Human-Autonomy Teaming: Can Autonomy be a Good Team Player?

2019 NDIA Systems Conference
April 17, 2019

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Sponsors
Office of Naval Research (N000141712382)
Air Force Office of Scientific Research (FA9550-18-1-0067)
Army Research Laboratory (W911NF1820271)
Center for Human/Artificial Intelligence/Robot Teaming (CHART)

CHART assembles multidisciplinary teams to address human-machine integration issues in transportation, emergency response, manufacturing, medicine, and defense.

Launched: 2017

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Overview

• Taking Teaming Seriously in Human-Autonomy Teaming
• CHART Human-Autonomy Teaming Research
  ❖ Complex Team Tasks
  ❖ Testbeds/Synthetic Task Environments
  ❖ Wizard of OZ
• In Depth: The Synthetic Teammate Project
Taking Teaming Seriously in Human Autonomy Teams

Team members have different roles and responsibilities – do not replicate humans and their roles. Exceptions?
Effective teams understand that each team member has different roles and responsibilities and avoid role confusion, but back each other up as necessary - autonomy needs understanding of whole task. What does this mean?
Effective teams share knowledge about the team goals and the current situation and this facilitates coordination and implicit communication – human-autonomy team training?
Effective teams have team members who are interdependent and thus need to interact/communicate even when direct communication is impossible—some other communication model than natural language?
Interpersonal trust is important to human teams – autonomy needs to explain and be explicable. But how much and is that enough? Should it be trusted?
CHART
Human-Autonomy Teaming Research

❖ Complex Team Tasks
❖ Testbeds/Synthetic Task Environments
❖ Wizard of OZ
❖ Biometric Sensing
I study the cognitive processing of teams in the context of sociotechnical systems to improve team effectiveness.
Action-Oriented Teams
Decision Making Teams
Human-Autonomy Teams
By Using Synthetic Task Environments, we bring the context into the lab

Generic Team Decision Making Environment

Remotely Piloted Aircraft Systems—Synthetic Task Environment

Simulation of RPA Full Motion Video

Urban Search and Rescue Human Robot Interaction

MEDIC Obstacle Course for Teams
Minecraft Testbed for Human-Robot Teaming for Urban Search and Rescue

- Minecraft simulates a collapsed building
- Wizard of OZ – robot on inside searches for victims and text chats with rescuer
- Human rescuer on outside who has map
- Task is to locate victims needing immediate assistance, mark them on the map and mark structural changes
- Manipulating type of explanation – human aware or not

**Measures**
- Situation Awareness
- Trust
- Team Verbal Behaviors
- Workload
- Performance
- Demographics

WoZ allows human-autonomy teaming concerns to drive development of autonomy
CHARTopolis: A Testbed for Studying Driver Interaction with Autonomous Vehicles

- Some vehicles will be autonomous and some remotely driven
- Human-driven cars will have to interact with the driverless cars
- Will be situated in a model urban setting
The Synthetic Teammate Project

Jerry Ball, Nancy Cooke, Mustafa Demir, Jamie Gorman, Craig Johnson, Nathan McNeese, Chris Myers, Steve Shope, Alex Wolff, Sophie He, Garrett Zabala
In our RPAS-STE three operators must coordinate over headsets or text chat to maneuver their RPA to take pictures of ground targets.
Air Vehicle Operator
controls RPA airspeed, heading, and altitude and monitors air vehicle systems

Payload Operator
controls camera settings, takes photos, and monitors camera systems

DEMPC
navigator, mission planner, plans route from target to target under constraints

Three team members with interdependent tasks

Interdependence requires interaction, communication, & coordination
Some Early Work with 3-Human Teams
Team Skill Acquisition

As teams acquire experience, performance improves, interactions improve, but not individual or collective knowledge.

- Individuals are trained to criterion prior to M1.
- Team performance is a composite score based on how many targets they accurately process.
- Asymptotic team performance after four 40-min missions (robust finding).
- Knowledge changes tend to occur in early learning (M1) and stabilize.
- Process improves and communication becomes more standard over time.

