Modeling Human-Autonomy Team Coordination using Layered Dynamics

Jamie C. Gorman

Engineering Psychology

Georgia Institute of **Tech**nology

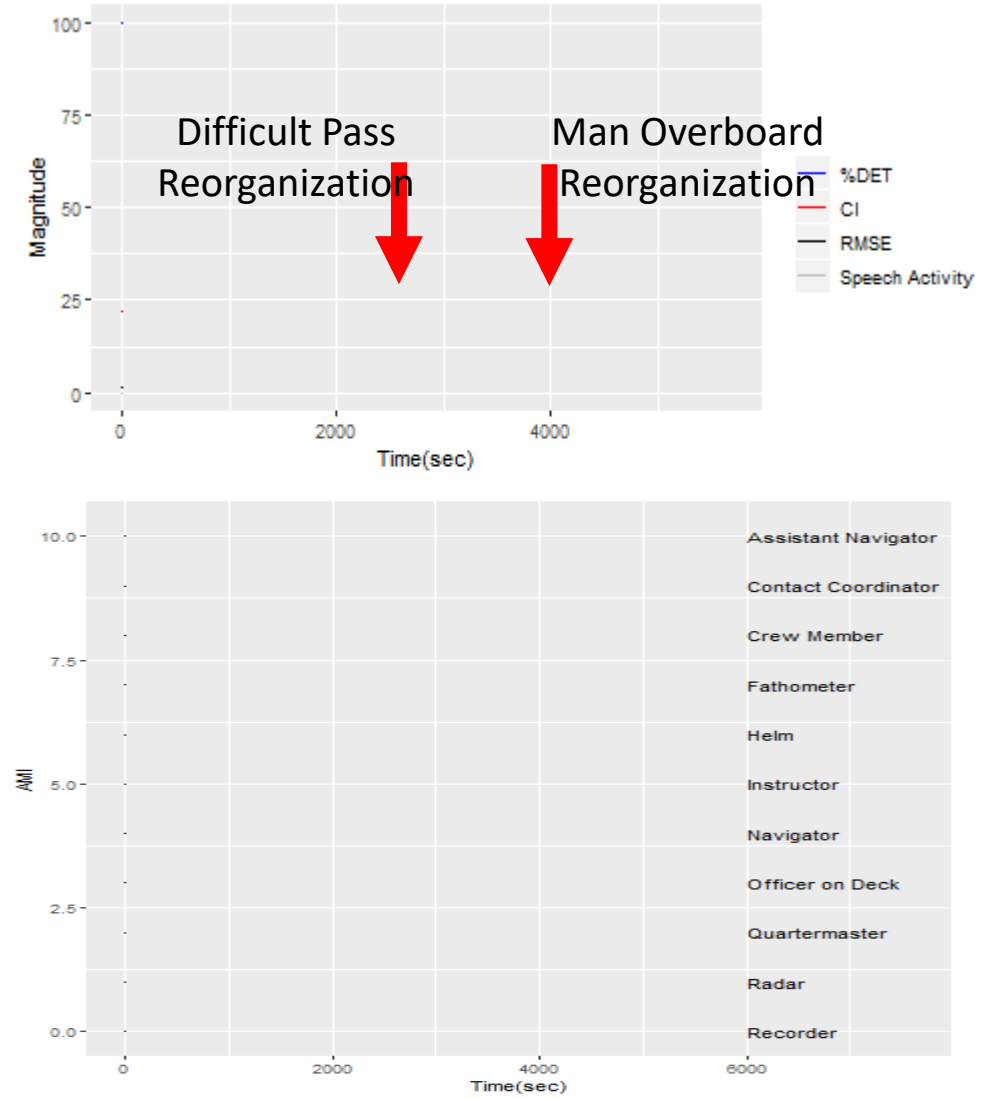
jamie.gorman@gatech.edu
http://spl.gatech.edu

NAS-BOHSI Human-AI Teaming Workshop
July 29, 2021

Layered Dynamics and the Law of Requisite Variety

W. Ross Ashby

Paraphrasing: For a team-environment system to maintain effectiveness ("stability"), a team ("controller") must be able to produce enough coordination variety (variety = number of states) to match or exceed the variety demanded by the environment.



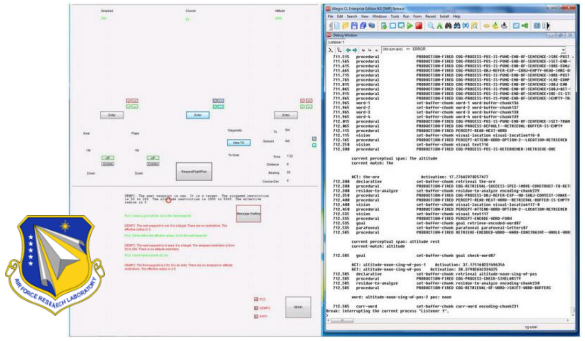
Gorman, Grimm, Stevens, Galloway, Willemsen-Dunlap, & Halpin (2020). *Human Factors.*

Real-time system coordination metrics that combine dynamic, heterogeneous sensors and signals

Communication (Verbal, Chat)

Interface Interactions

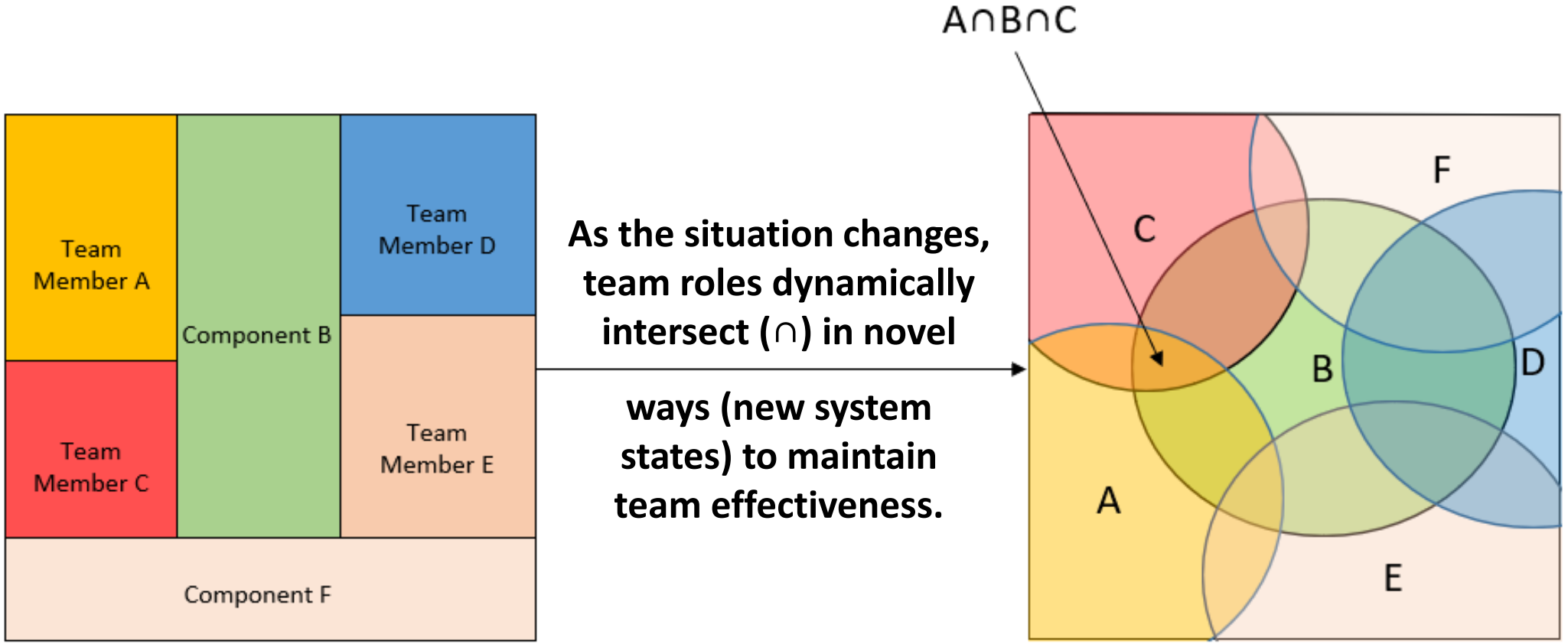
Physiological Signals (EEG)



