures in teaming. Assess such things as the human's training and experience, psychological traits, physical abilities, attitudes, cognitive resources, and mental workload or fatigue. Consider factors related to the machine's cognitive structure and hardware components, such as its programmed mission knowledge, its operating system and other software, and its physical sensors and the platform on which it is built.

Next, examine critical areas that may underlie interaction failures. These include the machine's situational awareness, resource allocation, and resource use in different situations. For instance, how much power a machine requires to use its sensors to find new survivors can affect whether the machine is available to assist with other team needs. These critical areas also include the human's perspectives and decision-making processes. For instance, a human's understanding of the situation can affect how they behave in that situation and whether they trust the machines they're working with.

Finally, consider potential vulnerabilities. What threats may prevent the team from accomplishing its goal? What consequences are there should the team fail? What additional problems may cascade from this failure? It's important to identify any problems so they can be alleviated or resolved going forward.

Ultimately, this briefing conveys two important takeaways for the T&E community:

- Challenges are different when evaluating an HMT than when evaluating humans using tools or systems. A team's humans and machines (called agents) must pursue the same goal, affect the current problem state, and coordinate action amongst themselves; these interactive factors expose the team to new vulnerabilities and more points of failure.
- Mission outcomes alone cannot be used to identify potential system vulnerabilities. Interactions among agents increase the problem space being evaluated.

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Assessing human-machine teams must involve more than outcome-based testing

This brief's framework extends past mission accomplishment metrics to include metrics for evaluating suitability and effectiveness

The framework:

- Identifies concepts critical to effective teaming
- Emphasizes the importance of interaction – an element that is not analyzed currently
- Provides a structure for identifying and selecting appropriate measures to evaluate team effectiveness

This framework allows us to understand whether a team is effective in general, not just effective during the observed task.

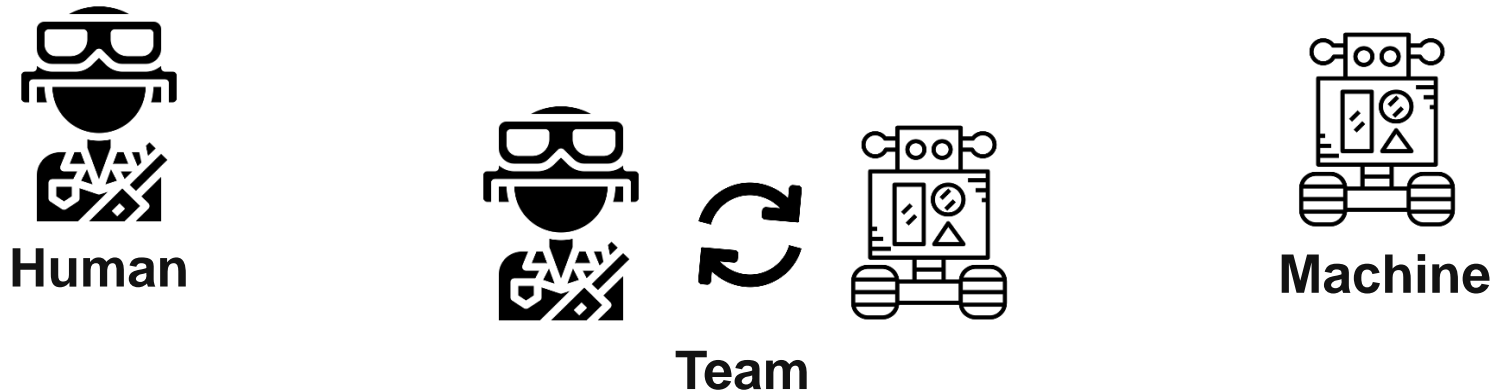
The DoD is investing in human-machine teaming systems and concepts



Our experience is with human teams and humans using tools. Human-machine teams are different.

Bruemmer, Marble, & Dudenhoeffer, 2002; Laird, Ranganath, & Gershman, 2019; Pellerin, 2015

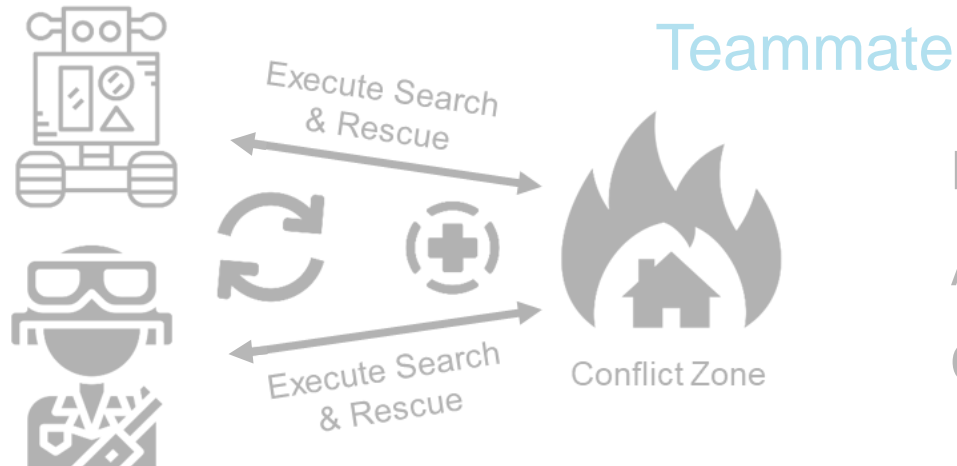
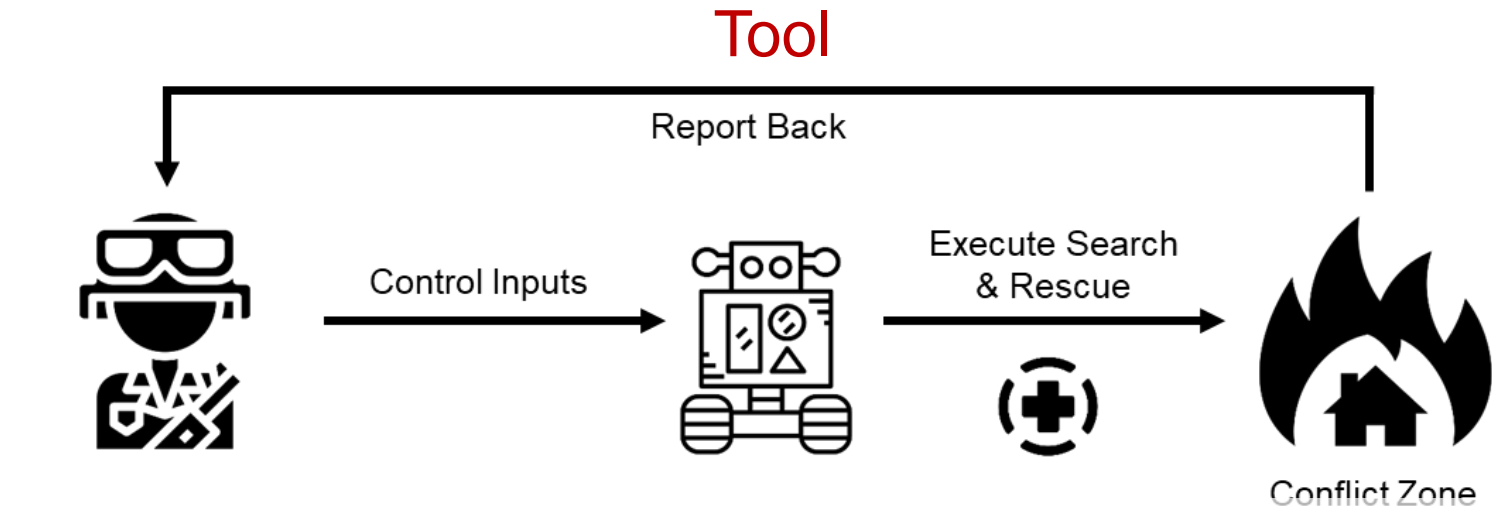
Team interaction adds a new degree of unpredictability that requires new approaches



In a teaming context, measuring the machine and the operator alone is insufficient; interaction between the human and machine increases the problem space

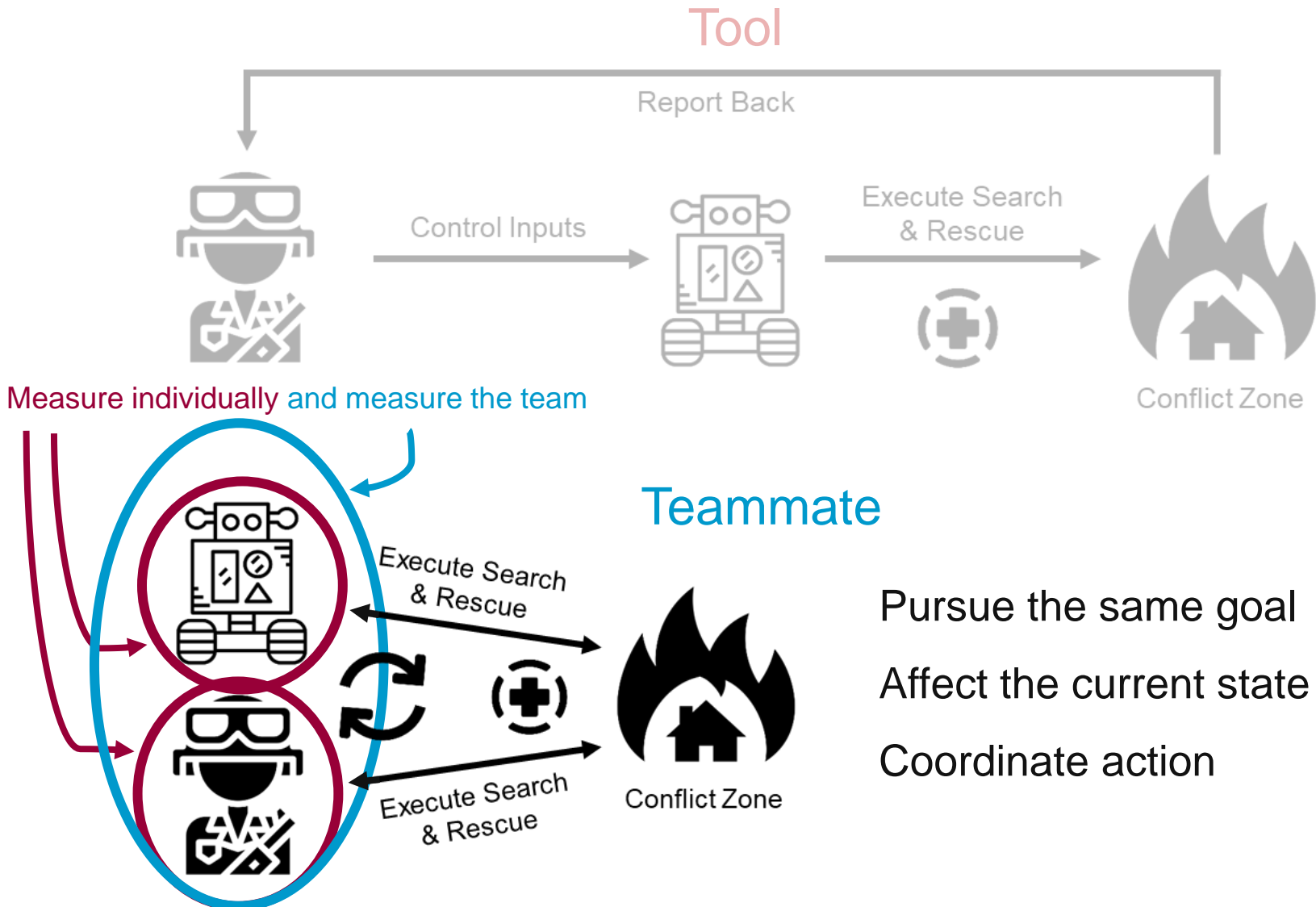
Test and evaluation (T&E) measures of the agents and the team should be mission relevant, quantitative, and (if possible) objective

