Empowering the problem solving team through a computer-human partnership
(FA9550-18-1-0088)

PI: Jonathan Cagan (Carnegie Mellon University)
Co-PI: Kenneth Kotovsky (Carnegie Mellon University)

AFOSR Program Review:
Computational Cognition and Machine Intelligence Program
(October 6-8, 2020, Arlington, VA)

Empowering the problem solving team through a computer-human partnership

Jonathan Cagan and Kenneth Kotovsky, Carnegie Mellon University

Objective:

- Study and empower the hybrid AI/human team as a partnership in problem solving.
- Study, model, and computationally implement methods that competent managers use to guide novice teams in problem solving and identify triggers for intervention.

Approach:

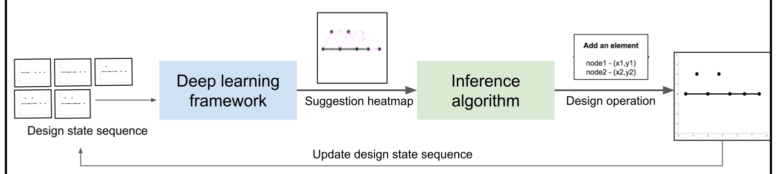
- Behavioral studies of expert intervention strategies to identify when and how to intervene in solving process, and impact of AI guidance of human teams
- Computational modeling and assessment of identified methods including real time application.

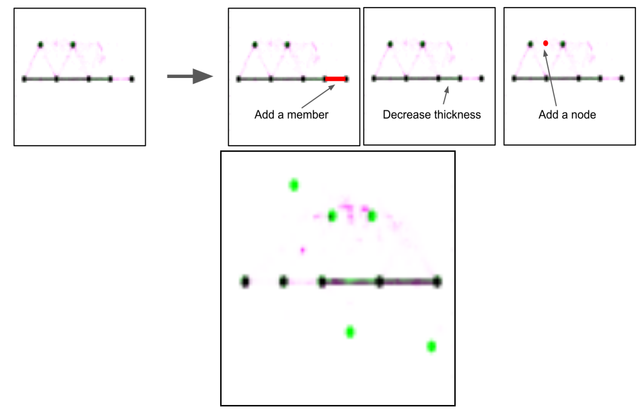
DoD Benefits:

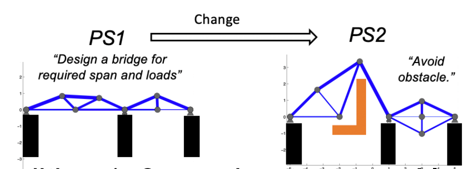
- Ability to track real time problem solving situation of humans to enable computers to:
  - meaningfully manage process by Intervening and shifting solving process & contribute solution concepts to stimulate solving using AI

Progress:

- Differentiate impact of proficiency of individual team members and identify their behavioral heuristics (via Hidden Markov Modeling)
  - Configuration design team is more dependent on most proficient member; improving their performance has greater effect than improving any other member
- Topic modeling analysis of design team discourse during problem-solving of managed and unmanaged teams results in different extracted topics
  - Process manager interventions significantly shift topic mixture of discourse toward interventions immediately after they are provided
- HSR study on impact of complex deep learning design AI (requiring visual interpretation) on team problem solving.
  - Accelerated bottom performing teams; mental demand on top performers lowered but performance reduced; further illustrates need for HCI design and interpretation (see figure)

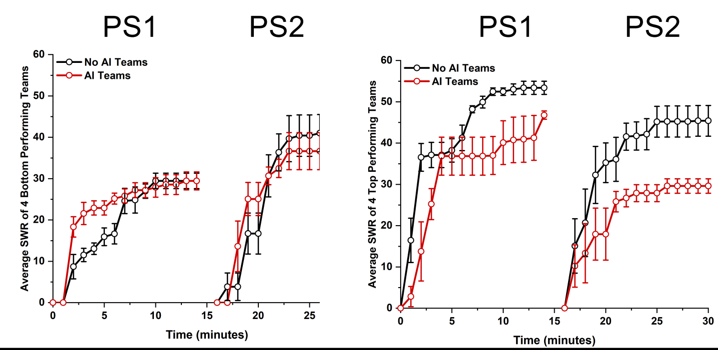






Condition 1: 3 member team no AI

Condition 2: 3 member team AI assist



List of Project Goals

1. Understand how effective managers direct collaborative team problem solving and create a computational test bed for further exploration
2. Leverage voice recognition and other concurrent methods to track and enable interaction analysis
3. Identify cognitive triggers that indicate teams straying during problem solving, and the appropriate timing of interventions, including during dynamic problem modification
4. Identify stimuli at different levels of abstraction to motivate re-direction during problem solving
5. Create multi-level generative model to enable conceptual design exploration
6. Computationally model and implement human-computer team collaboration in conceptual design problem solving via a shared grammatical representation