AI Agents, Synthetic Teammates

Vehicles and Equipment (simulated)

Eye Tracking



Dynamic Modeling Tracks Changes in Team State (Amount of "Reorganization")

McChrystal et al. (2015). *Team of Teams.*

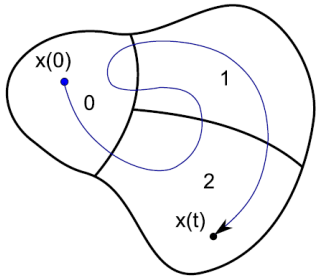
Symbolic Dynamics Modeling Language

Component states (q_i) $\mathbf{Q}$ ($\mathbf{q_i} \subset \mathbf{Q}$), where $\cup\, \mathbf{q_i} = \mathbf{Q}$ and $\mathbf{q_i} \cap \mathbf{q_j} = \emptyset$ for all $\mathbf{i} \neq \mathbf{j}$

System Component	Sample # (e.g., 1 Hz)					
	1	2	3	4	5	6
1 (q_1)	0 0	0 0	1 0	1 0	0 0	0 0
2 (q_2)	0 0	0 0	0 0	0 0	0 0	0 0
3 (q_3)	1 0	1 0	1 0	0 0	0 0	0 0
4 (q_4)	000	000	000	001	001	001
Binary System State (**Q'**)	000000110000	000010110000	100010110000	100000000001	000010000001	000010000001
Decimal System State (**Q'**)	48	176	2224	2049	129	129

Team states (Q')

System state space is defined by all possible intersections (not known a priori) of system components.



Attractors are symbolic trajectories through intersections.

Gorman, Demir, Grimm, & Cooke (2019). *Ergonomics.*

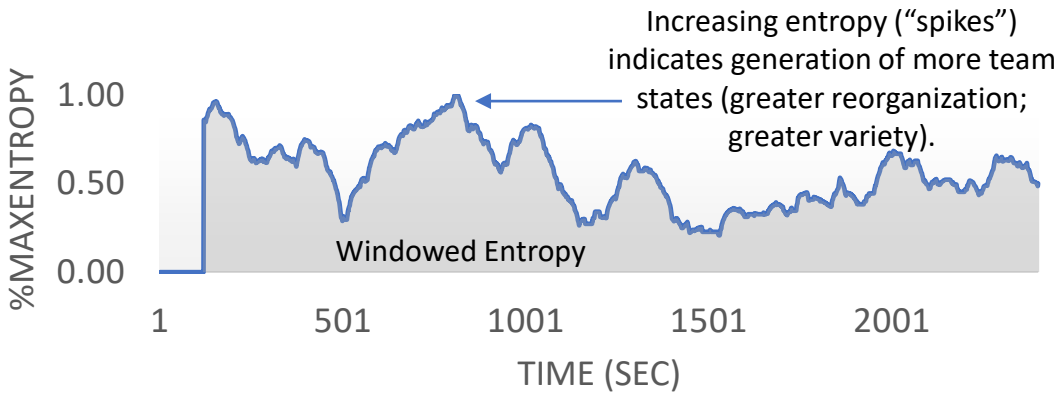
Measuring Reorganization: Layered Dynamics

Sliding window entropy is one operational definition of team reorganization.

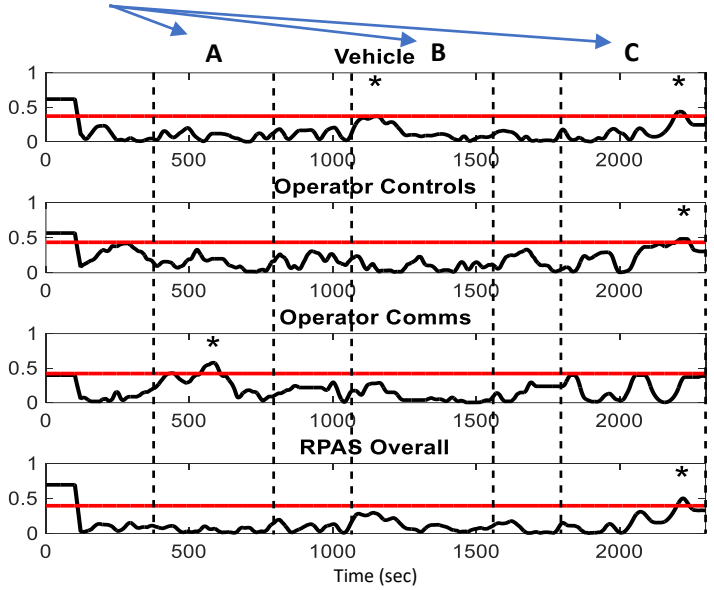
System Component	Sample # (e.g., 1 Hz)					
	1	2	3	4	5	6
1 (q_1)	000	000	100	100	000	000
2 (q_2)	000	010	010	000	010	010
3 (q_3)	110	110	110	000	000	000
4 (q_4)	000	000	000	001	001	001
Binary System State (**Q'**)	000000110000	000010110000	100010110000	100000000001	000010000001	000010000001
Decimal System State (**Q'**)	48	176	2224	2049	129	129

Sliding Window

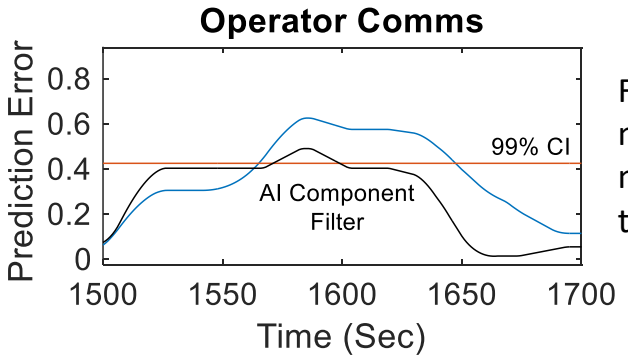
Calculate amount of reorganization across system states each time window is updated