Currently, measuring humans using tools characterizes performance well



Pursue the same goal
Affect the current state
Coordinate action

Teammates, working in parallel or synergy with one another, need to have more information to characterize performance



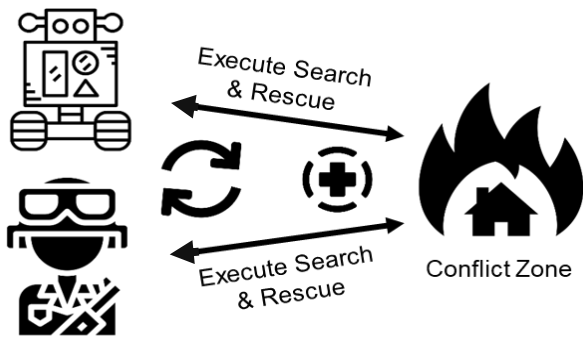
Human and machine collaboration must meet all three conditions to be considered teams

Machines as teammates:

Pursue the same goal

Affect the current state

Coordinate action

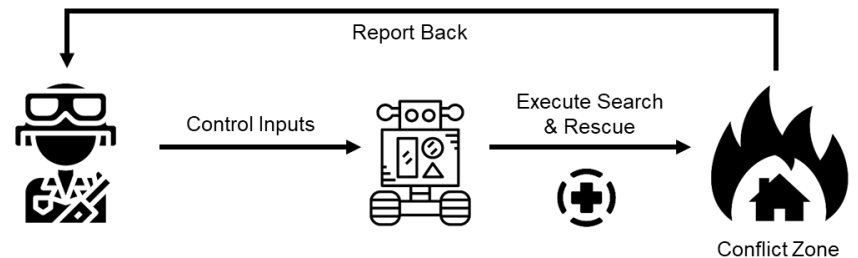


Machines used as tools:

Handle inputs, not goals

Require direct instruction for action

Only complete assigned functions



Humans and machines can support missions in different ways, but human-machine teams are special cases

Not Teams



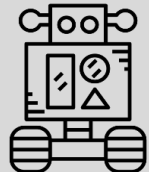
Human



Execute Search
& Rescue



Conflict Zone



Machine



Execute Search
& Rescue



Conflict Zone



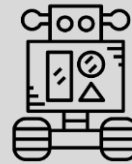
Human



Execute Search
& Rescue



Conflict Zone
Section 1



Machine



Execute Search
& Rescue

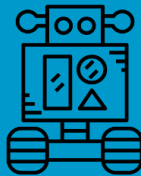


Conflict Zone
Section 2

Human-Machine Team



Human



Machine

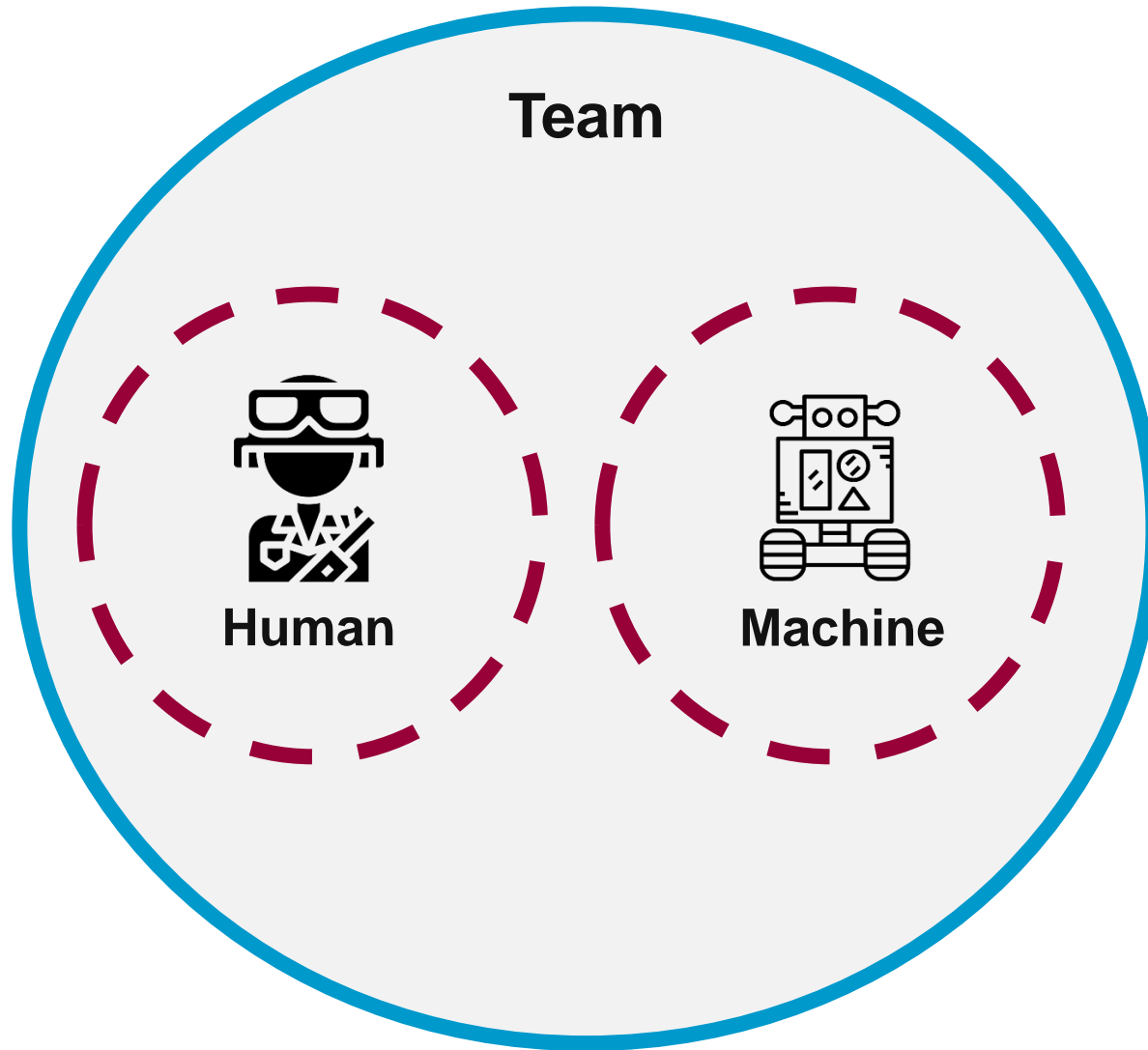


Execute Search
& Rescue



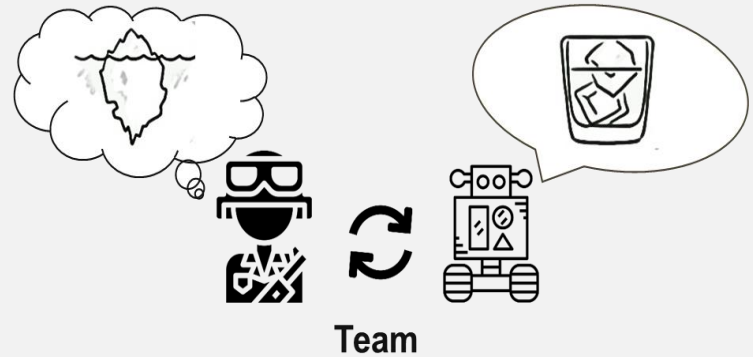
Conflict Zone

You cannot predict **team** performance from your knowledge of the **individual** team agents

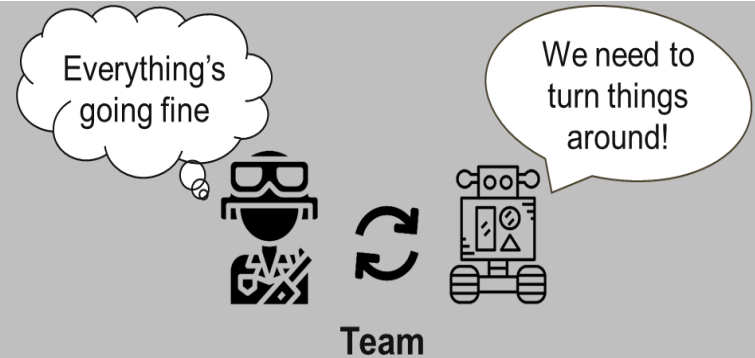


The team interaction is the new, complicating factor

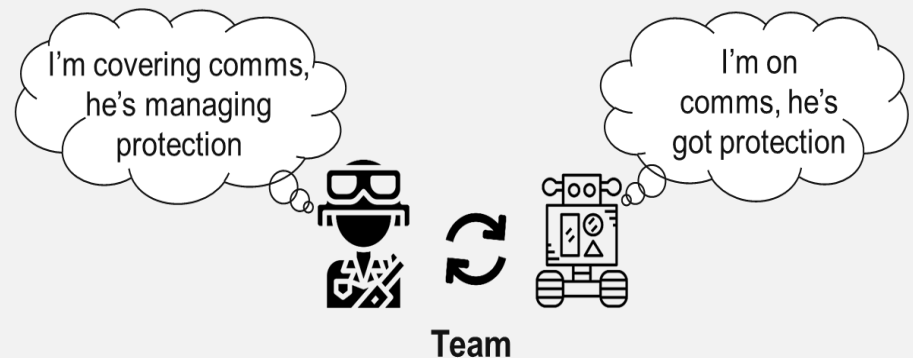
Agents' world or mental models may be opaque



Machines may direct communications within the team

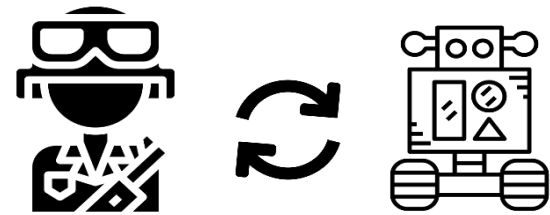


Machines may self task or (implicitly) task the human

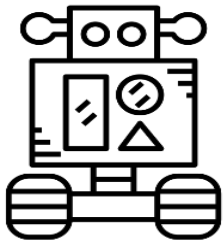


Testing mission outcomes alone will not capture team features such as potential vulnerabilities

Human-machine teams require a new focus on the team as the unit of analysis



RS47: Rescuing disaster victims



Locating victims
and transporting victims

Location information;
status report

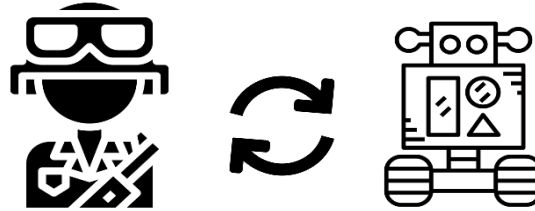


Status report;
transport request



Attending to victims

The team interaction is a new, critical factor



Capability

Team abilities and capacities that are relevant to a particular application environment and the specific applications (i.e., missions) the team must perform

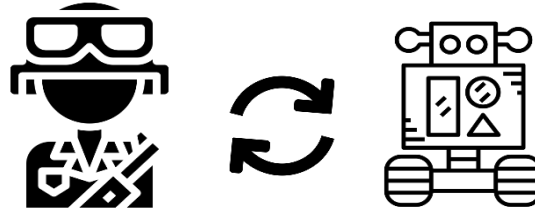
Interaction

How team members engage in coordination, cooperation, and efficient goal pursuit during execution

Performance

Assessment of decisions, results, and subsequent effects generated by or attributable to team action

These concepts reflect Joint Force Command doctrine describing HOW you use MEANS to achieve ENDS



Capability

MEANS: Abilities of the team to get closer to the goal state.
What the team can do coming into T&E.

