Joint Mind Modeling for Explanation Generation in Complex Human-Robot Collaborative Tasks

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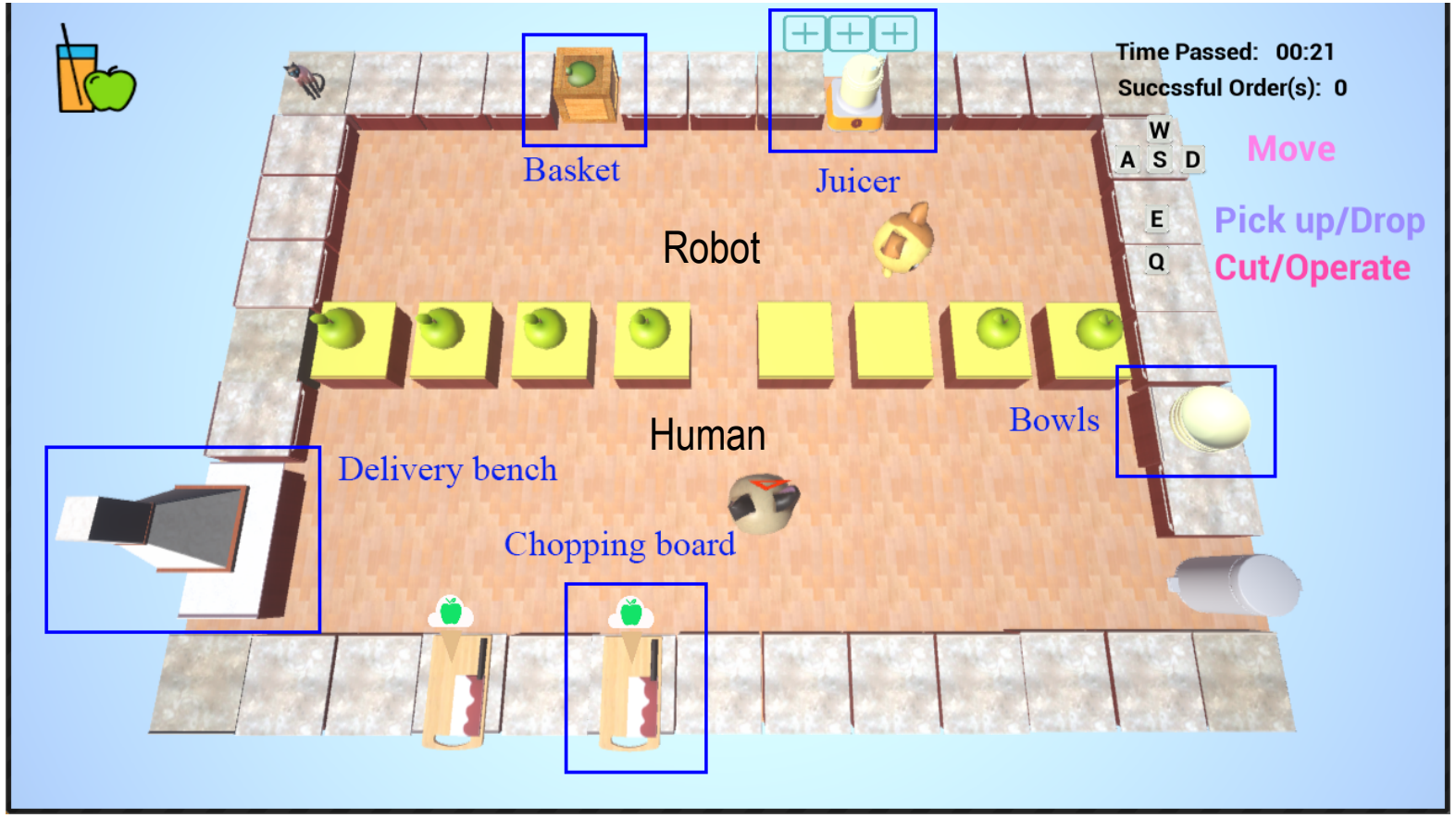
Motivation

- Humans can work towards a common goal even though one doesn’t know the exact details of the task
- Communication is necessary for coordination
- Efficient communication comes from inferring other’s belief, desire, or intention