Progress Towards Goals (or New Goals)

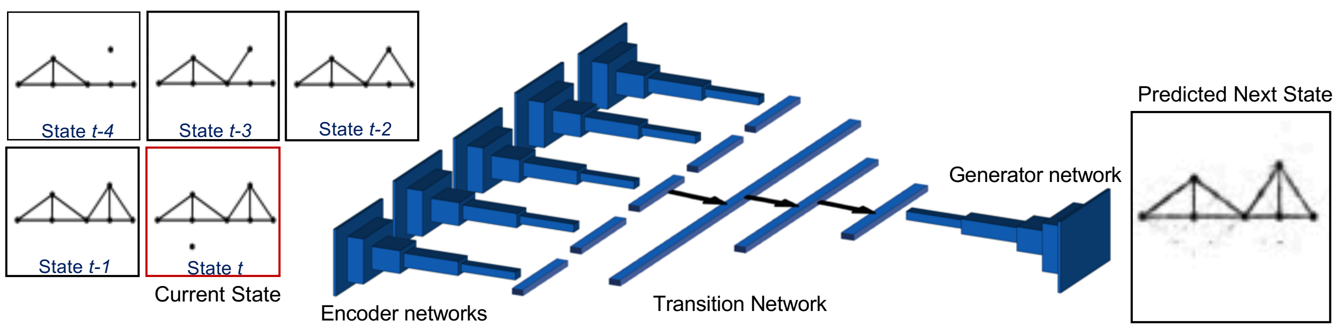
1. Understand how effective managers direct collaborative team problem solving and create a computational test bed for further exploration
   - Extensive study and assessment of manager intervention during conceptual design
2. Use voice recognition and other concurrent methods to track and enable interaction analysis.
   - Tracking of problem solving and use of LSA to assess team coherence
3. Identify cognitive triggers that indicate teams straying during problem solving, and the appropriate timing of intervention, including during dynamic problem modification
   - Assessment of intervention impact at solving phases, impact of task switching, impact of verbal communication, ability to mine solving strategies
4. Identify stimuli at different levels of abstraction to motivate re-direction during problem solving
5. Create multi-level generative model to enable conceptual design exploration
6. Computationally model and implement human-computer team collaboration in conceptual problem solving via a shared grammatical representation

A Cautionary Tale on Human-AI Collaboration in Design Teams

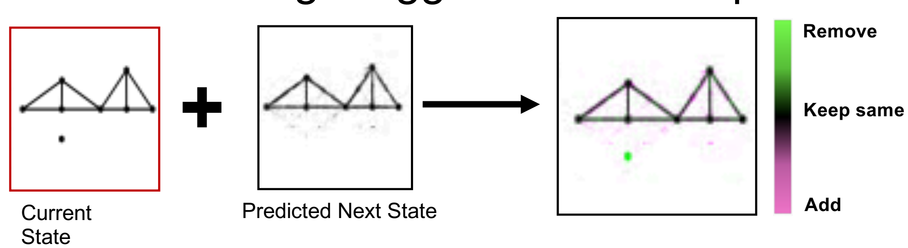
The AI: Deep Learning Agent

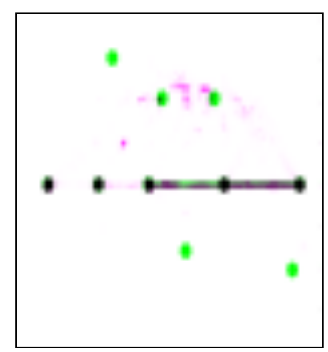
Input: Design State Sequence

Output:



Generating “suggestion heatmaps”:

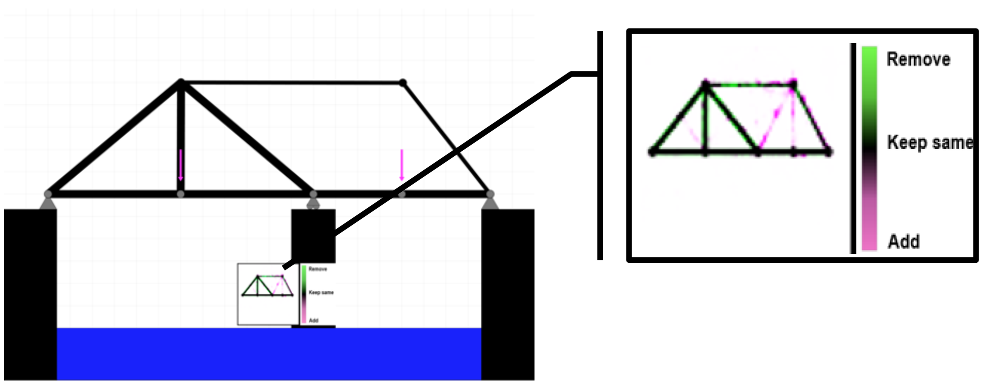


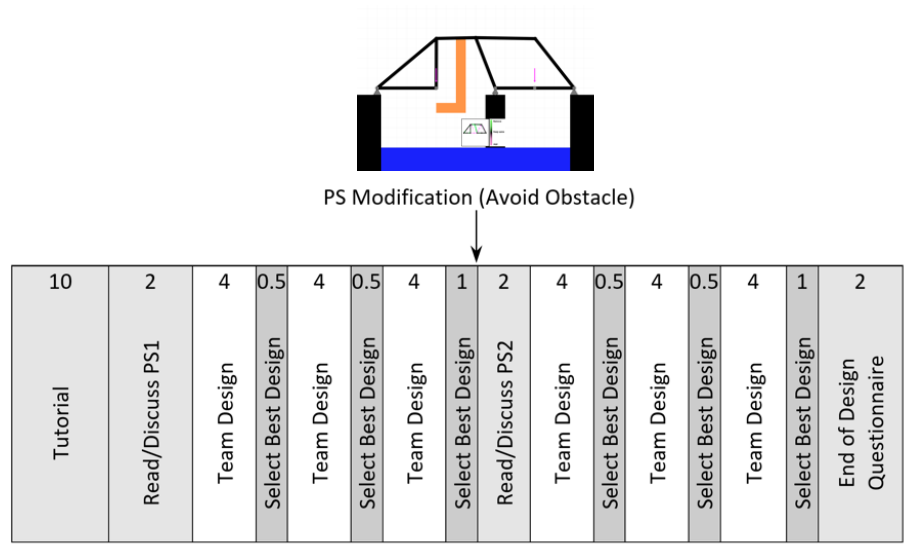


Raina, A., C. McComb, and J. Cagan, “Learning to Design from Humans: Imitating Human Designers Through Deep Learning,” *ASME Journal of Mechanical Design*, Vol. 141, No. 11, pp. 111102-1-11, 2019.

Truss Design Study Procedure

- Each participant is assigned into a team of 3 participants randomly.
- 12 teams are provided CNN (deep learning) **AI suggestion heat map** to aid their 2D truss design.
- Another 12 teams do not have AI suggestions to aid their truss design.
- The problem statement is modified in the middle of the study to include obstacle (which AI was not trained on)