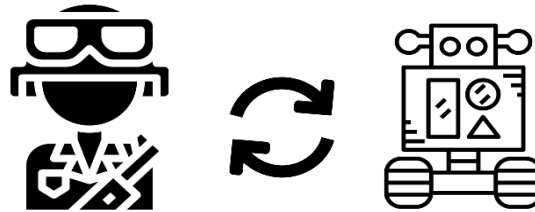
Interaction

HOW: Engagement processes between members, with the environment and the mission. Things that change during T&E.

Performance

ENDS: Outcomes that characterize mission accomplishment.
Large amount of MOEs, MOSs, etc.

The concepts we care about at the team level relate to the team interactions and outcomes



Capability

Communication structure

Structure-based
interaction

Architecture

Interaction

Team perspective

Cooperative behavior

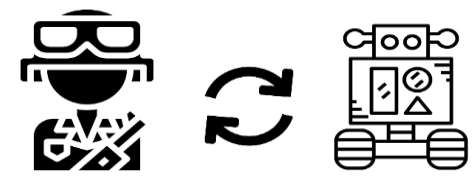
Workload

Performance

Collective decision making

Collective task performance

Team capabilities determine what is possible for the team

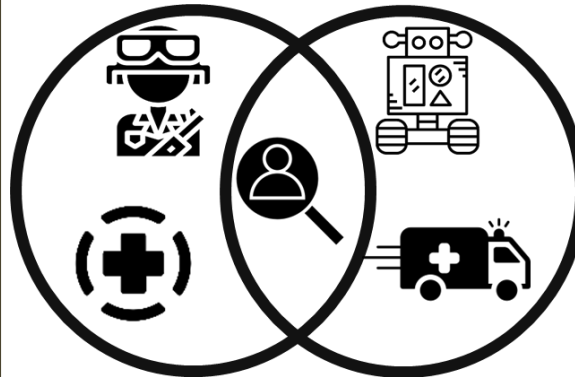


Communication Structure



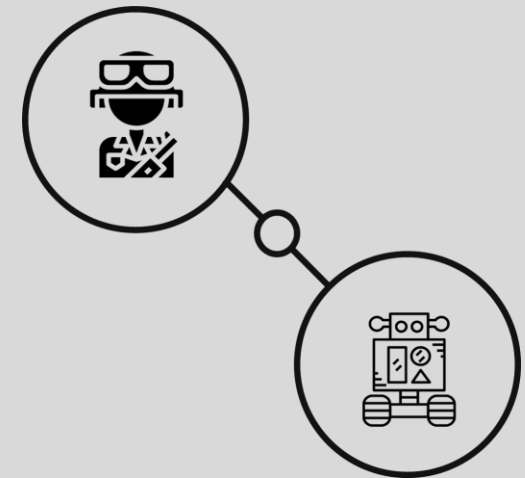
Joint mission knowledge

Structure-Based Interaction



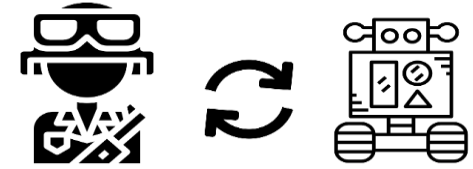
Role clarity and adaptability

Architecture

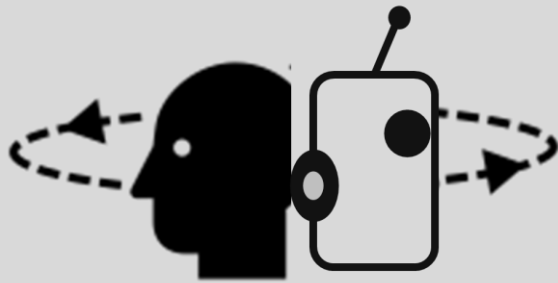


Hierarchical relationships

Team interaction captures how the team works and cooperates during the mission

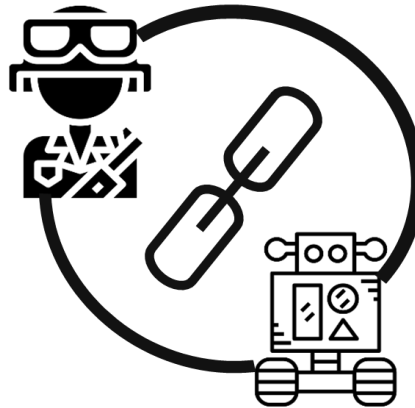


Team Perspective



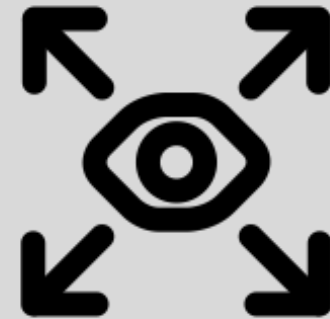
**Team
situational awareness**

Cooperative Behavior



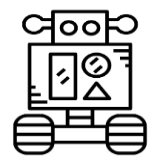
**Team
cohesion**

Team Resource Allocation

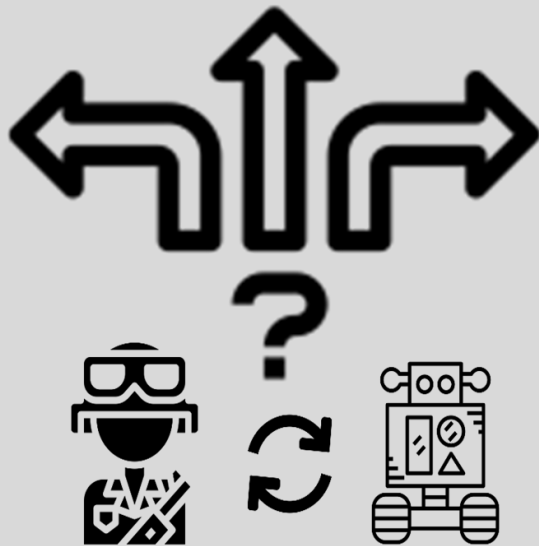


**Joint attention
allocation**

Team performance measures capture mission outcomes

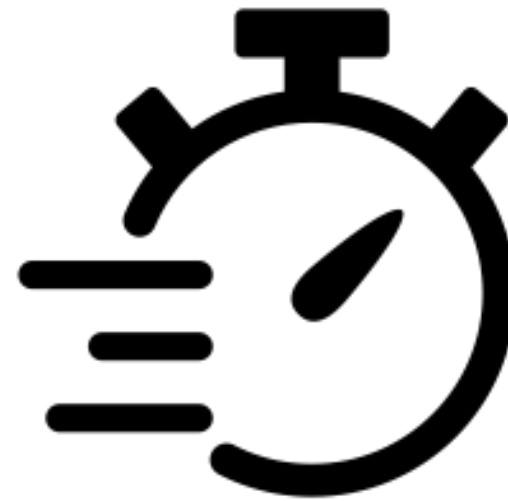


Collective Decision Making



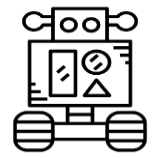
Decision-making optimality

Collective Task Performance



Timeliness

Team measures can be assessed only with two or more agents' active involvement

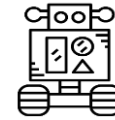


| Communication Framework | | Structure-Based Interaction | Architecture | |
|----------------------------|------------|-----------------------------|---------------------------------------|------------|
| Information flow | | Influence | Hierarchical relationships | |
| Joint world model | | Role clarity | Uni- and bi-directional relationships | |
| Joint mission knowledge | | Role adaptability | Learning patterns | |
| Team Perspective | | Cooperative Behavior | Team Resource Allocation | |
| Situational awareness | | Cohesion | Joint attention allocation | |
| Information accuracy | | Intervention | Workload transfer | |
| | | Team trust | Endurance | |
| | | Agency shifting | | |
| Collective Decision Making | | | Collective Task Performance | |
| Optimality | Risk level | | Task success/failure | Timeliness |
| Robustness | | | Planning recognition | Efficiency |

Individual actions cannot account for an entire team's performance, but they might still affect mission outcomes



Human



Machine

Capability

Training and
experience

Psychological
traits

Physical
abilities

Cognition
structures
and
algorithms

Cognition
software
and hardware

Standard
platform

Worldview

Judgment
and attitudes

Cognitive
allocation

Effort

Perspective

Resource
allocation

Resource
use

Performance

Decision making

Task performance

Decision making

Task performance

Human capabilities might be the underlying cause of failures in teaming



Training and Experience



Mission knowledge

Psychological Traits



Intelligence

Physical Abilities

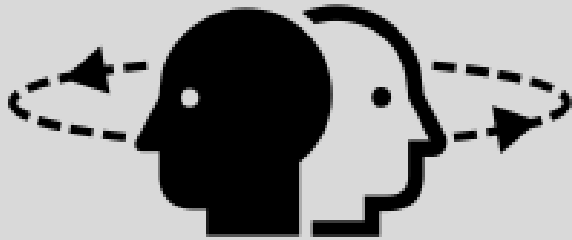


Physical fitness

Human judgment, attention, and effort might be the critical areas underlying interaction failures



Judgments and Attitudes



Situational awareness

Cognitive Allocation



Attention allocation

Effort

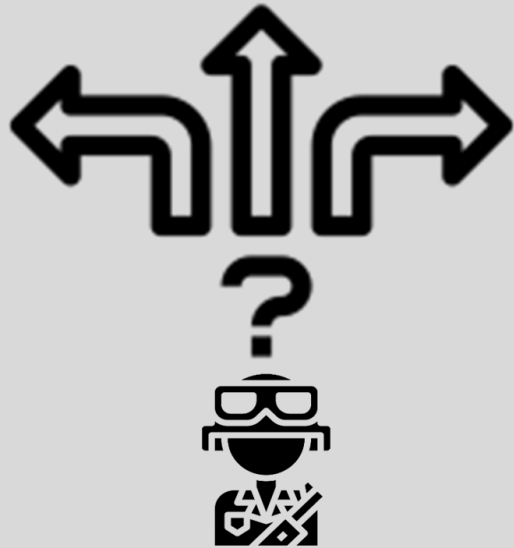


**Resource availability
(workload, fatigue)**

Human performance might be subpar without damaging team outcomes

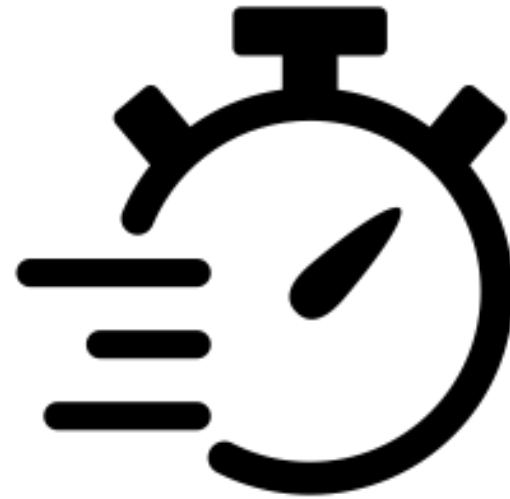


Decision Making



Decision-making optimality

Task Performance



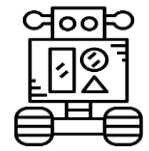
Timeliness

Human capabilities, judgments, and behaviors affect interaction with the machine and the mission

