Task Interdependence in Human-Robot Teaming

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***Abstract*— Human-robot teaming is becoming increasingly common within manufacturing processes. A key aspect practitioners need to decide on when developing effective processes is the level of task *interdependence* between human and robot team members. Task interdependence refers to the extent to which one's behavior affects the performance of others in a team. In this work, we examine the effects of three levels of task interdependence—*pooled, sequential, reciprocal*—in human-robot teaming on human worker's mental states, task performance, and perceptions of the robot. Participants worked with the robot in an assembly task while their heart rate variability was being recorded. Results suggested human workers in the *reciprocal interdependence* level experienced less stress and perceived the robot more as a collaborator than other two levels. Task interdependence did not affect perceived safety. Our findings highlight the importance of considering task structure in human-robot teaming and inform future research on and industry practices for human-robot task allocation.**

I. INTRODUCTION

Advancements in robotics and automation systems have enabled workers to work with robots in close proximity. Particularly in manufacturing settings, these *collaborative* robots have the potential to increase productivity of human labor, to allow greater flexibility in production, to improve ergonomics of manual tasks, and to provide economic benefit dependent on practitioners leveraging the optimal level of human-robot collaboration for their processes. Enabled by advancements in the technical aspects of the robotics systems, collaborative robots can further augment the human operator's work. Examples of such advancements include a real-time motion synthesis method presented by Rakita et al. [24] that operates without collisions and discontinuities, allowing safe and efficient human-robot collaboration in close proximity. Lasota and Shah [18] proposed a human-aware robot motion planning system that adaptively avoids the human working zone, allowing robots to assist human workers side-by-side safely and efficiently. Pearce et al. [21] proposed an optimization framework that minimizes both work time and human worker's physical stress in collaborative tasks. Finally, Chrubini and colleagues [7] implemented a system that uses active or passive behaviors based on human worker's needs in order to reduce worker workload and risk of strain injury. These developments in collaborative robotics have paved the way for robots to function as co-workers in manufacturing.

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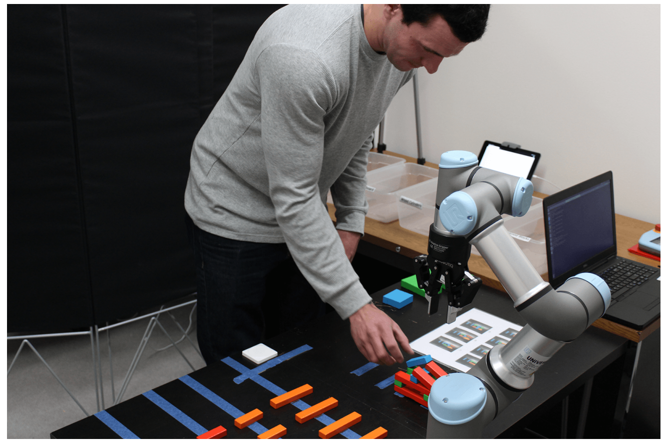
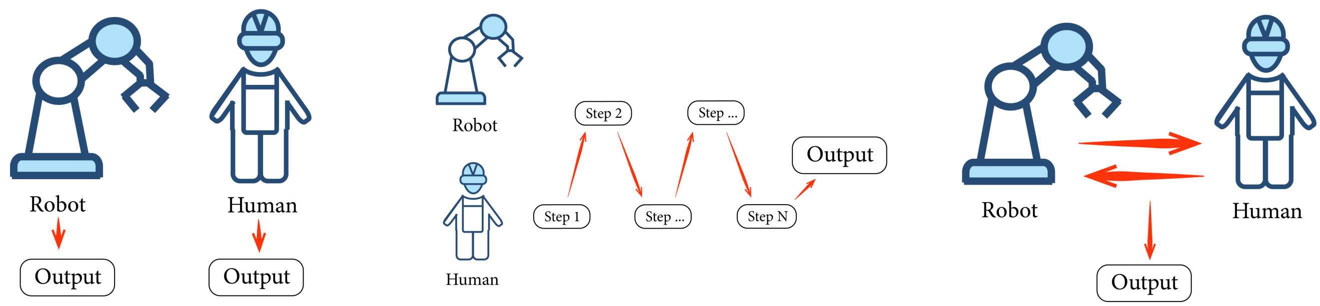


Fig. 1. In this work, participants collaborated with a UR3 collaborative robot to construct three objects under one of the three levels of task interdependence—*pooled, sequential, reciprocal*—while their physiological responses were recorded.