Perturbations



A – automation failure
B – autonomy failure
C – malicious cyberattack

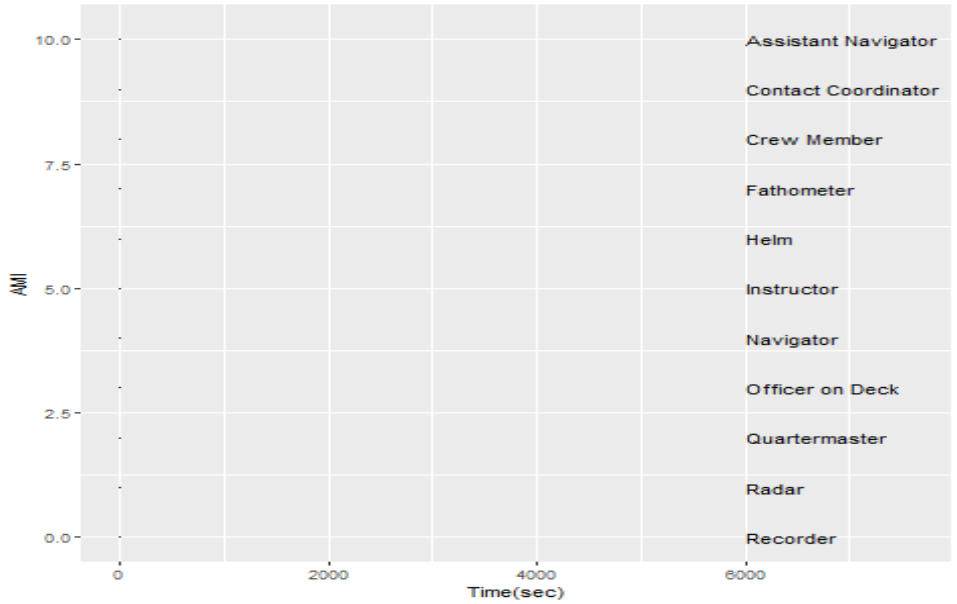


Filtering out team members to see how much each contributes to reorganization

What combination of team components contributes the most to team reorganization?

AMI = how much knowledge of each component's activities reduces our uncertainty in team (system) state

System Component	Sample # (e.g., 1 Hz)					
	1	2	3	4	5	6
1 (q_1)	000	000	100	100	000	000
2 (q_2)	000	010	010	000	010	010
3 (q_3)	110	110	110	000	000	000
4 (q_4)	000	000	000	001	001	001
Binary System State (**Q'**)	000000110000	000010110000	100010110000	100000000001	000010000001	000010000001
Decimal System State (**Q'**)	48	176	2224	2049	129	129



Frequency Cutoff: 2

Calculate

Communication	Count	Percent
MD1 -> MD2 & RN1 & CN1 & Tech1	59	26.57
U -> Unknown	35	15.76
MD1 -> MD2	18	8.10
MD1 -> Tech1	14	6.30
MD1 -> MD2 & RN1 & CN1 & Tech1 and MD2 -> Tec...	12	5.40
MD1 -> RN1 & CN1	10	4.50
MD1 -> MD2 & RN1 & CN1 & Tech1 and MD2 -> MD...	9	4.05
RN1 -> CN1	9	4.05
CN1 -> MD1 & MD2 & RN1	6	2.70
CN1 -> MD1 & RN1	6	2.70

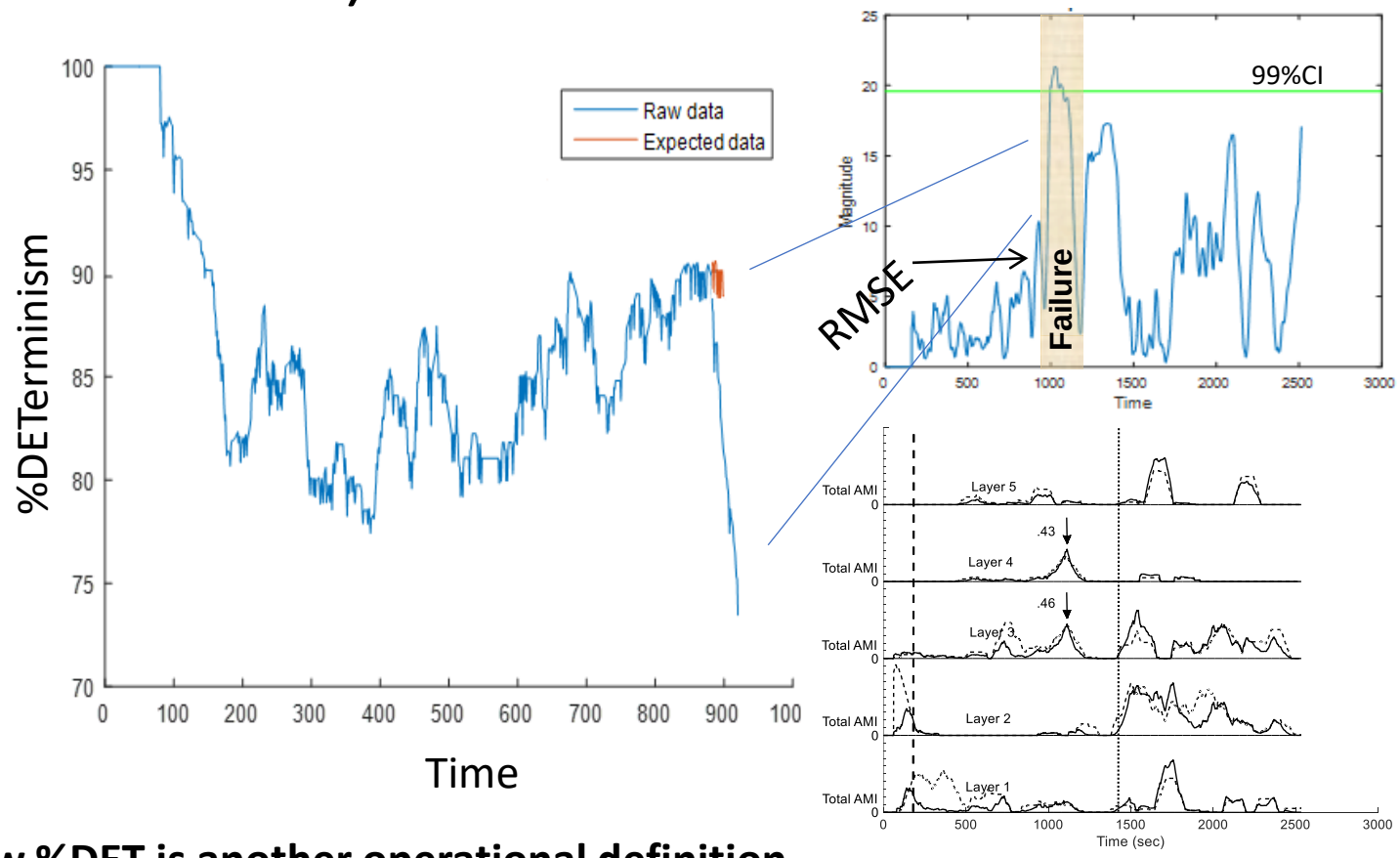
Credit: US Air Force

AMI Calculation Cutoff: 4

Calculate

Communication	AMI %	Base2
MD1 -> MD2 & RN1 & CN1 & Tech1	0.0144	100000
MD1 -> MD2 & RN1 & CN1 & Tech1 and MD2 -> MD...	0.0102	11000000
MD1 -> MD2	0.0058	10000000
MD1 -> MD2 & RN1 & CN1 & Tech1 and MD2 -> Tec...	0.0052	11111000
U -> Unknown	0.0033	01011100