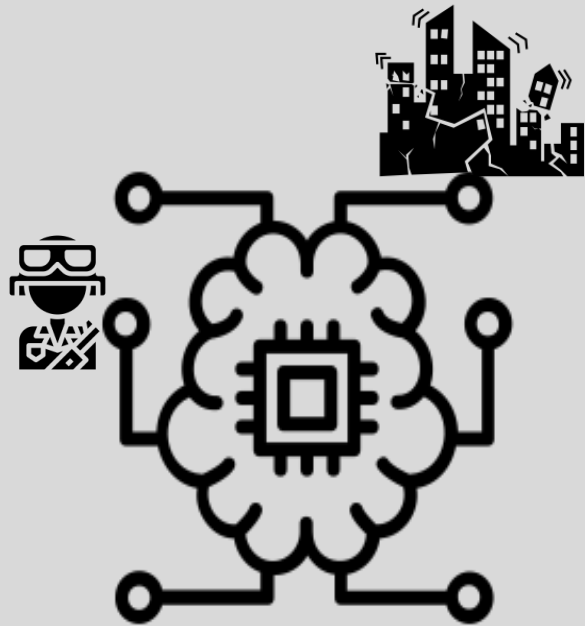


| Training and Experience | | Psychological Traits | Physical Abilities | |
|-----------------------------------|------------|--------------------------------|---|------------|
| Mental model | | Decisiveness and impulsiveness | Physical fitness | |
| Mission knowledge | | Flexibility | Sensors (organs/equipment) | |
| Teammate knowledge and experience | | Intelligence | | |
| Judgments and Attitudes | | Cognitive Allocation | Effort | |
| Situational awareness | | Working memory | Resource availability (workload, fatigue) | |
| Trust | | Attention allocation | Usability | |
| | | Other dependability monitoring | | |
| Decision Making | | | Task Performance | |
| Optimality | Robustness | | Error rates | Timeliness |
| Risk level | Reliance | | Other performance | |

Machine capabilities might be the underlying cause of failures in teaming



Cognition Structures and Algorithms



Mission knowledge

Cognition Software and Hardware



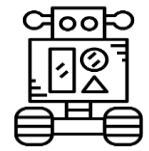
Operating system

Standard Platform

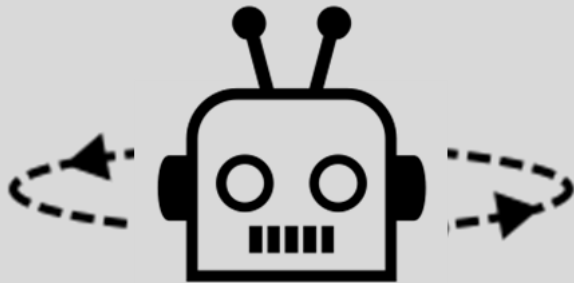


Sensors

Machine perspective, resource allocation, and resource use critically impact team outcomes



Perspective



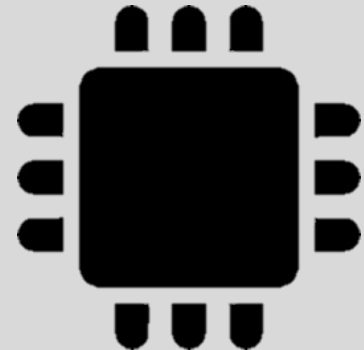
Situational awareness

Resource Allocation



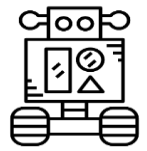
**Process/threat
monitoring**

Resource Use

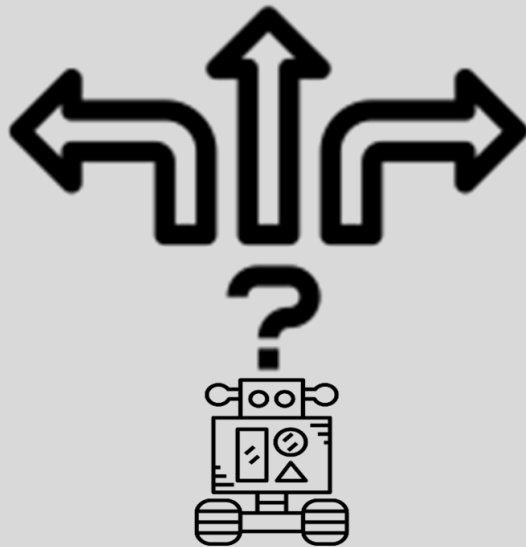


Processing

Machine performance might be subpar even if the team successfully completes the mission

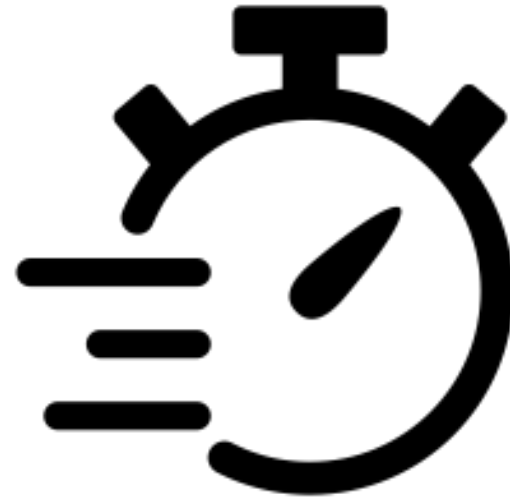


Decision Making/Action



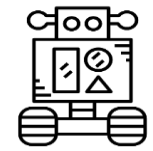
Decision-making optimality

Task Performance



Timeliness

Machine capabilities, awareness, and actions affect interaction with the human and the mission



| Cognition Structures and Algorithms | | Cognition Software and Hardware | Standard Platform |
|-------------------------------------|------------|---------------------------------|------------------------------------|
| World model | | Prioritization | Structural and mechanical elements |
| Mission knowledge | | Algorithm flexibility | Sensors |
| Teammate knowledge and experience | | Operating system | Computer and peripherals |
| Integration hardware | | | |
| Perspective | | Resource Allocation | Resource Use |
| Situational awareness | | Activity execution | Platform operating margin |
| | | Process/threat monitoring | Processing |
| | | Other dependability monitoring | |
| Decision Making/Action | | Task Performance | |
| Optimality | Robustness | Error rates | |
| Risk level | Reliance | Timeliness | |
| | | Other performance | |

By focusing on the team, this framework provides a guide for comprehensively evaluating human-machine teams

- Outlined critical approach for assessing effective teaming
- Emphasized the importance of interaction – focused on the team as the unit of analysis
- Provided a structure for identifying and selecting appropriate measures to evaluate team effectiveness

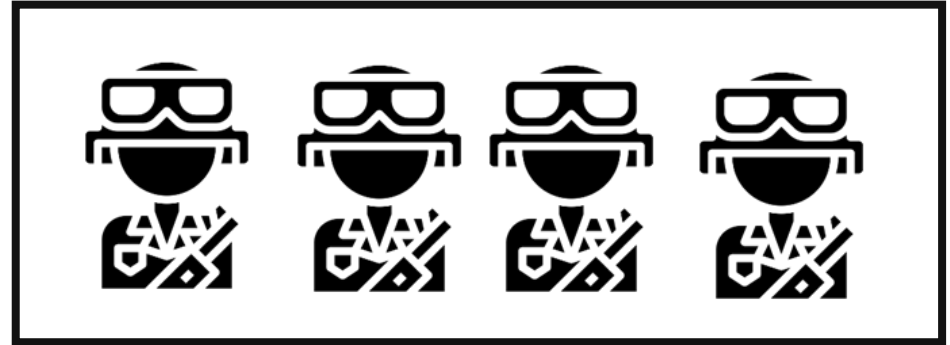
This framework allows us to understand whether a team is effective in general, not just effective during the observed task.

NEXT STEPS

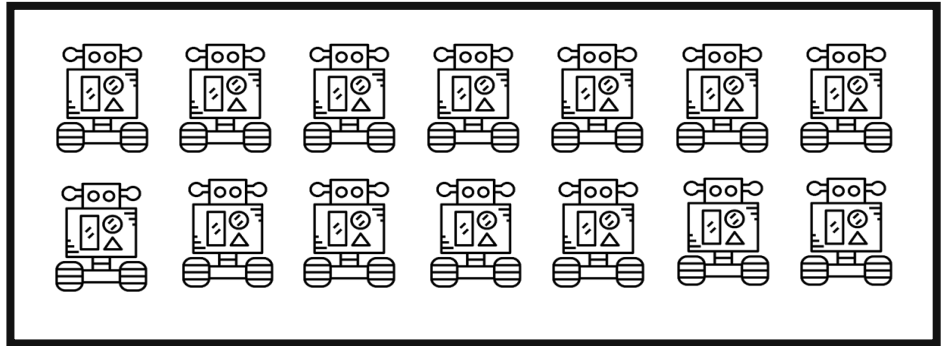
Apply the HMT framework to develop T&E methods for swarms and other unbalanced human-machine teams



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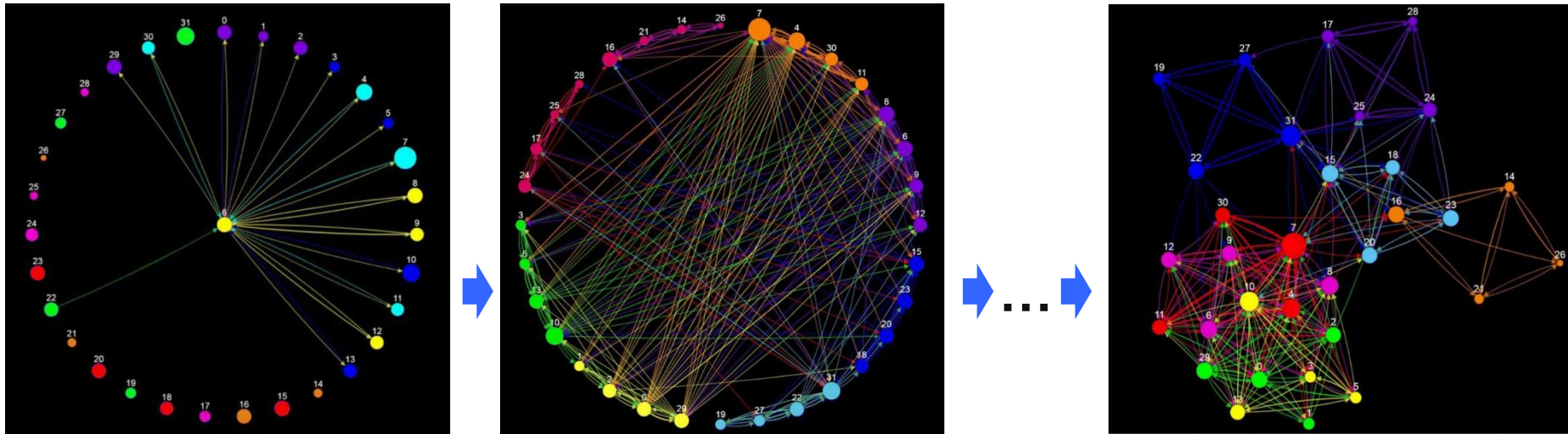
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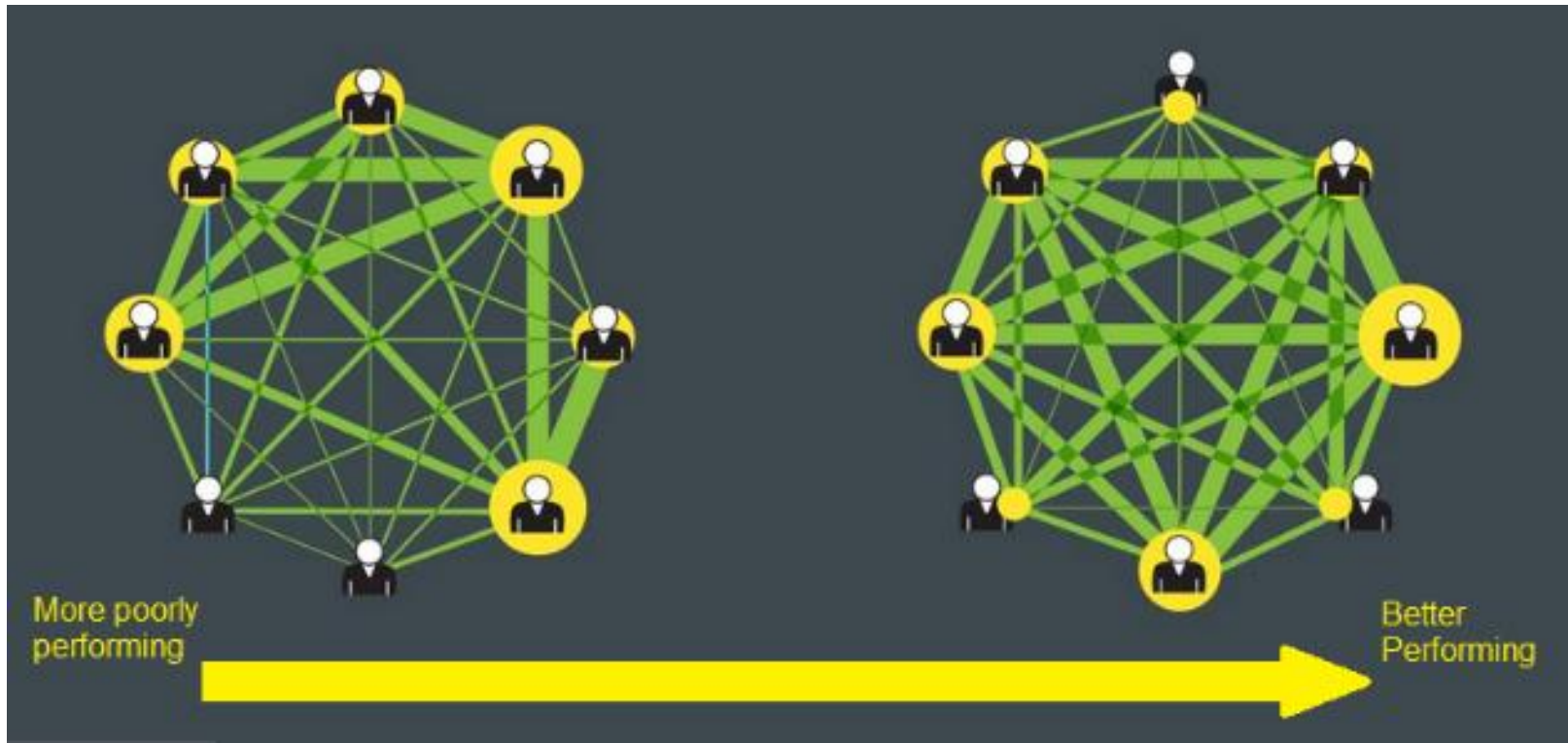
Examining human-machine teams (HMTs) with larger, more complex team structures can yield more advanced assessments of operator training, team training, and performance optimization