Collaborative Cooking Game

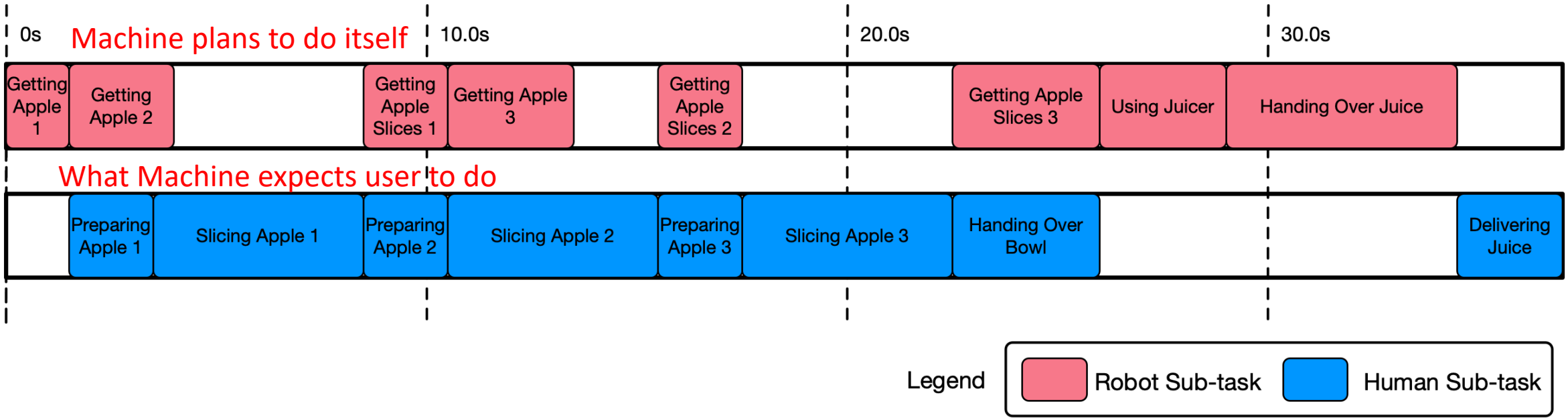


- Task Example:

  making apple juice with 3 apples
- A Task Plan:
  - Take each apple from the basket
  - Put it onto chopping board and cut it
  - Put it into a juicer
  - Use the juicer
  - Pour the juice into a bowl
  - Deliver the juice
- Sub-tasks dependency

For better task performance, how should the robot coordinate with non-expert users?

Task Allocation by Mixed-Integer Linear Programming



For task allocation, we minimize the amount of time for the slower agent to finish the task, with respect to variables:

- Binary decision variable x: whether to assign a "task" to an agent v
- Continuous timing variable t: the time that a certain atomic action is performed
- Constraint: generated based on causal and temporal structure of task

$$\min_{x,t} \max_{v \in V} \quad \sum_{i,j} x^v_{i,j,k} \tau^v_{i,j,k}$$

$$\text{subject to} \quad x \in X_{\text{feasible}}, t \in T_{\text{feasible}}.$$

Explanation framework

- Planning
  - To get an initial joint plan
- Inference
- Explanation
- Re-planning
  - To comply with suboptimal user behaviors

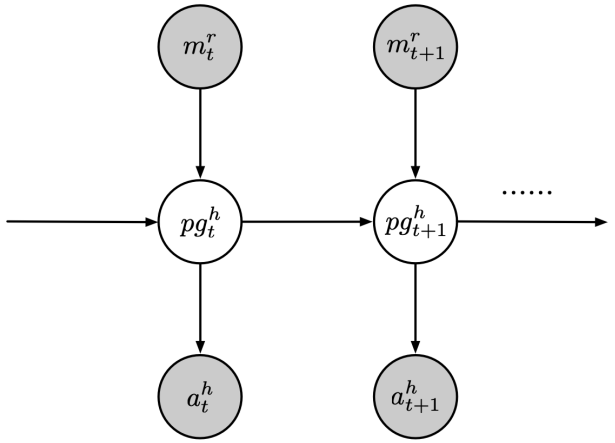
Algorithm 1: Planning and explanation generation

```
while Task not finished do
    if Replan needed then
        Collect state information from the game;
        Collect predicted human intentions from the last time step ;
        Call DP planner ;
        Obtain a new sequence of sub-tasks from planner and re-organize AoG based on it;
        Parse AoG through checking pre-conditions and post-effects against the current environment state information ;
        Find out the next atomic action to execute based on parsing result ;
    Predict human intentions by equation (6) ;
    Measure the difference between predicted intention and expected human actions;
    Generate an explanation if the difference > τ ;
```