Spring Break
Team Retention & Composition

- 117 males(92) & females(25) divided into 39 3-person (unfamiliar) Session 2 teams
- Two between subjects conditions (retention interval and familiarity) randomly assigned with scheduling constraints
- Participants randomly assigned to one of three roles
- Session 1: 5 40-min missions
- Session 2: 3 40-min missions

<table>
<thead>
<tr>
<th>Composition</th>
<th>Same Condition</th>
<th>Mixed Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retention Interval</td>
<td>3-5 weeks</td>
<td>10-13 weeks</td>
</tr>
<tr>
<td>10 Teams</td>
<td>10 Teams</td>
<td>9 Teams</td>
</tr>
<tr>
<td>10 Teams</td>
<td>10 Teams</td>
<td>10 Teams</td>
</tr>
</tbody>
</table>

**Diagram:**

- **Session 1**
  - AVO
  - PLO
  - DEMPC
- **Session 2**
  - AVO
  - PLO
  - DEMPC

Retention Interval

- Same Condition
- Mixed Condition
Team Retention and Composition

All but Short-Intact teams suffer performance loss after the break
But a different story for **Team Process**...

Team Process improves for mixed, but not intact teams after the break.

*This is unexpected and supports Interactive Team Cognition*

(There were no changes in knowledge after the break)

* Result also supported in mission planning testbed – change roles vs. seats
Interactive Team Cognition

*Team interactions often in the form of explicit communications are the foundation of team cognition*

**ASSUMPTIONS**

1) Team cognition is an **activity; not a property** or product
2) Team cognition is inextricably **tied to context**
3) Team cognition is best measured and studied when the **team is the unit of analysis**

Autonomous agent as a collaborator on a heterogeneous team (role and nature of agent) that operates a Remotely Piloted Aircraft to take reconnaissance photos
Autonomous agent as a collaborator on a heterogeneous team (role and nature of agent) that operates a Remotely Piloted Aircraft to take reconnaissance photos.
Autonomous agent as a collaborator on a heterogeneous team (role and nature of agent) that operates a Remotely Piloted Aircraft to take reconnaissance photos.
IMPLICATIONS OF INTERACTIVE TEAM COGNITION FOR SYNTHETIC TEAMMATE

1) Interaction goes beyond language understanding and generation

2) Coordination is central to this task – timely and adaptive passing of information among team members

3) Humans display sometimes subtle coordination behaviors that may be absent in the synthetic teammate

4) Failures of synthetic teammate will highlight the requisite coordination behaviors
The Synthetic Teammate

• Cognitively plausible agents capable of performing complex tasks & interacting with human teammates in natural language
• Effective team training any time anywhere, in DoD relevant, complex, dynamic environments
• Facilitate transition to new DoD applications

Take cognitive modeling to the level of functional systems
• The largest cognitive model built in ACT-R
  - 2459 Productions
  - 57,949 Declarative Memory chunks
• Among the largest cognitive models built in any cognitive architecture
  - 5 major components
• By computer science standards, a large program
<table>
<thead>
<tr>
<th>Sender</th>
<th>Sent</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEMPC</td>
<td>517.22</td>
<td>the speed restriction for f-area is from 150 to 200.</td>
</tr>
<tr>
<td>PLO</td>
<td>530.16</td>
<td>good photo. go on.</td>
</tr>
<tr>
<td>PLO</td>
<td>572.02</td>
<td>go to next waypoint.</td>
</tr>
<tr>
<td>DEMPC</td>
<td>633.1</td>
<td>the next waypoint is prk. it is entry.</td>
</tr>
<tr>
<td>AVO</td>
<td>736.63</td>
<td>What is the effective radius for oak?</td>
</tr>
<tr>
<td>AVO</td>
<td>747.35</td>
<td>What is the next point after prk?</td>
</tr>
<tr>
<td>DEMPC</td>
<td>768.78</td>
<td>no effective radius for oak.</td>
</tr>
<tr>
<td>DEMPC</td>
<td>803.77</td>
<td>the next waypoint is s-ste. it is target. the altitude restriction is from 3000 to 3100.</td>
</tr>
<tr>
<td>AVO</td>
<td>843.41</td>
<td>What is the next point after s-ste?</td>
</tr>
<tr>
<td>DEMPC</td>
<td>924.9</td>
<td>the speed restriction for s-ste is from 300 to 350.</td>
</tr>
<tr>
<td>DEMPC</td>
<td>982.94</td>
<td>the next waypoint is m-ste. it is target.</td>
</tr>
<tr>
<td>DEMPC</td>
<td>1123.08</td>
<td>the next waypoint is m-ste.</td>
</tr>
</tbody>
</table>
SYNTHETIC TEAMMATE VALIDATION EXPERIMENT