Expand HMT test and evaluation methods to manage additional complexity

- More complex teams
- Longer time scales and multiple tasks or missions
- Group and machine learning capabilities
- New collaborative modeling techniques



Use quantitative modeling methods to determine optimal team structures and properties



Teams can develop emergent structures and properties that can influence and potentially optimize decision making, problem solving, task delegation, and overall team functionality

Apply insights from the HMT framework to challenges in machine-machine coordination

Increased swarm capabilities

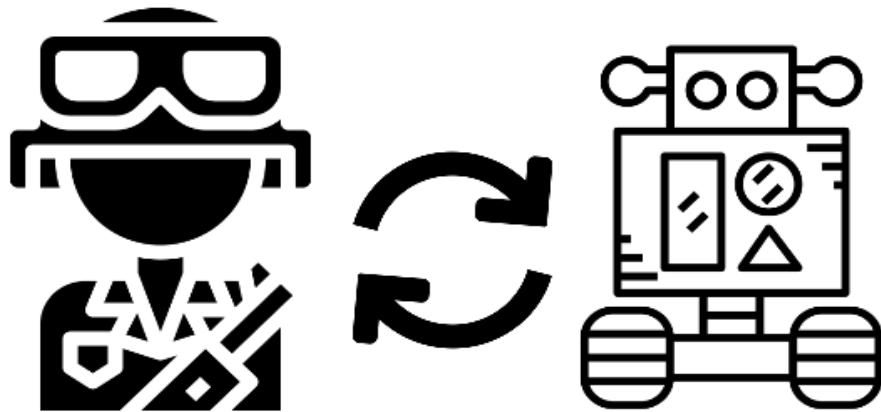
- Independent, but can coordinate with team (and operators)
- Deployable in more complex arrangements
- Deployable across larger range of missions

Future issues in swarms

- Systems integration issues can compound with larger or more complex swarms
- Particular challenges include:
 - Coordinated mobility
 - Communications limitations (bandwidth, physical separation)
 - Increased potential for emergent behavior

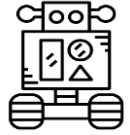
BACKUP

DEFINITIONS



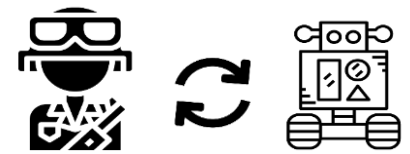
TEAM MEASURE DEFINITIONS

Capability



Team abilities and capacities that are relevant to a particular application environment and the specific applications (i.e., missions) the operator must perform

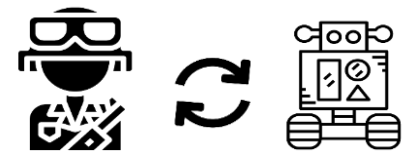
Capability: Communication Framework



Communication framework – The timeliness, capacity, dynamics, precision, and accuracy of information transfer within the team.

- **Information flow** includes the mechanics and capacity for data retention and transfer, including channels, directions, rates, control, interference, and system input-output (Burnham & Anderson, 2002; Arndt, 2004).
- **Joint world model** is the extent to which agents in the team have compatible knowledge structures (compatibility in what they can and cannot represent). Structures need not be alike (e.g., they may be complementary) but they must allow for collaboration with the other agent (Madni & Madni, 2018; Damacharla et al., 2018).
- **Joint mission knowledge** is the compatibility or complementariness of agents' knowledge of the mission, including a strategy for success and a basis for prioritizing competing goals or actions. The team members' knowledge need not be identical (even completely consistent), but must enable collaboration for mutual support in pursuing the mission. Example areas likely to be key include red and blue team tactics, techniques, and procedures (TTPs), standard operating procedures (SOPs), and target weak points (Canonico, 2019).

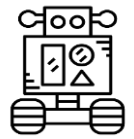
Capability: Structure-Based Interaction



Structure-based interaction – Team agent interactions that are determined and influenced by team organization and architecture.

- **Influence** is the ability of one team agent to elicit a response (cognitive, verbal, emotional, or behavioral) from other teammates (Crichton & Flin, 2004).
- **Role clarity and adaptability** includes awareness, maintenance, and—when necessary—adaptation of action boundaries (within the team and external to it), assigned roles and duties, action, and communication interfaces. Flexibility within teams to recognize the need for adjustment and the ability to implement necessary adjustment (Madni & Madni, 2018; Damacharla et al., 2018). Role clarity under all circumstances and adaptability (if present as a feature) will be of particular importance for the interactions within the team.

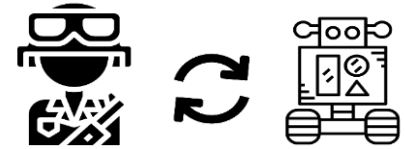
Capability: Architecture



Architecture – Group structure/architecture of team: imposed, implicit, or dynamic.

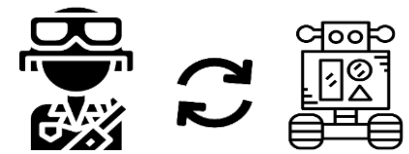
- **Hierarchical relationships** are the directional influence and command architecture(s) within the team, implied or imposed (Madni & Madni, 2018; Damacharla et al., 2018; Klein et al., 2006; Greening et al., 2015; Greening, 2014; Moore et al., 2012).
- **Uni- and bi-directional relationships** are the characterization of directional command, influence, communication, or action relationships between or among two or more team agents (Damacharla et al., 2018; Greening et al., 2015; Greening, 2014; Moore et al., 2012).
- **Learning patterns** represent the method(s) by which the team assimilates, applies information, adapts, and evolves over time in response to task and team knowledge architecture (Greening et al., 2015; Greening, 2014; Jiang, 2007; Moore et al., 2012).

Interaction



How team members engage in coordination, cooperation, and efficient goal pursuit during execution

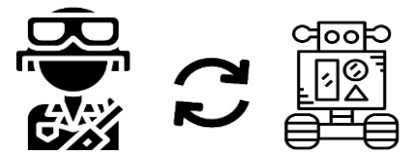
Interaction: Perspective



Perspective – What the team knows and/or believes about the world.

- **Situation awareness** is the extent to which a group perceives and distributes information regarding knowledge of collective group actions, tasks, or decisions based on the group's (1) architecture, (2) interaction dynamics, (3) comprehensive environment, and (4) effects, consequences, and influences of environmental factors (Endsley, 1995b). Includes contextual awareness; that is, the team's assessment of objective factors and their potential effects on a task and its completion potential – including physical, social, cultural, economic, and political environments (i.e., the social terrain), friendly vs. adversarial scenarios, etc. (Madni & Madni, 2018; Damacharla et al., 2018).
- **Information accuracy** is the correctness and precision of information passed between team members (Burnham & Anderson, 2002; Arndt, 2004).

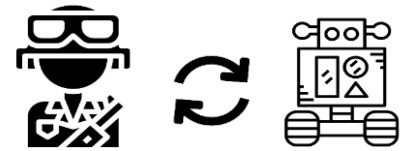
Interaction: Cooperative Behavior



Cooperative behavior – The extent to which the team works together to attain a mutual goal or complementary goals (see cooperation definition in *APA Dictionary of Psychology*, 2007).

- **Cohesion** is the dynamic process that is reflected in the tendency of a group to remain united in the pursuit of its instrumental objectives and the satisfaction of member needs (Damacharla et al., 2018).
- **Intervention** is the extent to which teammates interact with and affect with each others' actions (Damacharla et al., 2018). Interruption of or direct interaction with a teammate's actions may have a negative impact on overall team performance but it may also be necessary to resolve errors (Damacharla et al., 2018). Previous research indicates that the relationship between intervention and performance is non-monotonic; it is an inverted u-shaped curve where some interactions improve performance but too many hurt it (Damacharla et al., 2018).
- **Team trust** is the attitude that combined group effort “will help achieve [a team's] goals in a situation characterized by uncertainty and vulnerability” (Lee & See, 2004, p. 54). Lee and See's (2004) three general bases of trust in the context of automation (performance, process, and purpose) are likely to play a role in human-machine teams. Based on previous trust in automation research, levels of trust may be ill-calibrated (i.e., overly trusting or insufficiently trusting) due to erroneous judgments of a teammate's performance, process, or purpose (Madhavan & Wiegmann, 2004; Wickens et al., 2000).
- **Agency shifting** involves how and when roles and control in the team change, as well as how the team adapts to filling different roles, having different levels of control, and changes in roles and control (DeRue & Morgeson, 2007).

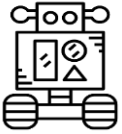
Interaction: Team Resource Allocation



Team resource allocation – Distribution and changing levels of cognitive, physical, and incentive factors among team members.