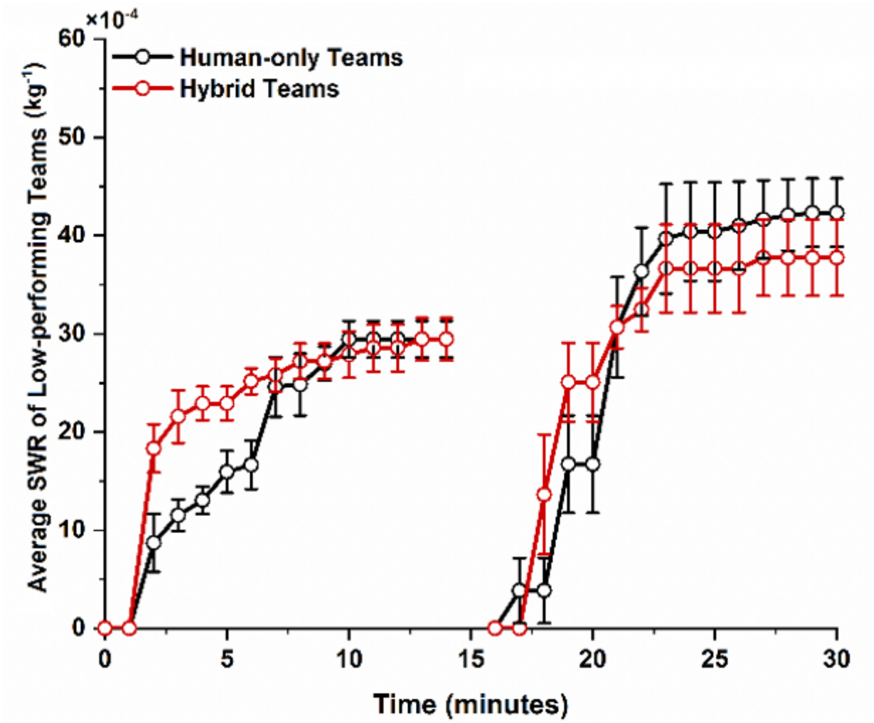




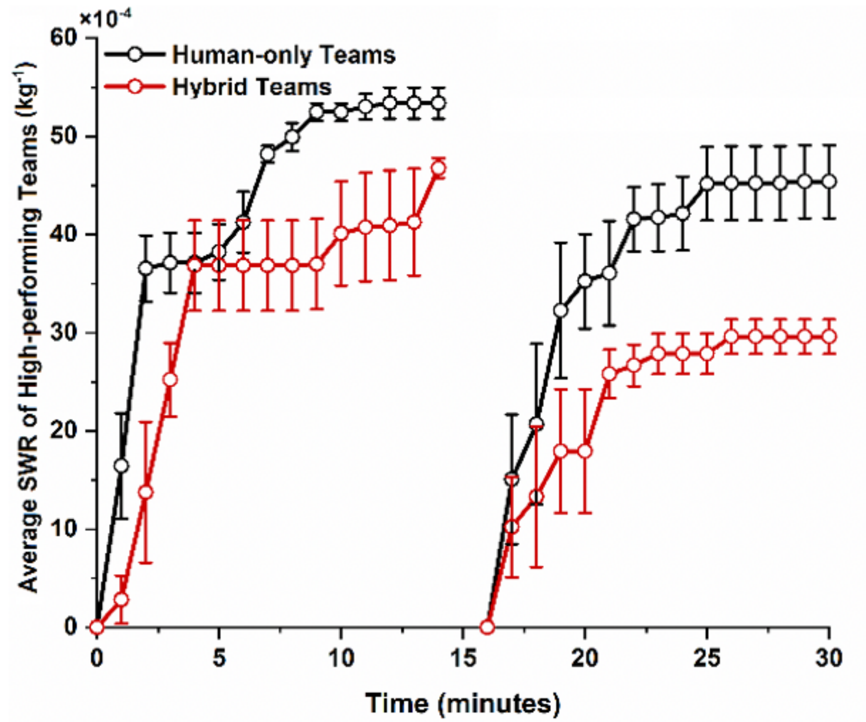
Time allocation of the 2D Truss design study (44 minutes in total)

Zhang, Raina, Cagan, McComb, "Is AI Better Off Alone? A Cautionary Tale on Human-AI Collaboration in Design Teams", 2020