Purpose: Compare synthetic teammate teams to all-human control teams and to an all-human team with an experienced AVO (Experimenter)

Method
Participants: 30 3-agent teams, 10 team per condition

Conditions
• Synthetic
  • AVO is ACT-R based cognitive model
  • Less expertise than experimenter
• Control
  • AVO is participant
• Experimenter
  • AVO is experimenter (experienced AVO)
  • Pushes and pulls information across team using a coordination script
SYNTHETIC TEAMMATE VALIDATION EXPERIMENT

Procedure

<table>
<thead>
<tr>
<th>Sessions</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Welcoming</td>
</tr>
<tr>
<td>2</td>
<td>Interactive Training PowerPoint Slides</td>
</tr>
<tr>
<td>3</td>
<td>Training Mission</td>
</tr>
<tr>
<td>4</td>
<td>Mission 1</td>
</tr>
<tr>
<td>5</td>
<td>NASA TLX/ Knowledge Measures</td>
</tr>
<tr>
<td>6</td>
<td>Mission 2</td>
</tr>
<tr>
<td>7</td>
<td>Mission 3</td>
</tr>
<tr>
<td>8</td>
<td>Mission 4</td>
</tr>
<tr>
<td>9</td>
<td>Mission 5</td>
</tr>
<tr>
<td>11</td>
<td>NASA TLX/ Knowledge Measures</td>
</tr>
<tr>
<td>12</td>
<td>Demographics/Debriefing</td>
</tr>
<tr>
<td>13</td>
<td>Post Checklist</td>
</tr>
</tbody>
</table>

- Consent forms.
- Interactive Training PowerPoint Slides.
- Hands on Training.
- Mission 1 is conducted.
- Session 1: Conducting taskwork and teamwork questions, and administering the workload questions.
- Mission 2 is conducted.
- Mission 3 is conducted.
- Mission 4 is conducted.
- Mission 5 is conducted.
- Session 2: Conducting taskwork and teamwork questions, and administering the workload questions.
- Conducting demographic questions, and giving debriefing.

Measures

- Team performance
- Team process (process ratings, communication flow, coordination, situation awareness, verbal behavior)
- Workload, NASA TLX
RESULTS: TEAM PERFORMANCE

Experimenter teams demonstrated superior team performance compared to the control and synthetic teams which were statistically equivalent.
RESULTS: TARGET PROCESSING EFFICIENCY

Target processing efficiency was poorer for Synthetic teams than Control teams which was poorer than the Experimenter teams; and the Synthetic teams’ processing efficiency declined over time.
The Synthetic pilot demonstrates different verbal behaviors compared to Control and Experimenter pilots (fewer status updates, positive communications, inquiries). Also Synthetic teams had fewer general status updates and more repeated requests for information. More pulling than pushing of information.
Team coordination: three key communication events at each target waypoint, Information-Negotiation-Feedback (INF), is captured by a Kappa Score ($\kappa$) (Gorman, Amazeen, & Cooke, 2010)
RESULTS: ATTRACTOR RECONSTRUCTION

• Attractor reconstruction was used to visualize team coordination dynamics

• Recover a system’s dynamical structure from a one-dimensional Kappa time series and time-delayed versions of the Kappa.

From Demir dissertation 4/2017
RESULTS: SYNTHETIC TEAMS MORE STABLE THAN OTHERS

Stability ($\lambda$) is inversely related to the largest Lyapunov Exponent - estimated from Kappa; Stability ($\lambda<0$) and instability ($\lambda>0$) of team coordination.