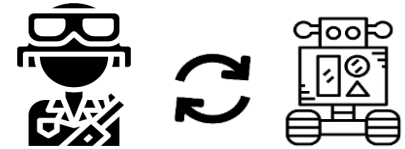
- **Joint attention allocation** measures the distribution of limited attention paid collectively to the team's tasks and the ability of the team to dynamically attend to and prioritize varied responsibilities such as strategic planning and current assignments (Madni & Madni, 2018; Damacharla et al., 2018).
- **Workload transfer** involves any general process by which one or more tasks are transferred from one subset of team members to another; similar to but more general than human-machine/machine-human intervention (Madni & Madni, 2018; Damacharla et al., 2018).
- **Endurance** is a measure of a team's collective capability to proceed with a task when under stress (Madni & Madni, 2018; Damacharla et al., 2018).

Team Performance



**Assessment of decisions, results, and
subsequent effects generated by
or attributable to team action**

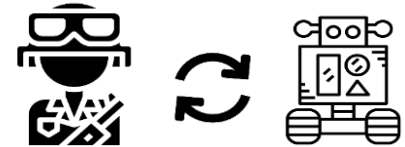
Team Performance: Collective Decision Making



Collective decision making – A team’s assessment of objective factors and their potential effects on the task and its completion potential.

- **Optimality** is the extent to which a decision maximizes utility and efficiency. That is, the extent to which the course of action taken maximizes the “value” of a decision. This is usually calculated by a combination of the values of the range of outcomes and the probability of that outcome occurring, given a decision (adapted from Edwards, 1961; Becker & McClintock, 1967). Notably, forming decisions according to statistical and mathematical models of optimal decision making is often complex and time-consuming, and it requires more information than is usually available in real-life decision making (Becker & McClintock, 1967, Kurz-Milcke & Gigerenzer, 2007).
- **Risk level** is extent to which the team’s collective decisions or actions take into account the perceived threat of a given situation and the vulnerability expected from taking a certain action (Krokhmal et al., 2003).
- **Robustness** is a measure of how effective the team’s decision-making framework is at choosing actions for different (types of) situations (Krokhmal et al., 2003). The extent to which the decision-making process “takes into account the stochastic nature of risk-inducing factors, and generates decisions that are not only effective on average (in other words, have good ‘expected’ performance), but also safe enough under a wide range of possible scenarios” (Krokhmal et al., 2003 p. 2; see also Gigerenzer & Gaissmaier, 2015).

Team Performance: Collective Task Performance



Collective task performance – The quality of team productivity, efficiency, and other important outcome measures for a given task.

- **Task success/failure** is the team's accuracy on a given task, regardless of resource use.
- **Timeliness** is the time to complete the task or a ratio of “time focused on task” to “time assigned to task” (Chen & Chen, 2011).
- **Planning recognition** is the ability of the team to identify (one or more possible sets of) steps and subtasks necessary for the completion of the task as a whole (Bolia et al., 2006).
- **Efficiency** is a measure of how effectively the team performs while using the least amount of resources within its resource constraints (Ho, 1972).



HUMAN MEASURE DEFINITIONS

Capability



A human agent's physical and psychological abilities and capacities that are relevant to a particular environment and the missions the agent must perform

Capability: Training and Experience



Training and experience – Relates to an operator's psychological and physical readiness for a mission, including knowledge of the mission, knowledge of mission systems and agents, natural talent, and prior interaction with other agents and systems that impacts the operator's ability to effectively perform the mission.

- **Mental model** is an internal representation of knowledge (the world, teammates, objects, processes), which can then be manipulated for reasoning processes (Johnson-Laird, 1989). While this concept encapsulates all types of knowledge, for test and evaluation purposes this can only be imperfectly estimated, with different communities using different terms (discussed in Staggers & Norcio, 1993).
- **Mission knowledge** is the range of one's information about and understanding of the mission (knowledge). Consists of representations within one's mental model allowing for flexible mission accomplishment (e.g., red and blue team TTPs and SOPs), target information (e.g., weak points, identifiers), strategies for mission success, and a basis for prioritizing competing goals or actions, among other components (Dept. of the Army, 2019).
- **Teammate knowledge and experience** is the range of one's understanding of or information on the machine teammate (knowledge). This might include operational guidelines and capabilities, system specifications, and system troubleshooting routines (c.f. Ericsson et al., 2018). Also includes the operator's ability or proficiency with the system (human interacting with machine), acquired through previous training or practice with the system (skill; c.f. Ericsson et al., 2018). This will be related primarily to their time and use of the relevant system(s) in the past, including the range of domains, functions, contexts, etc.

Capability: Psychological Traits



Psychological traits – “Relatively *enduring* characteristics” that “appreciably *differentiate* the individual from others” (Anastasi, 1948, emphasis in original). Traits are expected to manifest in the observable behavior of individuals; however, behavior also is impacted by the situation and by the individual’s state (“systematic changes in the condition of the organism over time periods of moderate duration”) (Anastasi, 1983, p. 348).

- **Decisiveness** is the tendency to engage in the decision-making process, particularly a tendency to simplify information which simplifies making decisions regardless of the quality of the decision (Kruglanski & Webster, 1996; Neuberg & Newsom 1993; Roets & Hiel, 2007; Wichary et al., 2008; Weissman, 1976). Decisiveness has also been related to need for closure (NFC) (Webster & Kruglanski, 1994) as a tendency to make decisions quickly in order to mitigate uncertainty. However, at least one study has disputed decisiveness as a facet of NFC (Kossowska, Van Hiel, Chun, & Kruglanski, 2002), and Roets and Hiel’s (2007) findings indicate that decisiveness can be operationalized as both an ability (more closely represented by Weissman’s 1976 conceptualization) and a need (consistent with a facet of the NFC). Decisiveness can be generalized or be context- or domain-specific (Potworoski, 2010), so selection of the appropriate scale needs to be based on researcher’s intent.
- **Impulsiveness** or impulsivity “is the tendency to be impulsive, spontaneous, and careless as opposed to controlled, reflective, and cautious” (Tellegen, 1982). Dickman (1990) distinguishes two kinds of impulsivity: dysfunctional impulsivity and functional impulsivity. “Dysfunctional impulsivity is the tendency to act with less forethought than most people” in a way that results in poor decision making and increased difficulty (Dickman, 1990, 95). Functional impulsivity “is the tendency to act with relatively little forethought when such a style is optimal” (Dickman, 1990, 95). More recent work characterizing impulsiveness is in Whiteside and Lynam (2001) and MacKillop et al. (2016).

Capability: Psychological Traits



Flexibility includes the ability to choose among approaches to tasks in the execution trade-space, including the use of multi-tasking (e.g., taking a different approach when the current one is not succeeding).

- **Multi-tasking** is the extent to which the operator is capable of engaging in concurrent or switching activities and their likelihood of engaging in such activities. Multi-tasking capability and frequency of multi-tasking engagement have been found to be negatively correlated (see Sanbonmatsu et al., 2013; Watson & Strayer, 2010). For a thorough discussion of multi-tasking, see Salvucci and Taatgen, 2010 (Janssen provides a summary in her 2012 review).
- **Adaptability** is “the capacity to make appropriate responses to changed or changing situations; the ability to modify or adjust one’s behavior in meeting different circumstances of different people” (VandenBos, 2007, p. 18). See Martin, 2017, for further discussion of the conceptual bounds of this construct and Martin et al., 2012, for validation of an adaptability scale.
- **Intelligence** is the ability to derive information, learn from experience, adapt to changing environments, understand, and correctly utilize thought and reason (definition of intelligence adapted from VandenBos, 2007, *APA Dictionary of Psychology*). See also Sternberg, 2005 and 2019, and McGrew, 2009, for psychometric approaches to intelligence. There is no generally agreed-upon definition of intelligence; here, it refers to the many executive and related functions (e.g., fluid intelligence, Raven et al., 1988; and cognitive flexibility, Monsell, 1996) that may impact T&E, not just Gf-Gc (fluid intelligence-crystalized intelligence) theory (Horn & Noll, 1997).

Capability: Physical Abilities



Physical abilities – The capability to perform some physical activity. Physical ability is defined by the requirements of a given task, occupation, or mission—one may possess physical ability to excel at performing in one occupation but lack the physical ability to perform in another (Hogan, 1991).

- **Physical fitness** includes strength, speed, and endurance.
 - **Strength** is the degree to which muscular force can be applied to perform a task. Physical strength generally is increased through repeated resistance training, and maximal strength can be measured by one's highest possible load (Friedl et al., 2015; Hogan, 1991). Improved strength is thought to reduce the risk of physical injury (Friedl et al., 2015).
 - **Speed** is the velocity at which an agent is able to progress from one physical location to another. Speed has been found to be closely related to agility and jumping ability among competitive-level, young sports athletes, indicating that these capabilities stem from the same physical attributes (Negra et al., 2017).
 - **Endurance** is the degree to which physical effort can be sustained or prolonged (Hogan, 1991). Physical muscle endurance can be increased through high repetitions of high loads (Friedl et al., 2015). Endurance generally is measured by the total time for which a particular activity can be maintained (Hogan, 1991; Vago et al., 1987).
- **Sensors (organs and equipment)** includes all input devices (e.g., sense organs) and capabilities of equipment, such as radar, chemical detectors, pressure sensors, video cameras, and microphones, among others. This includes sensors supporting the cognitive teaming function.

Worldview



The agent's resource-constrained processes to represent the current and changing state(s) of the environment(s), and the representation that results

Worldview: Judgment and Attitudes



Judgment and attitudes – Judgment refers to the process by which “multiple, fallible, incomplete, and sometimes conflicting cues” are integrated “to infer what is happening in the external world” as well as the inferences made by that process (Hastie, 2001, p. 657). Attitudes are “affective evaluation[s] of beliefs that guides people to adopt a particular intention” (Lee & See, 2004, p. 53). Attitudes are based on the informational foundation of perceptions and beliefs, but they are distinct from that foundation; similarly, attitudes guide human intentions, which translate into behaviors, but attitudes are not equivalent to the intentions or behaviors they influence (Lee & See, 2004).

- **Situational awareness** as defined by Endsley (1995, p. 65) “is the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their future status.”
- **Trust** is “the attitude that an agent will help achieve an individual’s goals in a situation characterized by uncertainty and vulnerability” (Lee & See, 2004, p. 54). Lee and See’s (2004) three general bases of trust in the context of automation (performance, process, and purpose) are likely to play a role in human-machine teams. Based on previous trust in automation research, levels of trust may be ill-calibrated (i.e., overly trusting or insufficiently trusting) due to erroneous judgments of a machine teammate’s performance, process, or purpose (Madhavan & Wiegmann, 2004; Wickens et al., 2000).

Worldview: Cognitive Allocation



Cognitive allocation – “A state in which cognitive resources are focused on certain aspects of the environment rather than on others, and the central nervous system is in a state of readiness to respond to stimuli. Because it has been presumed that human beings do not have an infinite capacity to attend to everything—focusing on certain items at the expense of others—much of the research in this field has been devoted to discerning which factors influence attention and to understanding the mechanisms that are involved in the selective processing of information. For example, past experience affects perceptual experience (we notice things that have meaning for us), and some activities (e.g., reading) require conscious participation (i.e., voluntary attention). However, attention can also be captured (i.e., directed involuntarily) by qualities of stimuli in the environment, such as intensity, movement, repetition, contrast, and novelty” (Attention, as defined in *APA Dictionary of Psychology*; see also McCallum, 2015).

- **Working memory** is the cognitive system or group of cognitive systems that are used to keep necessary information in mind to enable complex tasks such as reasoning, comprehension, and learning (Baddeley, 2010; Engle, 2002). Many measures of working memory have been developed (see Conway et al., 2005). For a comprehensive treatment of working memory, see Conway, 2016.
- **Attention allocation** refers to the focused direction or distribution of limited cognitive resources (Archibald, Levee, & Olino, 2015). Humans do not possess an infinite capacity to attend to stimuli; attention allocation thus captures the direction or distribution of stimuli that cognitive resources are devoted to for a given period of time.
- **Other dependability monitoring** refers to [typically implicit] processes used for health monitoring systems and indicated mitigations; it includes monitoring of teammates. It also includes safety and reliability, legal/moral/ethical considerations, and assurances that warfighters not only will do what you want but also will not do what you do not want.