Results of Bottom & Top Team Performance



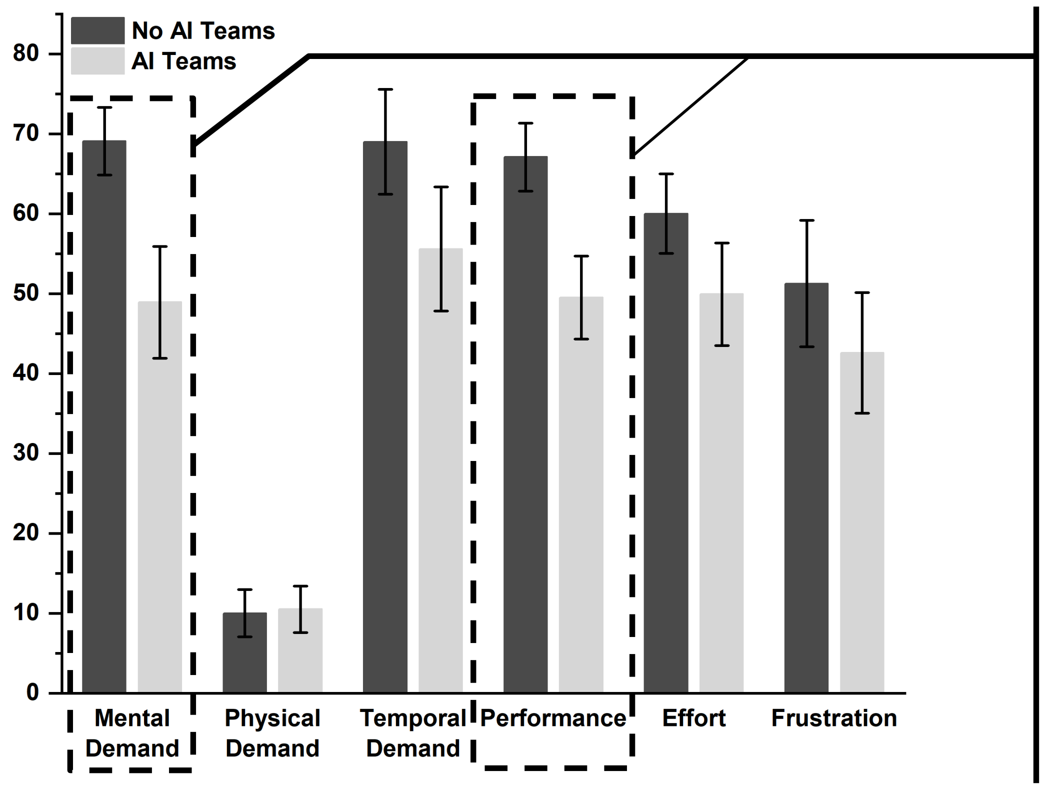
SWR of 4 Bottom Performing Teams



SWR of 4 High Performing Teams

Zhang, Raina, Cagan, McComb, “Is AI Better Off Alone? A Cautionary Tale on Human-AI Collaboration in Design Teams”, 2020

Results of Post-Study Questionnaire



NASA TLX Results of Top Performing Teams

- Top Performing Teams with AI Suggestion Heatmap perceived **lower mental demand.**
- Top Performing Teams with AI Suggestion Heatmap thought their designs are better as compared to no-AI teams.

Zhang, Raina, Cagan, McComb, "Is AI Better Off Alone? A Cautionary Tale on Human-AI Collaboration in Design Teams", 2020

Insights

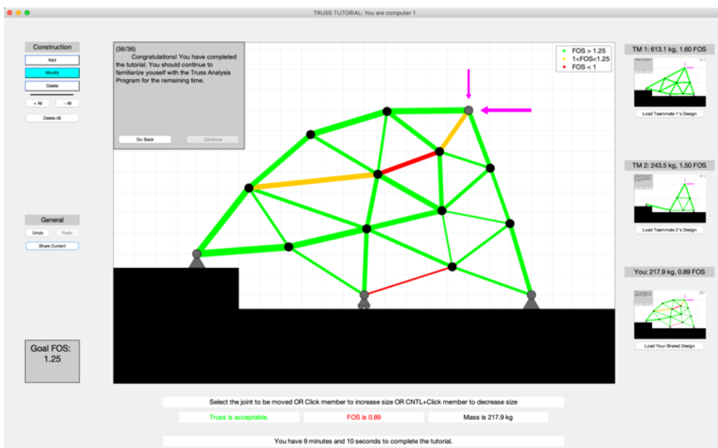
- Heatmap suggestions interpretation takes time and may also cause cognitive overload on participants' visual channel.
  - The interface and AI characteristics matter in determining hybrid team performance.
- AI was trained on variety of performance levels allowing heatmaps to capture better and worse suggestions, only on part of the solution set
  - None-the-less with heuristic guidance AI performs at high level
  - Must be interpreted by human
- Participants in high-performing hybrid teams perceive lower mental demand and believe they accomplish the design task more successfully compared to participants in the high-performing human-only teams, but in fact their performance is worse.
  - AI makes them lazy
- The context and interaction of the AI is critical for effectiveness and must be a core area of focus in the design of effective collaborative AIs.