Sample reconstructed attractors from three teams: a three-dimensional phase space as coordinates for the three-dimensional space $[\kappa(i), \kappa(i+\tau), \kappa(i+2\tau)]$

From Demir dissertation 4/2017
RESULTS: SYNTHETIC TEAMS MORE STABLE THAN OTHERS

Mean largest Lyapunov exponents = Stability across the conditions (vertical lines indicate SE) \textcolor{red}{synthetic} < \textcolor{blue}{control} = \textcolor{green}{experimenter}

From Demir dissertation 4/2017
JRQA was used to assess joint influence of one team member on the other

- JRQA was applied on communication flow data (i.e., sent time stamp from each UAV mission)
- % Determinism (DET): measure of system’s predictability was extracted from JRQA
RESULTS: SYNTHETIC TEAMS MOST STABLE/PREDICTABLE AND CONTROL LEAST

Mean % DET = **Predictability** across the conditions (vertical lines indicate SE) **synthetic > control < experimenter**

From Demir dissertation 4/2017
RELATION BETWEEN TEAM PERFORMANCE AND COORDINATION

From Demir dissertation 4/2017; Coordination stability “sweet spot” discovered
SYNTHETIC TEAMMATE VALIDATION RESULTS

❖ The synthetic teams performed as well as control teams, but had difficulties coordinating and processing targets efficiently – failure to anticipate

❖ A synthetic teammate can impact team coordination and performance - entrainment

❖ Experimenter condition demonstrates how a teammate who excels at coordination can elevate coordination of the whole team

❖ Conditions were nominal. Coordination especially important in off-nominal conditions.
Results: Target Processing Efficiency

Not only provides assessment of the synthetic teammate (along with weaknesses), but also demonstrates how subtle coaching of coordination can improve team performance.

Target processing efficiency was poorer for Synthetic teams than Control teams which was poorer than the Experimenter teams; and the Synthetic teams’ processing efficiency declined over time.
Applying Coordination Coaching to Code Blue Resuscitation

Sandra Hinski (2017) dissertation, ASU
Intensivist code leaders studied communication model for 5-10 min. prior to mock code

<table>
<thead>
<tr>
<th>Arrival to code</th>
<th>Introduces self as code team leader</th>
</tr>
</thead>
</table>
| **Contingency**                     | IF: Code RN does not immediately give the CTL a brief history, code status, and confirm advanced monitoring is established  
THEN: CTL must directly ask the Code RN for the information |
| **Within 30 seconds of arrival to code** | Asks about ABCs  
IF: No one person is performing CPR or performing bag mask ventilating upon arrival of CTL  
THEN: CTL must direct code team member to immediately perform CPR and the RT to bag the patient |
| **Once monitoring is established**   | Asks for ACLS therapies as indicated  
IF: Medication or shock delivery is delayed more than 10 seconds after identification of rhythm  
THEN: CTL must directly ask pharmacist or RN do deliver the meds and/or shock |
| **constant feedback**               | Asks if there are any problems, so CTL can troubleshoot or delegate task to another person, keeps team on task, should be in SBAR format |
| **Contingency**                     | IF: Code team does not clarifies ROSC/stabilization of ABCs OR clinical worsening  
THEN: CTL must clarify disposition (i.e. transfer to ICU, need for more advanced therapies, discontinuation of efforts, etc.) |
Code Team Errors

- CTL did not identify him/herself
- CTL not positioned properly
- First shock delayed
- ECG rhythm not verbalized
- Medication dose and route not verbalized

Control Group 1

Trained Group 2
Human-Autonomy Teaming
Under Degraded Conditions

**Purpose:** Identify challenges of human-autonomy teaming under degraded conditions and strategies of high performing teams to address them.

**Method**
*Wizard of Oz Paradigm:* synthetic pilot was mimicked by an experienced (remote) experimenter who failed in specific ways at specific times