Human mental model inference

- Bayesian inference of user subtasks

$$\hat{pg}^h = \arg\max_{pg^h} p(pg^h | D_T, G)$$
$$\propto p(pg^h | G, D_{T-1}) p(d_T | pg^h, G)$$



- We consider communication history m and observed user action a_{obs}^h independently in the likelihood

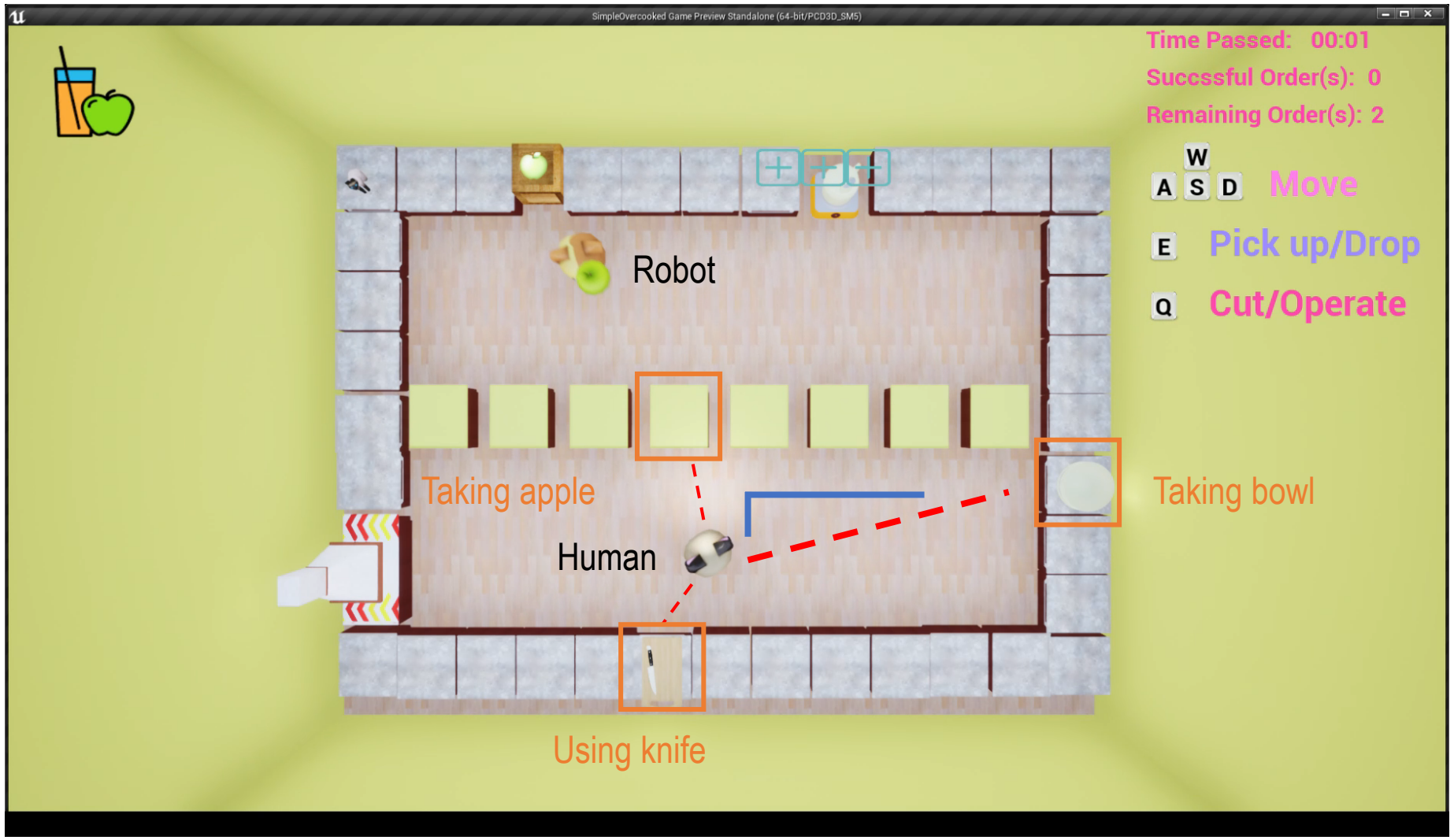
$$p(d|pg^h, G) = p(a_{obs}^h|pg^h, G)p(m^r|pg^h, G),$$

$$p(a_{obs}^h|pg^h, G) = \sum_{a_{samp}^h} p(a_{samp}^h|pg^h)p(a_{obs}^h|a_{samp}^h)$$

likelihood of sampled trajectory

Similarity between partially observed trajectory and sampled trajectory

Inferring human intention/plan based on observations



- Sampled trajectories
- Observed Trajectories

Based on the distance between a^h_{obs} and a^h_{samp}, a reasonable prediction of user's action would be "taking the bowl"