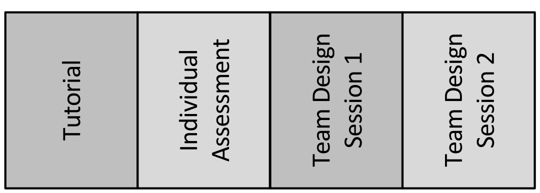
Zhang, Raina, Cagan, McComb, "Is AI Better Off Alone? A Cautionary Tale on Human-AI Collaboration in Design Teams", 2020

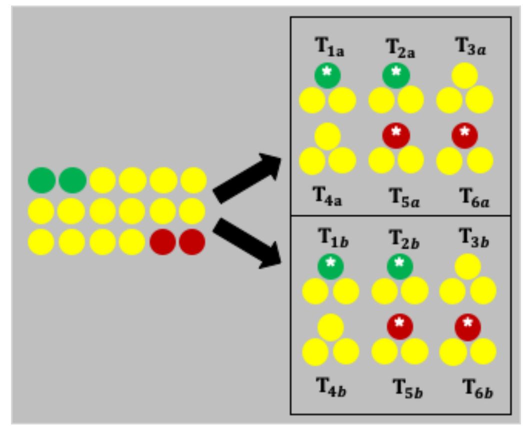
The Impact of Individual Team Member Proficiency in Configuration Design

Does the strongest or weakest member on a configuration design team have the most significant impact on team performance?

Bridge design problem







78 participants -> 23 teams

Behavioral study divided into 4 sections
- Introduce problem and interface
- Test individual proficiency
- Place individuals in teams and design collaboratively
  - Free interaction and at set interaction intervals
- Two problems and teams

Capture all moves to enable evaluation of individual effect

Brownell, E., J. Cagan, and K. Kotovksy, “Only As Strong As The Strongest Link: The Impact of Individual Team Member Proficiency in Configuration Design,” 2020.

Regression Analysis

$$TimeToReachScore = \beta_0 + LeastProfMem\,\beta_1 + MidProfMem\,\beta_2 + MostProfMem\,\beta_3$$

lower is better

- **Most proficient** member has consistent **positive effect throughout** design session

Brownell, E., J. Cagan, and K. Kotovksy, "Only As Strong As The Strongest Link: The Impact of Individual Team Member Proficiency in Configuration Design," 2020.

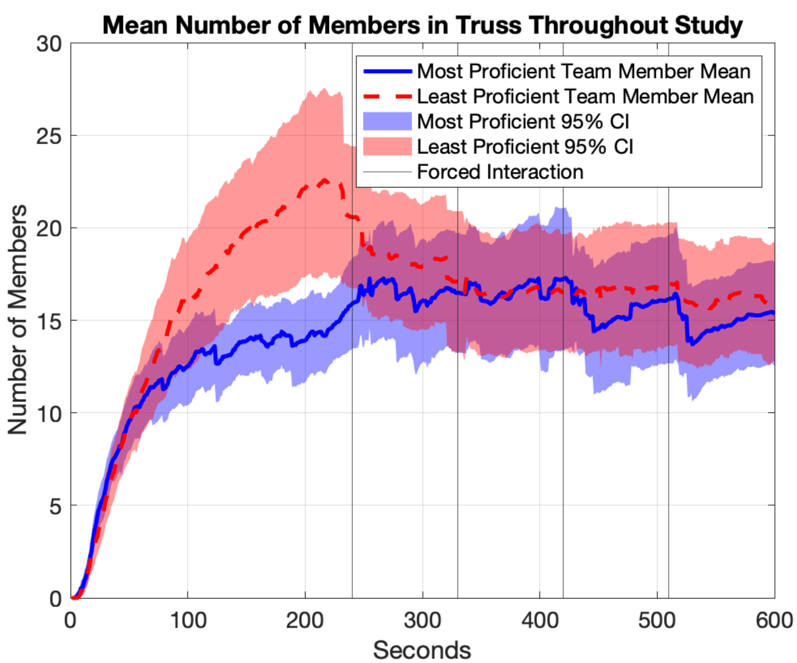
Behavioral Analysis: Hidden Markov Models