**Participants:** 21 3-agent teams

**10 Missions** (with multiple targets) across two sessions
Human-Autonomy Teaming Under Degraded Conditions

**Procedure** (Two Sessions separated by 1-2 week interval)

<table>
<thead>
<tr>
<th>SESSION-I (with breaks Total: 6 hours)</th>
<th>SESSION-II (with breaks Total: 7 hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1)</strong> Consent forms (15 min)</td>
<td><strong>1)</strong> Mission 5 (40 min),</td>
</tr>
<tr>
<td><strong>2)</strong> PowerPoint (30 min) and hands on training (30 min)</td>
<td><strong>2)</strong> NASA TLX I (15 min)</td>
</tr>
<tr>
<td><strong>3)</strong> Mission 1 (40 min)</td>
<td><strong>3)</strong> Mission 6 (40 min),</td>
</tr>
<tr>
<td><strong>4)</strong> NASA TLX I (15 min)</td>
<td><strong>4)</strong> Mission 7 (40 min),</td>
</tr>
<tr>
<td><strong>5)</strong> Missions 2 (40 min)</td>
<td><strong>5)</strong> Mission 8 (40 min),</td>
</tr>
<tr>
<td><strong>6)</strong> Mission 3 (40 min),</td>
<td><strong>6)</strong> Mission 9 (40 min),</td>
</tr>
<tr>
<td><strong>7)</strong> Mission 4 (40 min),</td>
<td><strong>7)</strong> Mission 10 (40 min),</td>
</tr>
<tr>
<td><strong>8)</strong> NASA TLX-II, Trust &amp; Anthropomorphism (30 min)</td>
<td><strong>8)</strong> NASA TLX-II, Trust, Anthropomorphism, Demographics, and Debriefing (30 min)</td>
</tr>
</tbody>
</table>

**Measures**

- Team performance (mission and target levels)
- Team process (process ratings, communication flow, coordination, situation awareness, verbal behavior)
- Team trust & resilience
- Workload (NASA TLX)
- Anthropomorphism
- Heart Rate (ECG), Electrical Activity of the Brain (EEG), & Facial Expression
Human-Autonomy Teaming Under Degraded Conditions

- **Automation Failures** – display fails

- **Autonomy Failures** – synthetic teammate comprehension failure

- **Malicious Attacks on Autonomy** provides appropriate feedback as it enters wrong area
# Human-Autonomy Teaming Under Degraded Conditions

Experimental Sessions and Application of Failures during specific targets for each mission

<table>
<thead>
<tr>
<th>Session</th>
<th>Target/ Automation</th>
<th>Target/ Autonomy</th>
<th>Target/ Malicious</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Session I</strong></td>
<td>Training</td>
<td>No Failure</td>
<td>No Failure</td>
</tr>
<tr>
<td></td>
<td>Mission 1</td>
<td>No Failure</td>
<td>No Failure</td>
</tr>
<tr>
<td></td>
<td>Mission 2</td>
<td>2\textsuperscript{nd}/ Type I</td>
<td>4\textsuperscript{th}/ Type I</td>
</tr>
<tr>
<td></td>
<td>Mission 3</td>
<td>4\textsuperscript{th}/ Type II</td>
<td>2\textsuperscript{nd}/ Type II</td>
</tr>
<tr>
<td></td>
<td>Mission 4</td>
<td>1\textsuperscript{st}/ Type III</td>
<td>3\textsuperscript{rd}/ Type III</td>
</tr>
<tr>
<td><strong>Session II</strong></td>
<td>Mission 5</td>
<td>2\textsuperscript{nd}/Type III</td>
<td>4\textsuperscript{th}/ Type II</td>
</tr>
<tr>
<td></td>
<td>Mission 6</td>
<td>4\textsuperscript{th}/ Type I</td>
<td>2\textsuperscript{nd}/ Type I</td>
</tr>
<tr>
<td></td>
<td>Mission 7</td>
<td>1\textsuperscript{st}/ Type II</td>
<td>3\textsuperscript{rd}/ Type II</td>
</tr>
<tr>
<td></td>
<td>Mission 8</td>
<td>3\textsuperscript{rd}/Type III</td>
<td>1\textsuperscript{st}/ Type III</td>
</tr>
<tr>
<td></td>
<td>Mission 9</td>
<td>3\textsuperscript{rd}/Type II</td>
<td>5\textsuperscript{th}/ Type II</td>
</tr>
<tr>
<td></td>
<td>Mission 10</td>
<td>2\textsuperscript{nd}/Type III</td>
<td>4\textsuperscript{th}/ Type III</td>
</tr>
</tbody>
</table>
RESULTS: OVERCOMING FAILURES AND ATTACKS

Automation & Autonomy Failures, and Malicious Attacks

• Proportion of 22 teams that overcame failures was approximately equal for both types: automation (65%) and autonomy (64%), and malicious attacks (41%)