Measuring novelty of team reorganization (RMSE between predicted and observed reorganization time series)



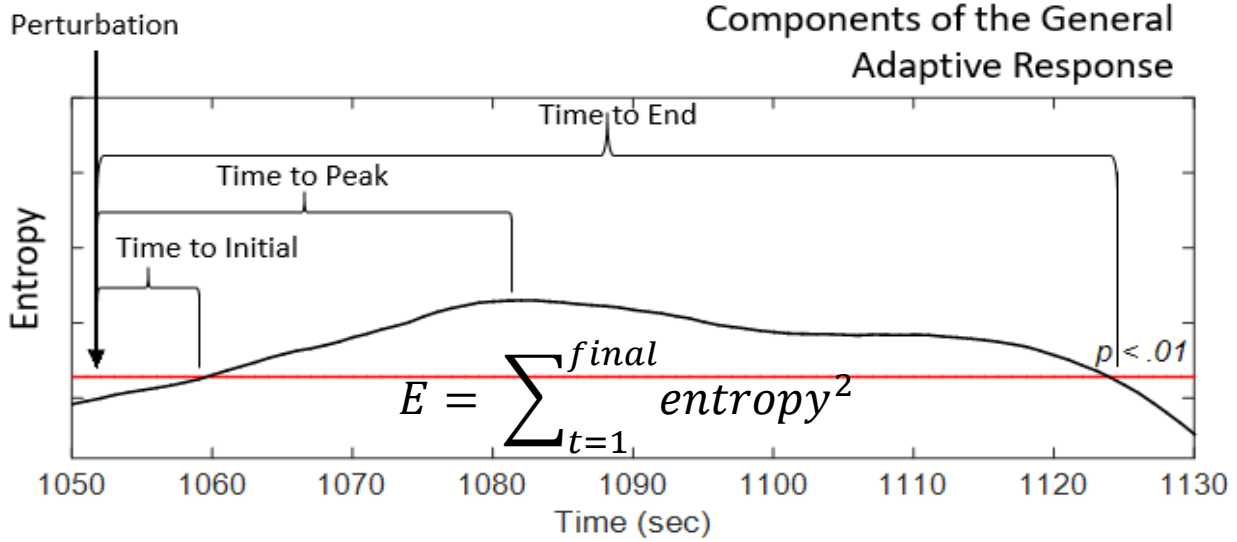
Challenge is to identify novel patterns of **reorganization** *as they occur*

Sliding window %DET is another operational definition of reorganization (measures predictability of patterns in the team interactions)

1.	Skilled teams quickly assess the current situation by perceiving relevant stimuli in the physical and social environment and coordinating this perception across relevant team members in order to **enact** a coordinated team response (Gorman, Cooke, & Winner, 2006).
2.	Skilled teams exhibit situation awareness by choosing an action that best fits the current situation by behaving in similar but non-identical ways. This requires a flexible team response that is perhaps similar to, but not identical with, responses used in the past (Gorman, Cooke, & Amazeen, 2010).
3.	Skilled teams have consistent behavior in similar (routine) situations but **adapt** their coordination patterns rapidly and appropriately in novel, non-routine situations (e.g., perturbations; Gorman et al., 2010; Gorman et al., 2020).
4.	Skilled teams quickly return to pre-challenge status following a novel, non-routine event, such that they are **resilient** and quick to recover in order to encounter the next challenge (Grimm, Demir, Gorman, & Cooke, 2018).
5.	Skilled teams have a repertoire of **adaptation mechanisms** through which characteristics 1-4 are expressed (e.g., leadership emergence; dynamic role restructuring; Gorman et al., 2020).