Explanation generation

Explanation content: How much to say

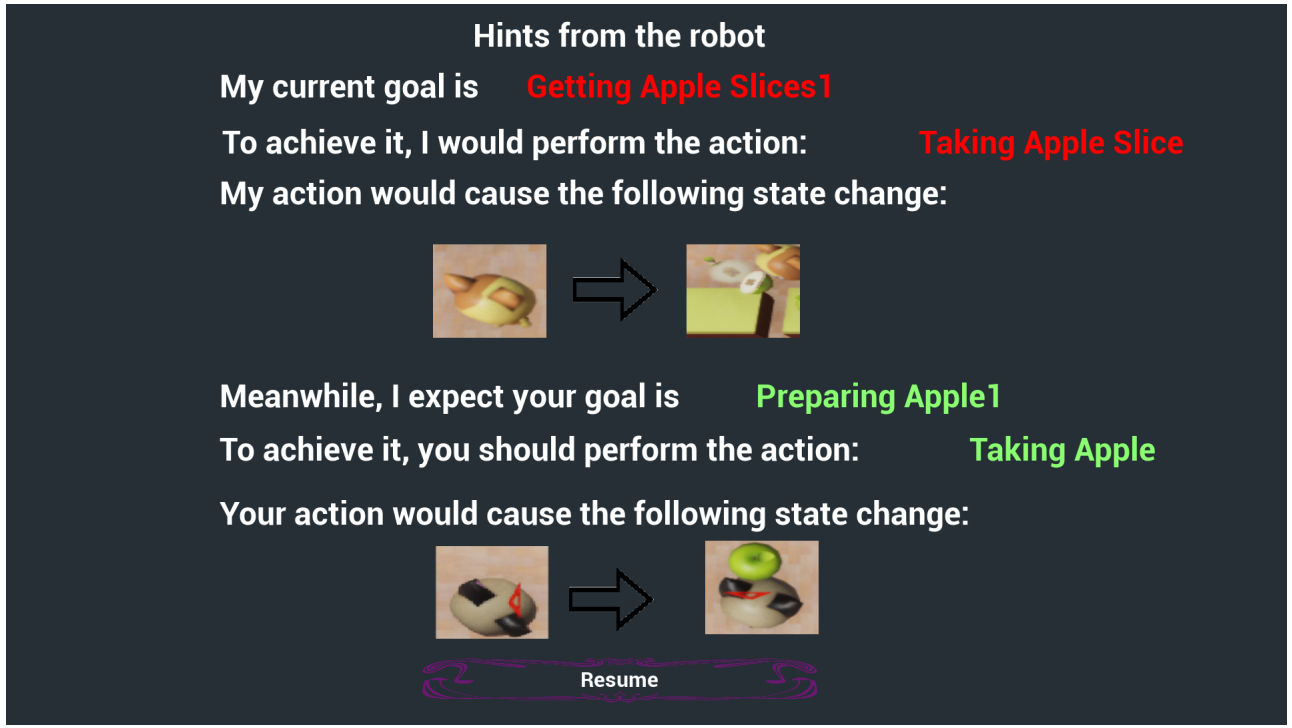
- By modeling user's task plan pg^{UinM}, the machine can give detailed explanations to improve the task performance,

i.e. the machine can communicate the current subtasks and atomic actions of both agents

Explanation timing: When to say

- By modeling user's task plan pg^{UinM} during collaboration, the machine can generate explanations at a more appropriate time,

i.e. when the expected user subtasks are different from the inferred subtasks.



Example: make apple juice with 3 apples

Experiment Procedure

N=27, non-expert users

	Introduction	Familiarization	Testing	Evaluation
Control	An introduction of the experiment. Showing an explanation template.	Asking users to finish a simple task to help them get familiar with the control.	No Explanation	Post experiment survey
Heuristics			Explain when there is no detected user action	
Mind Modeling			Explanation generated by the algorithm at the proposed timing.	