Effort – The expending of physical or mental exertion.

- **Resource availability** includes workload and fatigue.
 - **Workload** is the portion of operator physical or mental resources that are required to meet task demands (Lysaght et al., 1989); the costs to the operator to accomplish the mission. Workload might include the amount of work such as the number of tasks to complete and the difficulty of those tasks, the time that one has to complete the task, and the subjective experience of the human operator (Cain, 2007; Lysaght et al., 1989). Thus, workload might include objective and subjective measures but often workload is measured using a subjective scale of workload that measures the operator's experience of workload. The most well-known such scale is the NASA-TLX, which includes six subscales measuring different facets of workload (Hart & Steveland, 1988; Hart 2006), but validated single-item measures also exist (i.e., the AFFTC Revised Workload Estimate Scale or ARWES, Ames & George, 1993).
 - **Fatigue** is a “specific form of human inadequacy in which the individual experiences an aversion to exertion” and a sensation of an inability to continue activity (fatigue, physiology). Fatigue may be physical, experienced as a “an unpleasant bodily state, including headaches, tension, and vague pains in muscles and joints,” but it may also be cognitive, manifested by an “unfocused mental state (distraction, frustration, discomfort),” or affective, manifested by low mood, tiredness, or lethargy (Hockey, 2013, p. 1). Fatigue can be a consequence of everyday shifts in mood and quality of life; in more extreme cases it can be “felt as physical exhaustion, a total incapacity for any exertion, a profound lack of motivation, or depression” (Hockey, 2013, p. 1).

Worldview: Effort cont.



- **Usability** is generally defined as the ease with which an operator can use a system, but it is a multi-dimensional concept that is associated with five underlying attributes: learnability (or the ease with which a new operator can learn to employ the system), efficiency (the productivity an operator can attain once they learn to use the system), memorability (the ease with which an operator can return to use of the system after a period away, without having to relearn the system), errors (the error rate of the system should be low and it should recover quickly from errors that are made), and satisfaction (operators should be subjectively satisfied by the system; it should be pleasant to use) (Nielsen, 1994). The System Usability Scale (SUS) is generalizable to a wide range of systems and is often used as a subjective measure of usability (Brooke, 1996).

Performance



**Assessment of decisions, results,
and subsequent effects generated by
or attributable to agent action**

Performance: Decision Making



Decision making – “The entire process of choosing a course of action,” including the consideration of alternative courses of action, uncertain conditioning events, and consequences associated with potential outcomes (Hastie, 2001, p. 657).

- **Optimality** is the extent to which a decision maximizes utility. That is, the extent to which the course of action taken maximizes the “value” of a decision. This is usually calculated by a combination of the values of the range of [expected] outcomes and the probability of that outcome occurring, given a decision (adapted from Edwards, 1961; Becker & McClintock, 1967). Notably, forming decisions according to statistical and mathematical models of optimal decision making is often complex and time- consuming, and it requires more information than is usually available in real-life decision making (Becker & McClintock, 1967; Kurz-Milcke & Gigerenzer, 2007).
- **Robustness** is the extent to which the decision-making process “takes into account the stochastic nature of risk-inducing factors, and generates decisions that are not only effective on average (in other words, have good ‘expected’ performance), but also safe enough under a wide range of possible scenarios” (Krokhmal et al., 2003, p. 2; see also Gigerenzer & Gaissmaier, 2015).

Performance: Decision Making cont.



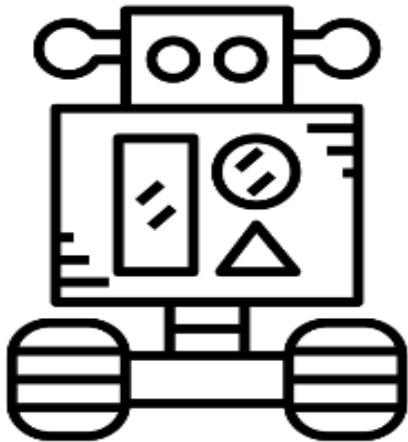
- **Risk level** is the extent to which a decision involves a gamble on its desired outcome or expected value as opposed to ensuring that desired or expected outcome (Kahneman & Tversky, 1980). Risk-averse decision making is characterized by decisions that show a preference for “the certain prospect (x) over any risky prospect with the expected value x” (Kahneman & Tversky, 1980, p. 264). In contrast, risk-seeking decision making is characterized by a preference for the gamble over its expected value (e.g., choosing to participate in a gamble to receive \$100 or nothing with a 50% chance of winning over winning a sure \$50). As outlined by prospect theory, humans tend to be risk averse when it comes to positive outcomes or gains—preferring higher certainty even if the gained value is lower (e.g., rather win \$45 than have a 50% chance to win \$100 and 50% chance to win nothing), but to be risk seeking when it comes to negative outcomes or losses—preferring to maximize the probability of avoiding loss even if the expected value of those decisions are lower (e.g., rather have a 50% chance of losing \$100 and 50% chance of losing nothing than a certain loss of \$45) (Kahneman & Tversky, 1980).
- **Reliance** is the behavioral act of dependence on another agent for the accomplishment of some goal. Reliance is influenced by trust but not determined by it (Lee & See, 2004; Madhavan & Wiegmann, 2007).

Performance: Task Performance



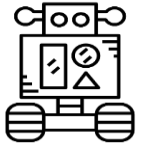
Task performance –The effectiveness with which agents engage in and complete activities that contribute to the overall mission either directly, such as through implementing an action or decision, or indirectly, such as by providing necessary information or services (Borman & Motowidlo, 1997). Task performance has been distinguished from contextual performance, which influences “effectiveness in ways that shape the organizational, social, and psychological context that serves as the catalyst for task activities and processes” (Borman & Motowidlo, 1997, p. 100). Contextual performance includes such factors as trust (found under worldview), whereas task performance is best measured using objective factors such as those described below.

- **Error rate** is the frequency or duration of deviations from correct task procedure throughout mission accomplishment relative to total tasks or task time performed for the mission. Examples of error rate measures include the number of errors in a given time period and the probability of a miss given the number of shots taken.
- **Timeliness** is the extent to which the agent completes the required task(s) within an allotted amount of time (Cothier & Levis, 1986). Examples of timeliness measures include time to complete [a task] (TTC), time to target (TTT), and time to detect (D_T or T_D).
- **Persistence** (the action of persevering) is the sustainment of effort on a task or towards a goal despite obstacles (persistence); that is, “directed effort extended over time” (Locke et al., 1981). Persistence has a positive connotation and persisting behavior has been shown to enhance performance (Maddi et al., 2012). Despite this, in some instances this behavior can impede completion of a higher goal (Lucas et al., 2015).



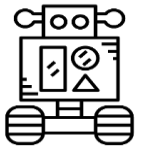
MACHINE MEASURE DEFINITIONS

Capability



A system's capability includes the key attributes of the system as a function of its application environment and specific applications (e.g., missions)

Capability: Cognition Structures and Algorithms

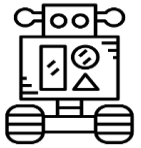


Cognition structures and algorithms – The knowledge structures and processes that the machine uses to represent information—stored and dynamic from sensors and communications—about the world, mission, and teammate(s). These capabilities inform task selection, task accomplishment, teaming, and communication, among related performance metrics.¹ While there are many ways to computationally represent and store the information to be used by the machine, here we build upon Laird’s (2012) Soar model as an example, with different types of knowledge stored in networked structures, similar to expert systems (Buchanan et al., 2018). While these may or may not be explicit or “explainable” (Samek et al., 2019), we note that during T&E critical capabilities representing the world, the mission, and teammate(s) must be testable.

- **World model** provides the structure for the machine knowledge (what it can and cannot represent, Laird, 2019). The key point is that the structure is not required to be complete or high fidelity—the structure must only be sufficient to support collaboration with any teammate(s) operating with a similar and/or different worldview.
- **Mission knowledge** is the range of the system’s information about and understanding of the mission (knowledge) within an information representation (c.f. Laird, 2019). Consists of representations allowing for mission support broadly defined, in and beyond breadth of Joint Forces Command, joint command, and operation doctrines (e.g., U.S. Army, 2017, including Red and Blue team TTPs and SOPs), target information (e.g., weak points, identifiers), strategies for mission success, a basis for prioritizing competing goals or actions, etc.

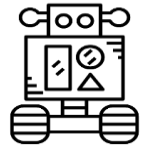
¹ As such, this is analogous to the training and experience, and to some extent the psychological traits, in the human. Unlike the human, a machine needs to be provided a structure or ontology (usually explicit) that allows for interaction with humans.

Capability: Cognition Structures and Algorithms cont.



- **Teammate knowledge and experience** is made up of representations allowing the machine to coordinate activities with any teammate(s). These include activities up to and beyond the relevant agent's capabilities and procedures: training and skills, mission orientation, best and most appropriate communication method(s), etc. Potentially, these activities could be updated as they are executed. Also includes the machine's ability or proficiency with the human acquired through previous training or practice with the human. This proficiency is related primarily to the machine's time and "experience" (possibly as a form of learning data), including the range of domains, functions, contexts, etc.

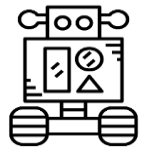
Capability: Cognition Software and Hardware



Cognition software – Software that executes or supports higher-level capabilities (cognitive algorithms). Cognition software includes processes that are analogous to lower-level human cognitive functions and that allow processing to occur (e.g., operating system, firmware, transport bus procedures, and other basic processes for executing computational processing) (Sandini et al., 2007). Controller and interface functions may be separated into software and hardware components during developmental T&E, but typically not during operational T&E.

- **Prioritization** is the process of deconflicting or deferring competing subsystem claims for cases of CPU, memory, bandwidth overload, etc. Given limits on system resources, rules or algorithms are required to decide where resources will be allocated, and these rules may depend on the system and mission (Wang et al., 2010).
- **Algorithm flexibility** is the ability to choose among algorithms in the execution trade-space (e.g., use a lower performing but lower latency algorithm when latency becomes an issue); the visible portions acting on the world are built into the action selection mechanisms within the agent architecture (Bryson, 2000). We are scoring this as a “controller” function rather than a “cognitive” function, thus its inclusion in cognition software.
- **Operating system/memory** includes the software, hardware, and firmware enabling computations, as well as any “controller” software specific to autonomous operation or teaming. This can include a range of processes for accessing, interfacing with, and engaging with hardware components.

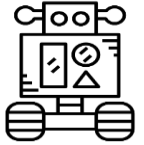
Capability: Standard Platform



Standard platform – Platform hardware features make it possible for the machine to receive, process, and transmit information and to interact with the world, including aspects required for information integration (c.f. Sage & Lynch, 1999). These features allow for computation, sensing, communications, and other interactions, including movement, engines, tires, wings, radar, audiovisual sensing, etc.

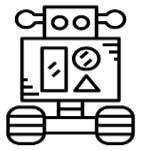
- **Structural and mechanical elements** include structural components such as frames, bearings, and axles; control mechanisms such as gear trains, brakes, and engines; control components such as actuators and controllers for other systems; and sensors that allow for integration (Lelikov, 2009; automotive applications discussed in Fleming, 2001).
- **Sensors** include all input devices not part of integration hardware or computer and peripherals (e.g., radars, chemical detectors, pressure sensors, video cameras, and microphones). These include sensors supporting the cognitive teaming function.
- **Computer and peripherals** involve additional mechanics not related to computation software. These can include hard drives, I/O hardware, etc. for platform operation. In some architectures, the teaming-specific function is handled by processors that also handle platform operation (Whitten & Bentley, 2005).
- **Integration hardware** overlaps with I/O hardware, wireless capabilities, and other items needed for successful teaming.