Team Cognition: Team-Level Competencies

Real-time measurement of **enaction**, **adaptation**, and **resilience**

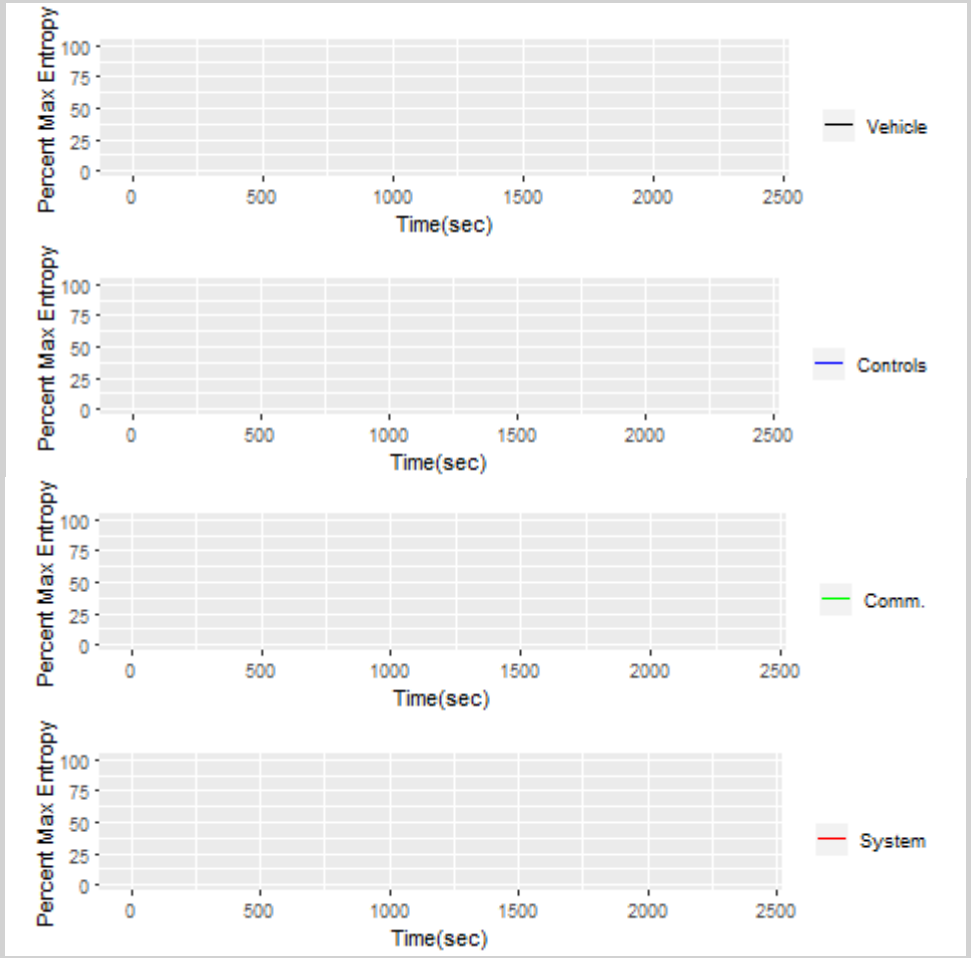


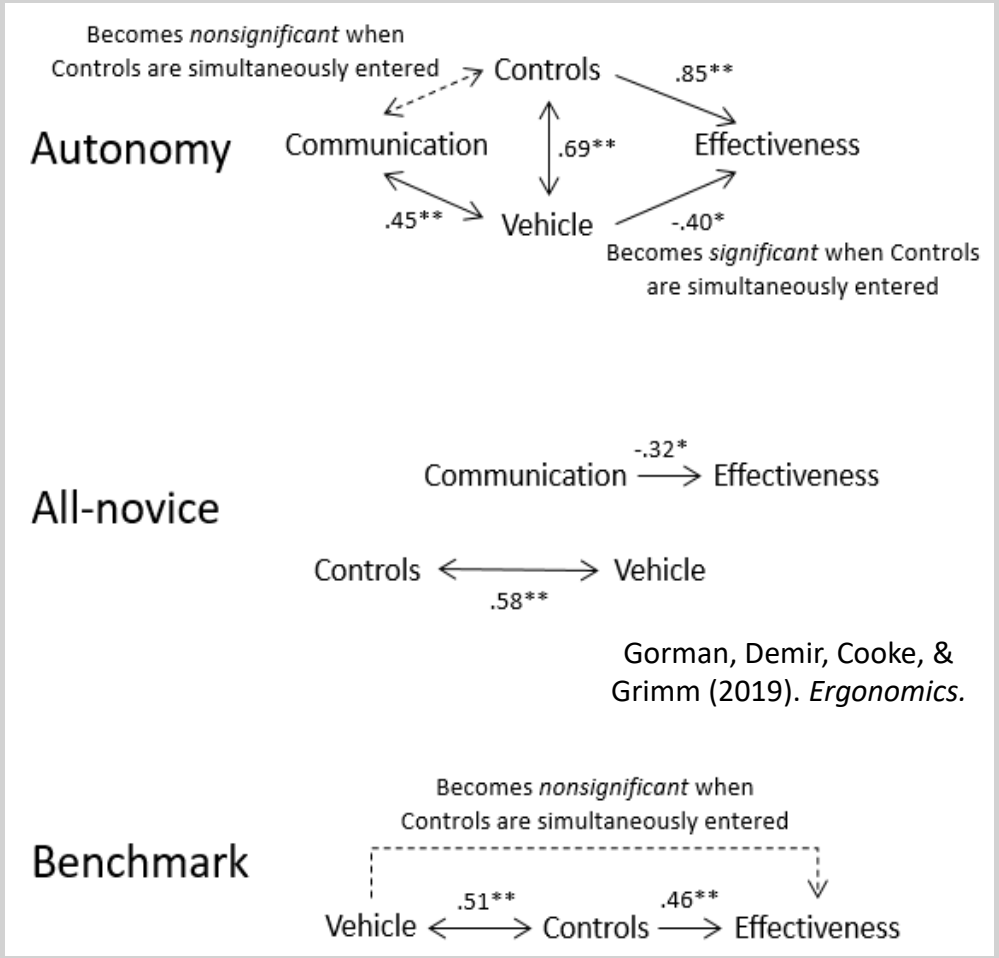
Metric	Definition	Characteristic
Time to initial redline entropy	Time to reach a significant level of reorganization	**Enaction**; time taken for a team to begin its reorganization behavior (***Characteristic 1**)
Time to peak redline entropy spike (adaptation time)	Time taken to reach greatest amount of reorganization	**Adaptation**; time to exhibit greatest amount of reorganization behavior (***Characteristics 2 & 3**)
Time to end redline entropy spike (relaxation time)	Time to return below significant level of reorganization	**Resilience**, recovery; time taken to return to stable levels of reorganization (***Characteristic 4**)

Failure Type	Real-time Dynamics Metrics	Outcome Measure	System Layer	Performance Correlation
Hybrid Failure	RMSE (Novelty)	Target Processing Efficiency (TPE)	Communication	**Enact (r = -.522, p = .011) Adapt (r = -.522, p = .011) Res. (r = -.524, p = .010)**
		Ground Truth Resilience Score (GTRS)	Communication	**Enact (r = .512, p = .012) Adapt (r = .513, p = .012) Res. (r = .513, p = .012)**
System Failure (Power Down)	Entropy (Reorganization)	Target Processing Efficiency (TPE)	System	**Enact (r = -.395, p = .028) Adapt (r = -.400, p = .026) Res. (r = -.394, p = .028)**
		Ground Truth Resilience Score (GTRS)	Control	**Enact (r = -.389, p = .031)**
Malicious Cyberattack	Entropy (Reorganization)	Team Performance (Mission Level)	Vehicle	**Enact (r = -.521, p = .003) Adapt (r = -.532, p = .002) Res. (r = -.437, p = .016)**
	RMSE (Novelty)	Ground Truth Resilience Score (GTRS)	Communication	**Enact (r = .521, p = .013) Adapt (r = .520, p = .013) Res. (r = .509, p = .016)**
			System	**Enact (r = -.464, p = .010) Adapt (r = -.466, p = .009) Res. (r = -.468, p = .009)**

