I develop robots that improve the performance of human-robot teams by shaping team dynamics to promote inclusion, trust, and cohesion. Human social behavior in groups is richly interconnected and highly nuanced, presenting computational challenges for sensing group-level dynamics from individual behavior. I build robots that not only perceive these dynamics, but also positively influence the behavior of group members through social cues and verbal interaction. Using computational models that detect relevant verbal and nonverbal social cues, predict high-level social dynamics, and generate decision-making policies for robot actions, I explore how a robot's actions within a group shape human team members' behavior.

Successful teams consist of members who discuss ideas in a constructive manner, who feel free to openly discuss their mistakes and errors, and who are sensitive to and aware of the emotions expressed by their team members. In order to build robots that support team success in this way, I identify two main challenges. First, perceiving and modeling high-level team dynamics (e.g. inclusion, psychological safety) is difficult because little to no work has demonstrated connections between low-level human behavior (e.g. head nodding, eye gaze) and these high-level team dynamics. Second, little is currently known about how robot social behaviors (e.g. attention, low-level social cues, verbal utterances) may positively influence team dynamics and performance. To address these challenges, I have (1) developed data-driven computational models to link low-level social cues to team dynamics [1,2] and (2) studied how a robot can shape team dynamics through human subjects experiments [3,4,5,6,7]. In future work, I envision building robots with social group intelligence, capable of reasoning about group dynamics and the influence of its actions on a group, that work alongside people in natural settings for extended periods of time.

MODELING TEAM DYNAMICS

In order for a robot to optimally improve team dynamics and performance, it is important for the robot to be able to sense and model current group dynamics to strategically act within the group. For example, if a robot senses that a group member feels excluded, the robot could affirm that member's comments when they bring up an idea. I have explored capturing critical group dynamics within two distinct populations: social dominance in young children (ages 6-8), and psychological safety and inclusion in collaborative adult teams. I have demonstrated success in predicting the social dominance of individual children interacting with two of their peers and two robots in an educational task [1]. I was able to show that a small set of hand-labeled nonverbal behaviors (e.g. time looked at by the other children) were able to predict whether a child was rated as high or low by their teacher in social dominance with 89% accuracy. In recent work, I have been able to show correlations between the team members' psychological safety and inclusion and the number of backchannels, behaviors that indicate active listening (e.g. "yeah", head nodding), expressed by members of the team [2].

Figure 1. I developed a model to predict social dominance of children from their nonverbal behavior [1].

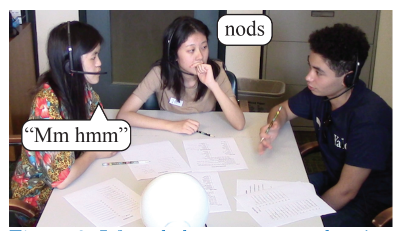

Figure 2. I found that group members' backchanneling predicted their inclusion and psychological safety [2].

SHAPING TEAM DYNAMICS WITH ROBOT BEHAVIOR

Through several human-subject experiments, I have investigated the ability of robots to shape several key team dynamics that have been established by the literature to critically influence team performance: trust [3,4], inclusion [5,7], cohesion [6], and psychological safety [7].

Trust is also a critical ingredient to positive team dynamics and performance and can be described as the willingness of team members to be vulnerable with one another. I found that human team members in a group with a robot making vulnerable comments, as opposed to neutral comments, were more likely to display vulnerable behavior (e.g. explaining a mistake) to their fellow human team members in the aftermath of a team member's error in a collaborative game [3]. I also discovered that individuals in groups with robots that made vulnerable comments, as opposed to neutral comments, have longer and richer conversations over time and distribute their conversation more equally between their fellow human group members [4]. Through these findings, **I was the first to demonstrate that a robot's behavior can influence how the people in the group interact with one another**: the human team members displayed more trusting behavior toward their fellow human team members if the robot they interacted with modeled trust and vulnerability.

I have also investigated two strategies to improve the **inclusion** of the human members of a human-robot team: 1) a specialized role to interact with the robot and 2) supportive utterances from the robot. I discovered that a specialized role to interact with a robot can lead to decreased perceptions of inclusion, however, a robot's supportive utterances demonstrated an increase of verbal contribution in human team members who were more excluded in a collaborative task [5].