• Performance of overcoming automation failures increased across the missions, but decreased for autonomy failures
RESULTS: TEAM PERFORMANCE

Team Performance (Mission Level)

Team performance increased across the missions.
Clusters Based on Performance

- Identify high vs. low performing teams
- Team clusters via K-Means Cluster analysis
- Data
  - Mission performance score
  - Target performance score
  - Number of failures overcome
- Resulted in 3 groups of teams

<table>
<thead>
<tr>
<th>Metrics\Conditions</th>
<th>High-Performed</th>
<th>Average</th>
<th>Low-Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Teams</td>
<td>6</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>
RESULTS: TARGET PROCESS RATING

High-performing teams demonstrated superior team process compared to the average and low teams which were statistically equivalent.
RESULTS: NASA TLX WORKLOAD

The average teams had lower workload than the low- and high-performing teams; and the photographer had lower workload than the navigator.
RESULTS: TRUST

1) lower levels of trust in the autonomous agent in low performing teams than both medium and high performing teams

2) there is a loss of trust in the autonomous agent across low, medium, and high performing teams over time

3) both low and medium performing teams also indicated lower levels of trust in their human team members
Coordination Dynamics Under Degraded Conditions

- These analyses utilize database files that contain timestamped information of vehicle, controls, and communication state throughout a mission
  - *Layered dynamics* – visualizing and tracking changes in how the system (RPAS) is organized over time
  - *Deep dive* – content analysis of mission chat transcripts to understand how the humans and autonomy dealt with automation failures and how the humans dealt with autonomy failures
Layered dynamics

A. Input Database

B. Symbol Encoding

C. Calculate moving window entropy of symbolic time series

- Windowed entropy measures the number of arrangements a system occupies over a fixed amount of time.
- Entropy is one operational definition of system reorganization (others are %DET and %REC).
Layered dynamics

Different layers for visualizing and tracking where failures are addressed in the system
Layered Dynamics

Reorganization time – time from failure onset to peak significant system reorganization

A – automation failure   B – autonomy failure   C – malicious attack on autonomy

Effective teams tend to:
- Autonomy failures
  - Short reorganization time in the Controls/Vehicle layers ($p < .05$)
- Automation failures
  - Long reorganization time in the Communication layer ($p < .05$)

Effective = successfully overcoming failures
For building resilient teams, intervention(s) may be developed around the core concepts of locus of resilience and loci of reorganization.

Summary: What we Have Found from the Dynamics Thus Far

For building resilient teams, intervention(s) may be developed around the core concepts of locus of resilience and loci of reorganization.
Human-Autonomy Teaming Under Degraded Conditions

- High performing teams exhibit superior process behaviors, and also higher workload
- Trust in autonomous agent declines over time with increasing failures and is especially low for low performing teams
- Response to failures in automation requires team coordination
- Response to failures in autonomy may be more linked to attitude and trust
- Next study will test an intervention to improve response to failures
Next Steps: Taking Team Performance Measurement Out of the Lab

- Outcome can be measured in the lab because we know ground truth
- Outside of the lab, there is often no ground truth (cyber, intelligence, RPAS, USAR)
- Often team performance is measured as outcome
  - In the lab effective teams have positive outcomes
  - Outside the lab there is no obvious outcome (science teams) or outcome ≠ effectiveness (Code Blue Resuscitation, sports)
Outcome vs. Effectiveness
Measuring Team Effectiveness

What is team effectiveness?

– Adaptivity: Teams respond quickly to a perturbation
– Resilience: Teams bounce back quickly from a perturbation

Measure Team effectiveness through performance dynamics

Effective teams are adaptive and stable
Dynamics and Team Effectiveness

![Graph showing dynamics and team effectiveness with time, moving window size, adaptation, and resilience metrics.](image-url)
Collaborators

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Dr. Mustafa Demir
Paul Jorgenson
Dr. Steven Shope
Testbed, empirical studies and validation

GEORGIA TECH
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Dynamical system modeling; coordination measures

AFRL/L3
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Ms. Mary Freiman
Ms. Erin Hanson
Dr. Chris Myers
ACT-R cognitive modeling
Develop Synthetic Teammate and Iterate

CLEMSON
Nathan McNeese
trust, resilience

Thank You to Our Collaborators!
Thanks to My Collaborators

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