Grimm (2020). *GT MS Thesis.*

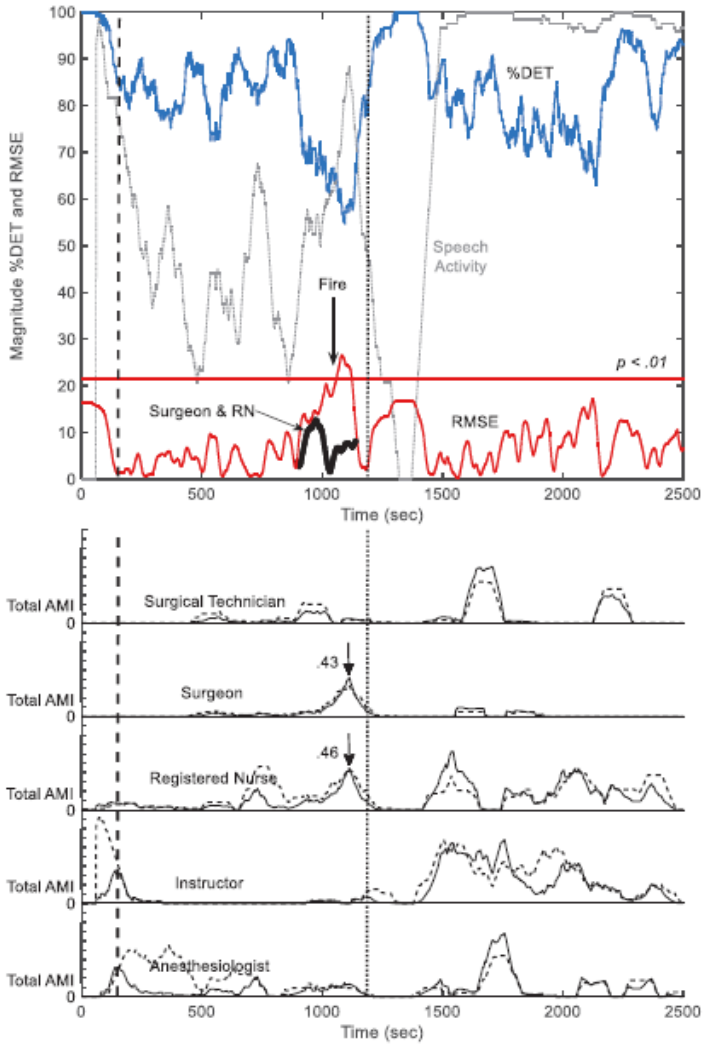
Layered dynamics have also been informative of how (on average) components relate to each other to maintain team effectiveness.





Gorman, Demir, Cooke, & Grimm (2019). *Ergonomics.*

Expert-novice differences are revealed by reorganization profiles



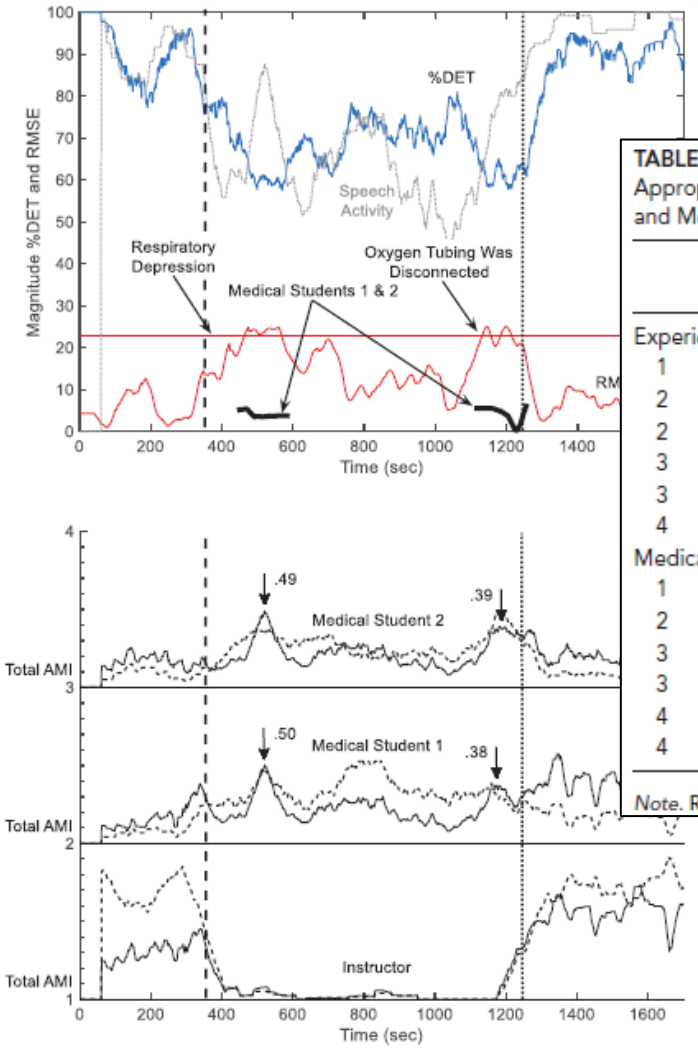


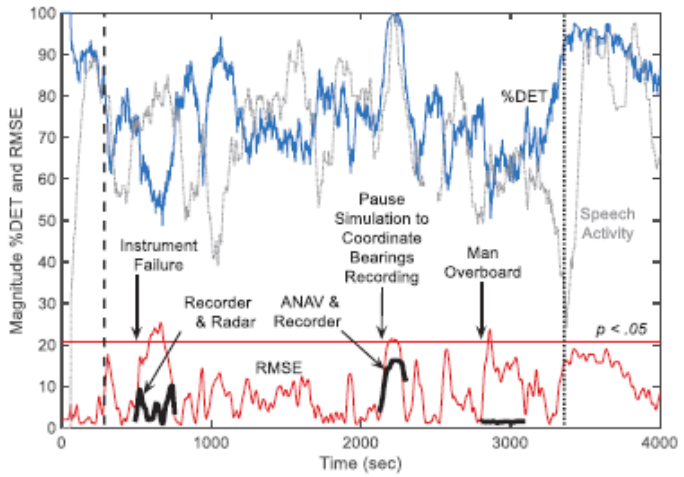
TABLE 1: Training Event Onset Time, Time of Significant Reorganization (RMSE Significance), Appropriateness of Response (Overcame), and Figure Number for All Training Events for Experienced and Medical Student Teams (All Times Are in Seconds)

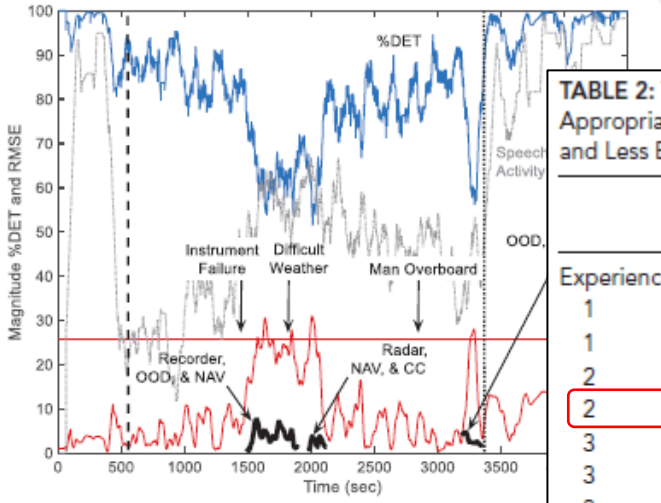
	Training Event	Event Onset	RMSE Significance	Overcame	Figure
Experienced team					
1	Fire	1,051	1,061	Yes	4
2	Changing members	645	650	Yes	5
2	Seizure	977	False negative	Yes	5
3	Handoff/introductions		546	False positive	6
3	Fire	1,353	1,354	Yes	6
4	Lidocaine reaction	908	920	Yes	7
Medical student team					
1	Allergic reaction	1	56	No	8
2	Seizure	423	539	No	9
3	Respiratory depression	413	463	No	10
3	Respiratory depression	413	1,132	Yes	10
4	Unknown drug	41	60	No	11
4	Seizure	1,367	1,372	Yes	11