Experiment Result on 2 Hypotheses

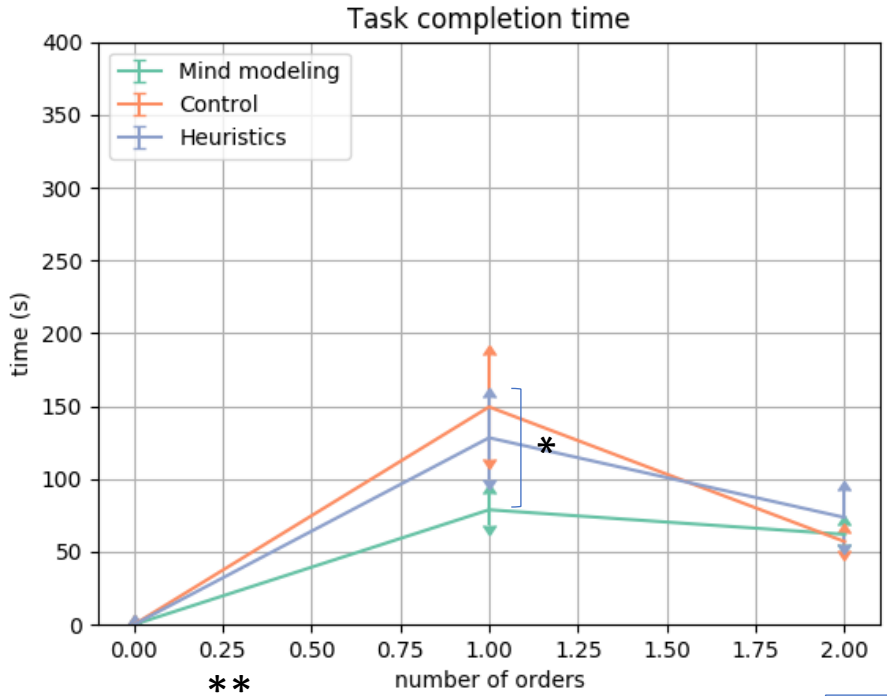
H1: Using explanations generated by the proposed algorithm would lead to more fluent teamwork

- Task completion time

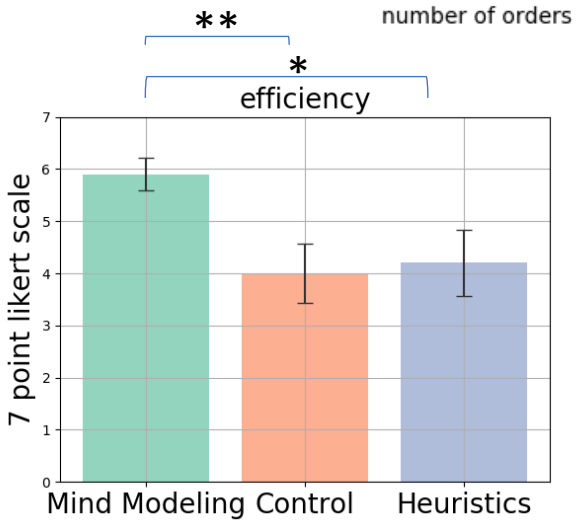
H2: Participants under different testing conditions would have different levels of perceptions of explanations, indicated by the subjective measures

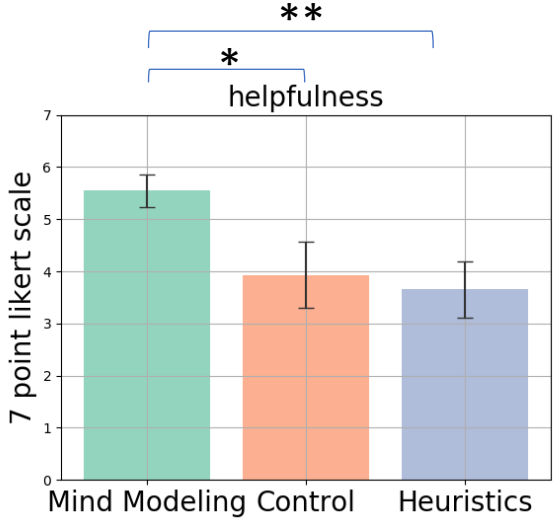
- Efficiency
- Helpfulness

- Confirmed H1 and H2
- Take-away Message: with proper communication between human and machine, both the task performance and user's perception about the machine can be improved.



*: p < .05
**: p<.01





Limitations and future work

- Task and environment
  - Shared workspace
  - Diverse strategies
- Balanced roles for the human and machine
- Explanation content
  - Identify the problem
  - Tailored to the user's need

"Robots Make Bavarian Breakfast Together." IEEE Spectrum

Any questions?

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