Worldview



**The agent's resource-constrained processes
to represent the current and
changing state(s) of the environment(s),
and the representation that results**

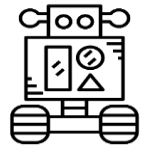
Worldview: Perspective



Perspective – What the machine knows and/or believes about the world. This is consistent with the technical definitions from art or drawing—with explicit acknowledgment that a perspective can be misleading. This largely maps to the *sense* portion of robotics’ “sense-plan-act” design philosophy (Siciliano & Khatib, 2008), which allows for planning and acting (decision making in this framework).

- **Situational awareness** is “the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their future status” (Endsley, 1995, p. 65).
- **Physical world** refers to knowledge and processing about the machine’s environment, primarily used for physical navigation (i.e., locomotion and wayfinding; Montello, 2005), to include agents other than teammates. It includes but is not limited to terrain, weather, where red units and structures are, and possible threats (Anderson et al., 2016).
- **Internal** refers to the machine’s awareness of its own design performance and deviations therefrom enabled by sensors, integration, and other capabilities (Anderson et al., 2016).
- **Cyber situational awareness** is the collection and processing of data to provide an understanding of cyber health or compromise (Jajodia et al., 2010; reviewed in Franek & Brynielsson, 2014), including the Identify, Protect, Detect, Respond, Recover framework (NIST, 2018).
- **Teammate** refers to the machine’s knowledge of the human: location, activity, health, processing capability, etc. (Chakraborti et al., 2017)

Worldview: Resource Allocation



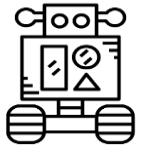
Resource allocation – Processes that enable resource claims on machine operation (e.g., CPU usage, sensor operation), especially those processes that enable teaming (e.g., explore-exploit tradeoffs in task completion and communication) (Wilson, 1996).

- **Activity execution** refers to the subsystems the machine employs to organize, schedule, and integrate tasking of various OSs, devices, algorithms, etc. (i.e., processor management to larger control-systems, parallel to human “working memory”). Can be among a range of techniques, including dynamic programming, reinforcement learning, combinatorial optimization (Busoniu et al., 2010), and lower-level task scheduling (Cerotti et al., 2015).
- **Process/threat monitoring** denotes the I/O streams that feed normal operations and may be associated with cyber intrusions, such as computer, user, access, SIEM, externals, certificates, credentials, and other details for security assurance (Splunk, Snort, Wireshark) (passive and active sources in Curry et al., 2013). *Note:* Machine Cyber SA above is the awareness that results.
- **Other dependability monitoring** refers to health monitoring systems and indicated mitigations; includes machine monitoring of humans, if data are available to machine. Also includes safety and reliability, legal/moral/ethical considerations, and assurances that the machine not only will do what you want but also will not do what you do not want.

Note 1. The output of the resources allocated to monitoring feeds the situational awareness under “perspective.”

Note 2. “Allocation,” as opposed to “use” which follows, is biased toward the cognitive rather than the physical resources, allowing this to be more parallel with the human.

Worldview: Resource Use

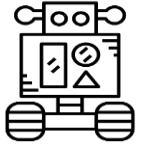


Resource use – Resource utilization in machine operation (electrical power, CPU usage, sensors, integration of inputs). Measurements required for the machine to function include the following (most of these are lower level processes that permit the dependable functioning of complex mechanical systems; Siciliano & Khatib, 2008):

- **Platform operating margin** refers to SWaP-C limits; analogous to limits on non-autonomous systems.
- **Processing** refers to CPU and memory margins (thermal and power constraints on processing could go here or line above).

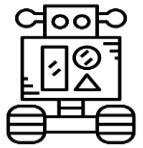
Note 1. The monitoring in “resource allocation” is a “demand” signal on resource use for the sensors and other subsystems. Resource use is the provided resources, whatever the demand.

Performance



**Assessment of decisions, results,
and subsequent effects generated by or
attributable to agent action**

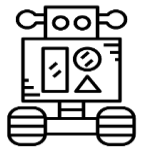
Performance: Decision Making



Decision making/action – “The entire process of choosing a course of action,” including the consideration of alternative courses of action, uncertain conditioning events, and consequences associated with potential outcomes (Hastie, 2001, p. 657; various autonomous forms discussed in Veres et al., 2011). Also includes the enacted choice itself.

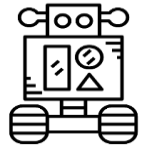
- **Optimality** is the extent to which a decision maximizes utility. That is, the extent to which the course of action taken maximizes the [expected] value of a decision. This is usually calculated by a combination of the values of the range of outcomes and the probability of that outcome occurring, given a decision and available information (adapted from Edwards, 1961; Becker & McClintock, 1967).
- **Robustness** is the extent to which the decision-making process “takes into account the stochastic nature of risk-inducing factors, and generates decisions that are not only effective on average (in other words, have good ‘expected’ performance), but also safe enough under a wide range of possible scenarios” (Krokhmal et al., 2003 p. 2; see also Gigerenzer & Gaissmaier, 2015).

Performance: Decision Making/Action cont.



- **Risk level** is the extent to which a decision involves a gamble on its desired outcome or expected value as opposed to ensuring that desired or expected outcome (Kahneman & Tversky, 1980). Risk-averse decision making is characterized by decisions that show a preference for “the certain prospect (x) over any risky prospect with the expected value x” (Kahneman & Tversky, 1980, p. 264). In contrast, risk-seeking decision making is characterized by a preference for the gamble over its expected value (e.g., choosing to participate in a gamble to receive \$100 or nothing with a 50% chance of winning over winning a sure \$50). Design of autonomous machines can attempt to bias the machines’ decision making in either risk-tolerant or risk-averse fashions, leading calibration to be important for T&E. Incomplete understanding of contributors to the decision making by designers, commanders, or teammates may result in a risk tolerance incompatible with the commander’s intent. This is a subject for T&E determination.
- **Reliance** is the behavioral act of dependence on another agent to accomplish some goal.

Performance: Task Performance



Task performance – The effectiveness with which agents engage in and complete activities that contribute to the overall mission either directly (such as through implementing an action or decision) or indirectly (such as by providing necessary information or services) (Borman & Motowidlo, 1997). Task performance has been distinguished from contextual performance, which influences “effectiveness in ways that shape the organizational, social, and psychological context that serves as the catalyst for task activities and processes” (Borman & Motowidlo, 1997, p. 100). Contextual performance includes such factors as situational awareness of teammates (found under worldview), whereas task performance is best measured using objective factors such as those described below.

- **Error rate** is the frequency or duration of deviations from correct task procedures throughout mission accomplishment relative to total tasks or task time for the mission.
- **Timeliness** is the extent to which the agent completes the required task(s) within an allotted amount of time (Cothier & Levis, 1986).
- **Persistence** (the action of persevering) is the sustainment of effort on a task or towards a goal despite obstacles (persistence). Persistence has a positive connotation and persisting behavior has been shown to enhance performance (e.g., demonstrated in humans in Maddi et al., 2012). Despite this, in some instances this behavior can impede completion of a higher goal (Lucas et al., 2015).

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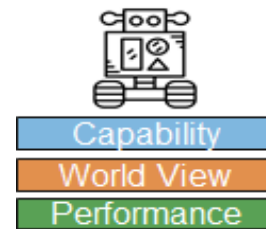
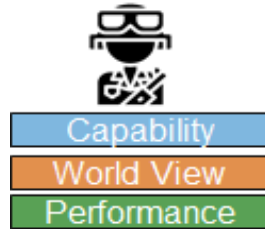
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BACKUP SLIDES

We are interested in measuring individual human and machine agents on similar concepts



Capability

Physical and psychological abilities and capacities that are relevant to a particular application environment and the specific applications (i.e., missions) the operator must perform

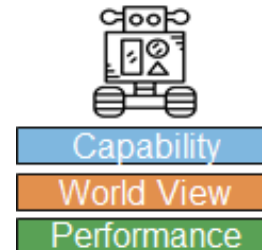
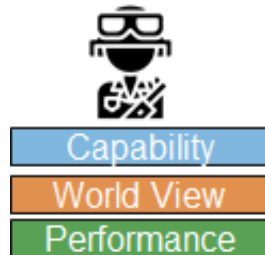
Worldview

The agent's resource-constrained processes to represent the current and changing state(s) of the environment(s), and the representation that results

Performance

Assessment of decisions, results, and subsequent effects generated by or attributable to agent action

Joint Force Command doctrine describes HOW you use MEANS to achieve ENDS. Each is important for evaluation.



Capability

MEANS: Abilities of agents of the team to get closer to the goal state.
What the agents can do coming into T&E.

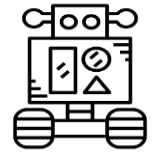
Worldview

HOW: Agent engagement processes with the environment and the mission. Factors that change during T&E.

Performance

ENDS: Outcomes that characterize mission accomplishment.
Large amount of MOEs, MOSs, etc.

Team measures can be assessed only with two or more agents' active involvement



| Communication Framework | | Structure-Based Interaction | Architecture | |
|----------------------------|------------|-----------------------------|---------------------------------------|------------|
| Information flow | | Influence | Hierarchical relationships | |
| Joint world model | | Role clarity | Uni- and bi-directional relationships | |
| Joint mission knowledge | | Role adaptability | Learning patterns | |
| Team Perspective | | Cooperative Behavior | Team Resource Allocation | |
| Situational awareness | | Cohesion | Joint attention allocation | |
| Information accuracy | | Intervention | Workload transfer | |
| | | Team trust | Endurance | |
| | | Agency shifting | | |
| Collective Decision Making | | | Collective Task Performance | |
| Optimality | Risk level | | Task success/failure | Timeliness |
| Robustness | | | Planning recognition | Efficiency |

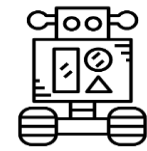
Human capabilities, judgments, and behaviors affect interaction with the machine and the mission



| Training and Experience | | Psychological Traits | Physical Abilities | |
|-----------------------------------|------------|--------------------------------|---|------------|
| Mental model | | Decisiveness and impulsiveness | Physical fitness | |
| Mission knowledge | | Flexibility | Sensors (organs/equipment) | |
| Teammate knowledge and experience | | N/A* | N/A* | |
| | | Intelligence | N/A* | |
| Judgments and Attitudes | | Cognitive Allocation | Effort | |
| Situational awareness | | Working memory | Resource availability (workload, fatigue) | |
| Trust | | Attention allocation | Usability | |
| | | Other dependability monitoring | | |
| Decision Making | | | Task Performance | |
| Optimality | Robustness | | Error rates | Timeliness |
| Risk level | Reliance | | Other performance | |

*No human equivalent to the machine version of this concept.

Machine capabilities, awareness, and actions affect interaction with the human and the mission



| Cognition Structures and Algorithms | | Cognition Software and Hardware | Standard Platform |
|-------------------------------------|------------|---------------------------------|------------------------------------|
| World model | | Prioritization | Structural and mechanical elements |
| Mission knowledge | | Algorithm flexibility | Sensors |
| Teammate knowledge and experience | | Operating system | Computer and peripherals |
| | | N/A* | Integration hardware |
| Perspective | | Resource Allocation | Resource Use |
| Situational awareness | | Activity execution | Platform operating margin |
| N/A* | | Process/threat monitoring | Processing |
| | | Other dependability monitoring | |
| Decision Making/Action | | Task Performance | |
| Optimality | Robustness | Error rates | |
| Risk level | Reliance | Timeliness | |
| | | Other performance | |

*No machine equivalent to the human version of this concept.

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