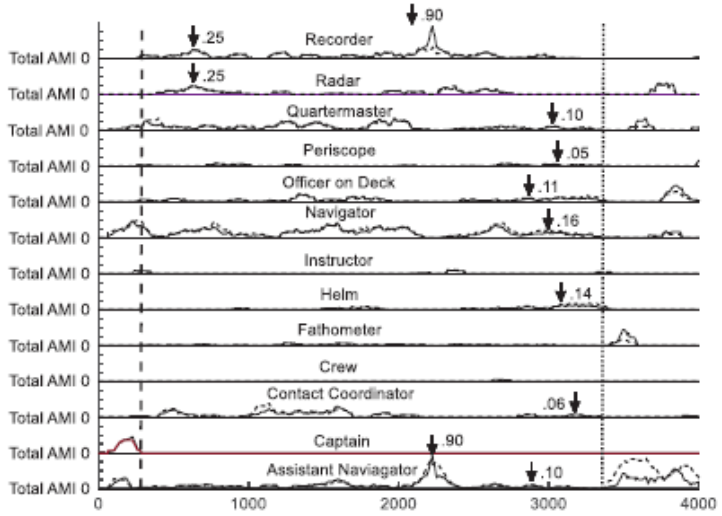
Note. RMSE = root mean square error.

Gorman et al. (2020). *Human Factors.*

These reorganization dynamics generalize across team task domains







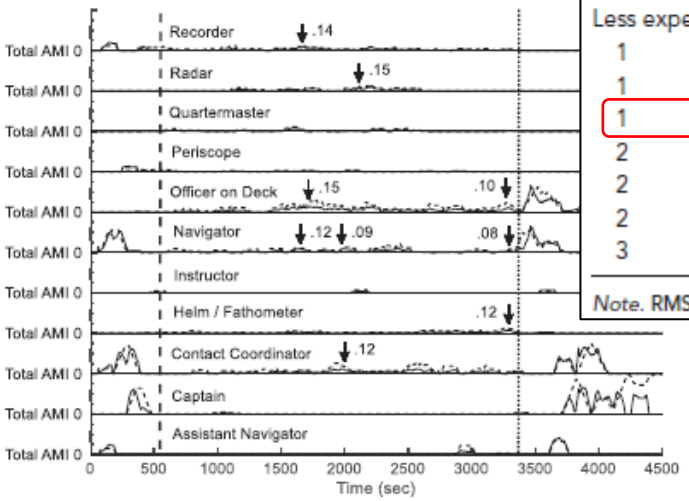


TABLE 2: Training Event Onset Time, Time of Significant Reorganization (RMSE Significance), Appropriateness of Response (Overcame), and Figure Number for All Training Events for Experienced and Less Experienced Crews (All Times Are in Seconds)

	Training Event	Event Onset	RMSE Significance	Overcame	Figure
Experienced crew					
1	Calibrate visual aids	NA	787	False positive	12
1	Close contact	3,271	3,354	Yes	12
2	Difficult pass	2,493	2,633	Yes	13
2	Man overboard	4,251	4,273	Yes	13
3	Instrument failure	533	584	Yes	14
3	Pause simulation	2,152	2,186		14
3	Man overboard	2,804	2,850	Yes	14
Less experienced crew					
1	Instrument failure	1,450	1,617	Yes	15
1	Difficult weather	1,822	1,988	Yes	15
1	Man overboard	2,874	3,265	No	15
2	Coordinate a round	NA	409	False positive	16
2	Course confusion	1,658	1,777	No	16
2	Instrument failure	2,371	2,469	Yes	16
3	Instrument failure	1,462	2,173	Yes	17

Note. RMSE = root mean square error.

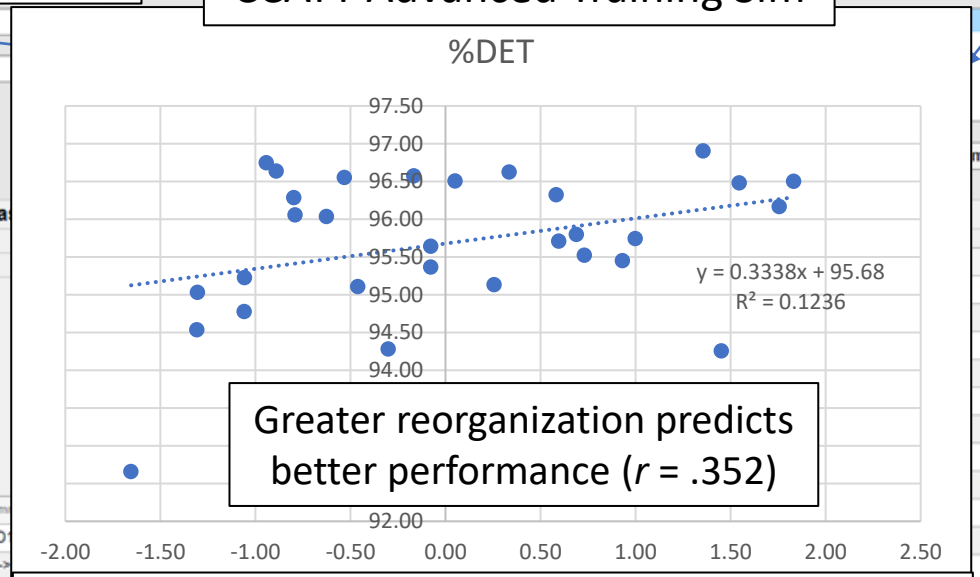
Gorman et al. (2020). *Human Factors.*

Team Dynamics Measurement System

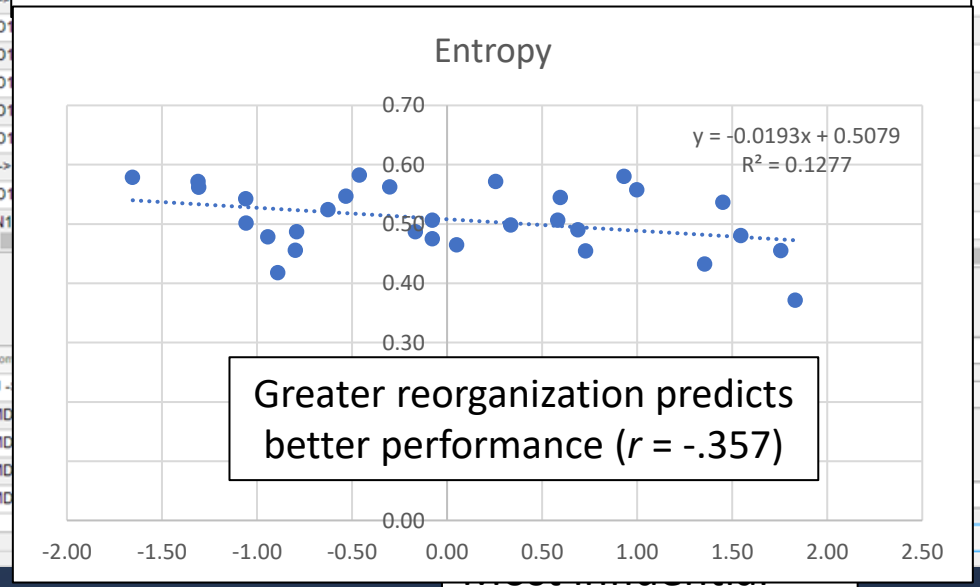
CCATT Advanced Training Sim

Select data subsets for more in-depth analysis

Reorganization
Predictability
Novelty



Greater reorganization predicts better performance (*r* = .352)