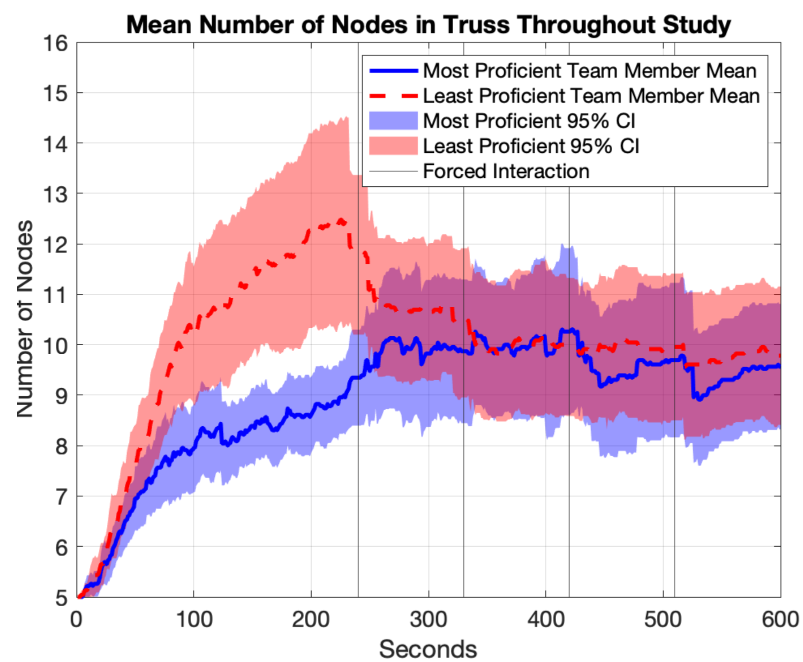
Proportion of Timesteps in States: 0-150 seconds			Proportion of Timesteps in States: 150-300 seconds			Proportion of Timesteps in States: 300-450 seconds			Proportion of Timesteps in States: 450-600 seconds		
State	High Proficient	Low Proficient	State	High Proficient	Low Proficient	State	High Proficient	Low Proficient	State	High Proficient	Low Proficient
1: Build Topology**	0.319 (0.045)	0.601 (0.061)	1: Build Topology	0.239 (0.045)	0.268 (0.040)	1: Build Topology**	0.141 (0.040)	0.031 (0.007)	1: Build Topology	0.134 (0.037)	0.071 (0.020)
2: Mixed Topology**	0.199 (0.029)	0.081 (0.020)	2: Mixed Topology	0.010 (0.013)	0.091 (0.014)	2: Mixed Topology	0.199 (0.043)	0.187 (0.041)	2: Mixed Topology	0.069 (0.023)	0.135 (0.032)
3: Shape and Broad Sizing	0.077 (0.021)	0.112 (0.030)	3: Shape and Broad Sizing*	0.085 (0.023)	0.202 (0.045)	3: Shape and Broad Sizing*	0.169 (0.043)	0.332 (0.068)	3: Shape and Broad Sizing*	0.145 (0.041)	0.345 (0.062)
4: Fine Sizing*	0.405 (0.054)	0.205 (0.053)	4: Fine Sizing	0.577 (0.050)	0.439 (0.071)	4: Fine Sizing	0.491 (0.049)	0.450 (0.069)	4: Fine Sizing*	0.653 (0.056)	0.450 (0.068)

Proportion of timesteps in each state on segments of the design session for the high and low proficiency members

Action Name	Action Class
1. Add Node	Topology
2. Add Member	Topology
3. Delete Node	Topology
4. Delete Member	Topology
5. Resize All Members	Sizing
6. Resize Single Member	Sizing
7. Move Node	Shape
8. Delete All	Topology
9. Switch Designs	~

Topology Comparison





Brownell, E., J. Cagan, and K. Kotovksy, "Only As Strong As The Strongest Link: The Impact of Individual Team Member Proficiency in Configuration Design," 2020.

Insights

- Teams **with** the **strongest member** usually perform best
  - Team members have unequal effects on team performance
  - The **relative contribution** of a team member matters
- To create better configuration design teams:
  - Invest resources in best member
    - Raising the average level is fine but raising the best performer is more impactful
- Behavior helps tell us why
  - Proficient designers:
    - Spend less time building topology
    - Build simpler trusses
  - Other designers adopt simpler designs
- Note that "configuration design" is broader than engineering

Brownell, E., J. Cagan, and K. Kotovksy, "Only As Strong As The Strongest Link: The Impact of Individual Team Member Proficiency in Configuration Design," 2020.

List of Publications, Awards, Honors, etc. Attributed to Grant

Awards

•Robert A. Doherty Award for Sustained Contributions to Excellence in Education, Carnegie Mellon University, 2018 (J. Cagan)

•ASME Design Automation Award, 2019 (J. Cagan)

•Reviewers' Favourite Award, 2019 International Conference on Engineering Design (Gyory, et al.)

•ASME Ruth and Joel Spira Outstanding Design Educator Award, 2020 (J. Cagan)

Journal Papers

•Gyory, J., J. Cagan, and K. Kotovsky, "Are You Better Off Alone? Mitigating the Underperformance of Engineering Teams During Conceptual Design Through Adaptive Process Management," Research in Engineering Design, 30(1): 85-102, 2018.