To examine possible ways a robot can influence the **cohesion** between team members, I investigated the influence of task-focused and relationship-focused discussion questions administered by a robot companion during a collaborative task completed by two children. Although the question type did not influence ratings on a cohesion questionnaire, I found that relationship-focused questions, as opposed to task-focused questions, led children to have higher perceptions of their team's performance [6].

I am currently investigating a robot's ability to improve team members' **inclusion** and **psychological safety** ("a shared belief [...] that the team is safe for interpersonal risk taking"[8]) by having the robot backchannel human team members. Yale students in a two week course project conducted four of their team meetings either in the presence of a backchanneling robot or without a robot [7]. I am currently finishing data collection and beginning data analysis for this project.

Figure 3. I demonstrated that a robot's expressions of vulnerability can increase the likelihood that other members of the group are vulnerable to one another [3].

Figure 4. I found that a specialized robot liaison role decreases inclusion, but a robot's supportive utterances increase participation from outsiders [5].

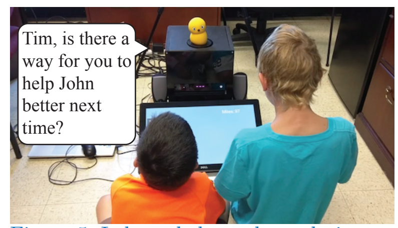

Figure 5. I showed that robot relationship-focused questions increased children's performance perceptions [6].

FUTURE DIRECTIONS

In my Ph.D. work, I focused on robots shaping interactions within collaborative human-robot teams. In the coming years, I plan to broaden my research to consider enhancing robot interactions with groups of people in diverse, complex, and long-term settings (e.g. household assistant robots interacting with families, food delivery robots navigating crowds, storefront robots assisting customers). My vision is to develop ***robots with social group intelligence***, capable of reasoning about group dynamics and the influence of its actions on a group, that work alongside people in ***natural settings*** for ***extended periods of time***. My planned future work aligns closely with the Strengthening Teamwork for Robust Operations in Novel Groups (STRONG) program of the Army Research Laboratory, the National Robotics Initiative 2.0, and the Cyber-Human Systems program of the National Science Foundation.

1. **Sensing and Modeling Social Dynamics Online.** For robots to interact intelligently with groups of people, they first must be able to perceive and understand the important social dynamics (e.g. power, influence, norms) of the groups with whom they interact. In my Ph.D. work, I have used hand-labeled data to establish correlations between low-level behaviors (e.g. gaze, backchannels) with social dynamics (e.g. social dominance, inclusion). Building on this work, my future work will focus on building online social dynamic detection models that will allow robot perception of social dynamics in real-time to enable personalized interactions and interventions in the group. This will involve training models to predict the occurrence low-level social signals (e.g. verbal backchannels, annoyance) as well as constructing models (e.g. HMMs) to represent higher order group dynamics like inclusion. Additionally, when considering interactions with people over longer time horizons, I plan to build robots that recognize and store salient events in order to model how these past events influence future interactions.
2. **Developing Socially Adaptive Decision Making Algorithms.** Robots interacting in a socially intelligent manner with groups of people will pursue a range of social goals that could, for example, include building rapport, adhering to the social norms of the group, and being an agreeable team

member. In the pursuit of such social goals, it is vital that robots personalize their actions to the specific dynamics of the group with which they are interacting as well as adapt to errors and unexpected events (using methods such as reinforcement learning). My future work will use the online social dynamics perception models I describe above to inform robot decision making policies to further social goals. Additionally, due to the importance of maintaining trust and rapport in long-term social interactions, I plan to design algorithms to detect and repair unexpected events and errors.

3. **Exploring Robot Social Influence.** In my Ph.D. work, I have demonstrated that robots have the ability to powerfully shape the dynamics of human-robot teams with behaviors that range from direct questions, to expressions of vulnerability, to verbal affirmations. Beyond the contributions I have made in my Ph.D. work, many questions remain, such as: How might a socially capable robot not only shape the dynamics of the small team it works most closely with, but also the organization as a whole? How could a household assistant robot influence family dynamics within the home? In my future work, I plan to investigate ways in which robots can influence groups in important contexts (e.g. the workplace, the home) evaluated over longer periods of time.

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