Greater reorganization predicts better performance (*r* = -.357)

Real-time link to video/audio playback

Enaction
Adaptation
Resilience

team intersections

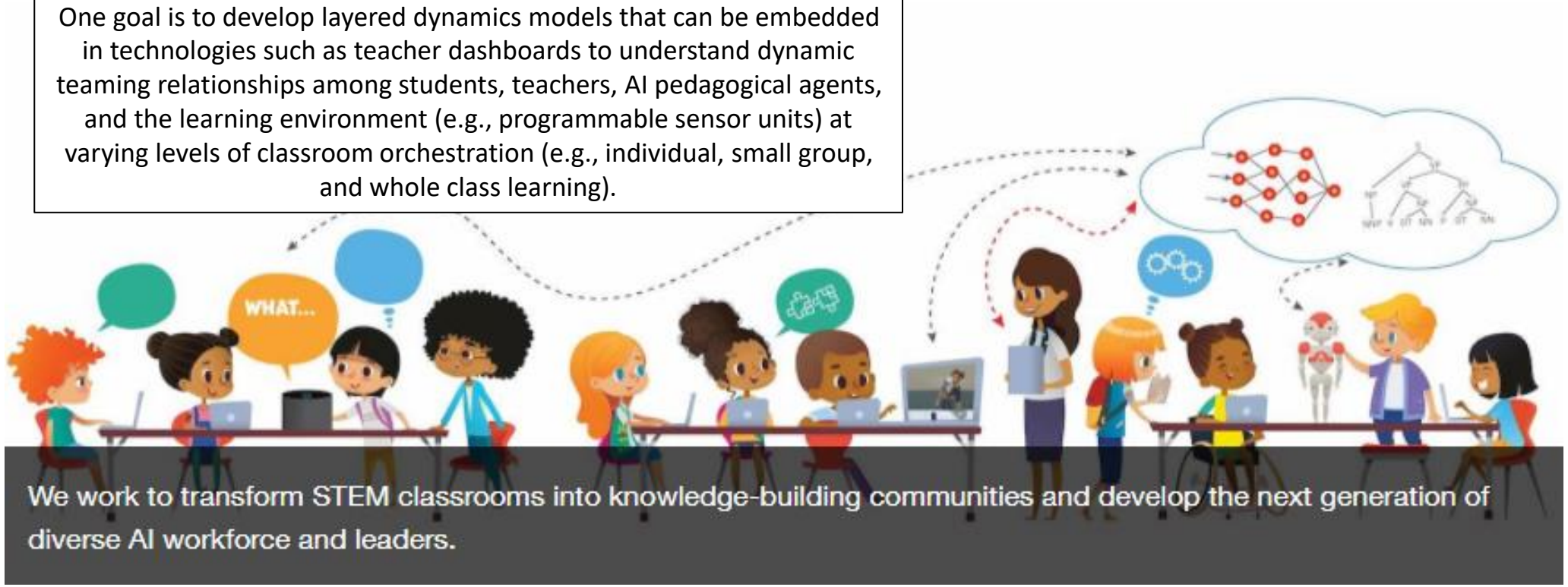
Institute for Student-AI Teaming (iSAT; PI: D'Mello)

University of Colorado **Boulder**

NSF National AI Institute for Student-AI Teaming

Menu

One goal is to develop layered dynamics models that can be embedded in technologies such as teacher dashboards to understand dynamic teaming relationships among students, teachers, AI pedagogical agents, and the learning environment (e.g., programmable sensor units) at varying levels of classroom orchestration (e.g., individual, small group, and whole class learning).



Modeling Multi-Team HAT System Using Layered Dynamics

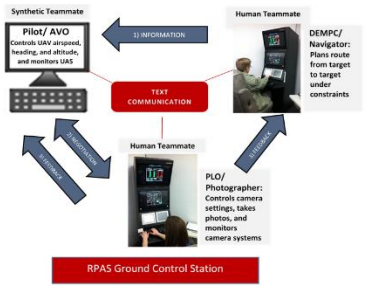
Space Challenge

Credit: NASA Goddard Space Flight Center

Space Challenge: Agent modeling (future)

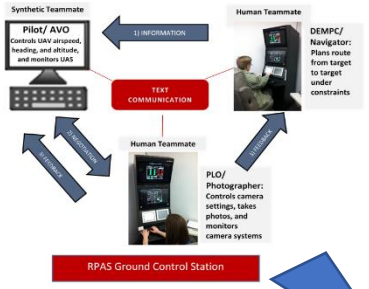
Team of Teams Coordination Modeling

Georgia Tech



Mars Orbiter

ASU

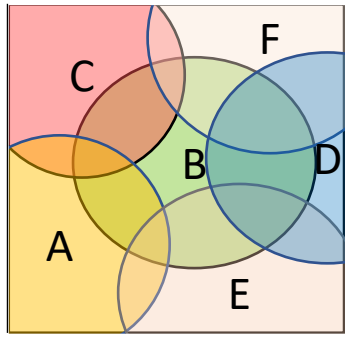


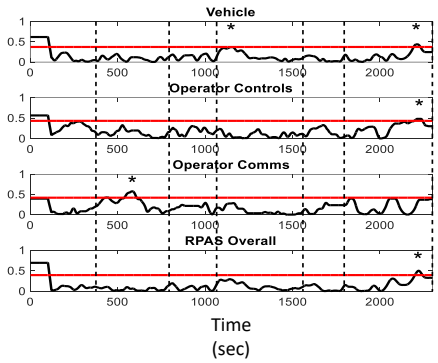
Lunar Orbiter

ASU

MCC, JPL, Rovers

System Coordination/Interdependencies (Layered Dynamics)





Cognitive State Variables

- Situation Awareness
- Workload
- Fatigue
- Stress

IRA A. FULTON SCHOOLS OF engineering

AFOSR AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Acknowledgments

Research Collaborators:
Jennifer Winner (AFRL)
Capt. Jessica McCool (AFRL)
Chrisopther Myers (AFRL)
Nancy Cooke (ASU)
Polemnia Amazeen (ASU)
Nathan McNeese (Clemson)
Michael Hunter (GT)
iSAT Strand 2 (Sidney D'Mello, Leanne Hirshfield, Peter Foltz, Sadhana Puntambekar, Mike Tissenbaum)
John Flach (Mile 2)
Ronald Stevens (UCLA, Team Neurodynamics)
Graduate Students:
Terri Dunbar
David Grimm
Julie Harrison
Matthew Scalia
Shiwen Zhou
Adam Werner

Research Sponsors:

jamie.gorman@gatech.edu
http://spl.gatech.edu