•Ulu, N.G., M. Messersmith, K. Goucher-Lambert, J. Cagan, L. B. Kara, "Wisdom of Micro-Crowds in Evaluating Solutions to Esoteric Engineering Problems," ASME Journal of Mechanical Design, Vol. 144, No. 8, 2019.

•Goucher-Lambert, K., J. Gyory, K. Kotovsky, and J. Cagan, "Adaptive Inspirational Design Stimuli: Using Design Output to Computationally Search for Stimuli that Impact Concept Generation," ASME Journal of Mechanical Design, Vol. 142, No. 9, pp. 091401-1-10, 2020.

•Andersen, E., K. Goucher-Lambert, J. Cagan, and A. Maier, "Attention Affordances: Applying Attention Theory in the Design of Complex Visual Interfaces," submitted, 2018.

•Gyory, J. T., K. Kotovsky, and J. Cagan, "The Influence of Process Management: Uncovering the Impact of Real-Time Interventions via a Topic Modeling Approach," submitted, 2020

•Sio, U.N., K. Kotovsky, and J. Cagan, "Determinants of creative thinking: The effect of task characteristics on creative problem solving,", submitted 2020.

•Brownell, E., Cagan, J., and K. Kotovsky, "Only As Strong As The Strongest Link: The Impact of Individual Team Member Proficiency in Configuration Design," submitted, 2020.

•Zhang, G., A. Raina, J. Cagan, C. McComb, "Is AI Better Off Alone? A Cautionary Tale on Human-AI Collaboration in Design Teams" submitted, 2020.

List of Publications, Awards, Honors, etc. Attributed to Grant

Reviewed Conference Papers

•Gyory, J., J. Cagan, and K. Kotovsky, “The Effect of Managerial Intervention on Engineering Design Team Performance,” Design Computing and Cognition ’18, J.S. Gero, ed., Milan, Italy, June 30-July 1, 2018.

•Gyory, J., J. Cagan, and K. Kotovsky, “Investigating Performance While Working Together or Alone in Conceptual Engineering Design,” DETC2018-85602, ASME IDETC – Design Theory and Methodology Conference, Quebec City, Quebec, Canada, August 26-29, 2018.

•Goucher-Lambert, K., J. Moss, and J. Cagan, “Inspired Internal Search: Using Neuroimaging to Understand Design Ideation and Concept Generation with Inspirational Stimuli,” DETC2018-85690, ASME IDETC – Design Theory and Methodology Conference, Quebec City, Quebec, Canada, August 26-29, 2018.

•Gyory, J. T., K. Goucher-Lambert, K. Kotovsky and J. Cagan, “Exploring the Application of Network Analytics in Characterizing a Conceptual Design Space,” accepted: International Conference on Engineering Design, ICED ’19, The Netherlands, August 5-8, 2019.

•Goucher-Lamber, K., J. T. Gyory, K. Kotovksy, and J. Cagan, “Computationally Derived Adaptive Inspirational Stimuli for Real-Time Design Support During Concept Generation,” DETC2019-98188, ASME IDETC – Design Theory and Methodology Conference, Anaheim, CA, Canada, August 18-21, 2019.

•Gyory, J. T., K. Goucher-Lambert, J. Cagan, and K. Kotovksy, “A Proposed Metric to Assess the Overall Innovative Potential of Conceptual Designs,” ASME IDETC – Design Theory and Methodology Conference, Anaheim, CA, August 18-21, 2019.

•Chong, L., K. Goucher-Lambert, K. Kotovsky, and J. Cagan, “Does a Constrained Design Space Constrain Effective Ideation?”, accepted: Ninth International Conference on Design Computing and Cognition - DCC'20, Atlanta, GA, June 29-July 1, 2020.

•Brownell, E., J. Cagan, and K. Kotovksy, “Only As Strong As The Strongest Link: The Impact of Individual Team Member Proficiency in Configuration Design,” DETC2020-19196, ASME IDETC – Design Theory and Methodology Conference, St. Louis, MO, August 16-19, 2020.

•Gyory, J., J. Cagan, and K. Kotovksy, “A Topic Modeling Approach to Study the Impact of Manager Interventions on Design Team Cognition,” DETC2020-19192, ASME IDETC – Design Theory and Methodology Conference, St. Louis, MO, August 16-19, 2020.