Although the ultimate goal of introducing collaborative robots is to improve productivity and to maintain work safety, human-robot teaming raises many new questions: how do we maintain effective workflow between the human and the robot in a shared workspace? What is the optimal task allocation between the human and the robot? Namely, little is known about how the level of collaboration between the human and the robot affects work efficiency. Recent research by Kolebeinsson and colleagues [15] has argued that a classification of human-robot collaboration levels in manufacturing would benefit effectiveness and satisfaction in the factory of future. Prior work has also explored methods to facilitate effective workflow in human-robot collaboration, e.g., how human-robot turn-taking can be improved by adding facial expressions on robots in order to increase trust in collaborative tasks [26]. Hinds and colleagues [12] examined the effects of robot appearance and team roles in collaborative tasks and found that humanoid robots were more appropriate in high-stress work whereas machine-like robots were more suitable for mundane tasks. Despite these efforts, the effects of *work structure* on work performance in a human-robot team remain unexplored. Understanding the degree to which human and robot workers need to rely on each other during collaboration and the effects of interdependence on work performance is critical to effective human-robot teaming.

Another question raised by human-robot teaming is, how does the task allocation and workflow affect human worker's mental and physical experience? In traditional manufacturing cells, human workers are at high risk of injury due to repetitive



(a) Pooled Interdependence (b) Sequential Interdependence (c) Reciprocal Interdependence

Fig. 2. Illustrations of the levels of task interdependence within human-robot team explored in this work: *pooled*, *sequential*, and *reciprocal*.

work and accidents from machine errors [7]. The integration of collaborative robots aims to reduce such physical risks in human workers. However, studies have also shown that human workers tend to experience *mental* strain when collaborating with robots in shared workspaces [2], [9]. This mental strain could be triggered by the robot's appearance (e.g., size, appearance) or its motion (e.g., sudden movements, speed, moving distance, proximity, etc.) [2]. These risks could further be affected by how closely human workers interact with robots. We posit that collaborating with a robot in close proximity could put human team members under greater stress and anxiety. Yet, little is known about the effects of how work is structured between human and robots on the *mental well-being* of the human workers.

In this study, we explore the relationship between different team structures and team productivity and human worker experience in human-robot collaboration (Fig.1). Drawing on theories from human-human and human-animal teamwork, we focus on one dimension of team structure—*task interdependence*—and investigate its effects on work performance and human worker's real-time mental states.

II. RELATED WORK

A. Task Interdependence in Human-Robot Teams

Task interdependence refers to the extent to which one's task actions affect the performance of others in a team. It is determined by three major components: (1) *team workflow*, the process that team members follow to complete the task, (2) *requirements for the worker's own actions*, the degree of discretion, coordination, and input needed from the worker, and (3) *requirements for the actions of others*, those needed from team members [31]. Phillips et al. [22] reviewed evidence from human-animal teaming and identified three levels of task interdependence that could apply to human-robot teams: *pooled interdependence*, *sequential interdependence*, and *reciprocal interdependence* (Fig.2). In *pooled interdependence*, each worker completes tasks separately; there is minimal interaction and coordination among team members; and actions of one worker would not affect the actions of the others. Teams with pooled interdependence are in *low* task interdependence. In *sequential interdependence*, workers in a team work together to complete tasks in a pre-defined order. Any disruption in one's behavior could directly affect the performance of others. Thus, workers rely heavily on each other. However, because the workflow is pre-defined, each team member only needs to exert minimal effort to coordinate with each other. Therefore, sequential interdependence involves a *medium/moderate* level of task interdependence. In *reciprocal interdependence*, each worker specializes in a certain skill or a specific aspect of the task. Temporal structures (i.e., order) are not required in reciprocal interdependence. Portions of a task can be carried out in a flexible order. Apart from assigned tasks, team members are required to actively coordinate with each other to achieve shared goals. Thus, reciprocal interdependence can be seen as *high* task interdependence.

In human teamwork, task interdependence is strongly related to team performance, efficiency, creativity, and experience. During a task, team members work together toward a common goal, and task interdependence provides a sense of control [14] and responsibility [30]. Aube and colleagues [4] found that higher task interdependence leads to higher goal commitment among team members, resulting in better team performance and experience. Thus we form our first hypothesis:

- **H.1a** *Participants in teams with higher task interdependence will outperform participants in teams with lower task interdependence. Specifically, teams with reciprocal interdependence will complete the task faster than those with sequential and pooled interdependence.*
- **H.1b** *Participants in teams with reciprocal and sequential interdependence will perceive the robot more as a teammate or a collaborator, while participants in teams with pooled interdependence will perceive the robot more as a machine or a tool.*
- **H.1c** *Participants in teams with higher task interdependence will have a higher sense of team collaboration than those with lower task interdependence.*

B. Stress and Physiological Computing in HRI

People's affective states can manifest themselves in their physiology. For example, when people feel stressed, or experience fear, their heart rate increases; their blood pressure goes up; and they start to sweat. In the autonomic nervous system (ANS), the sympathetic nervous system (SNS) coordinates "fight or flight" situations, while the parasympathetic nervous

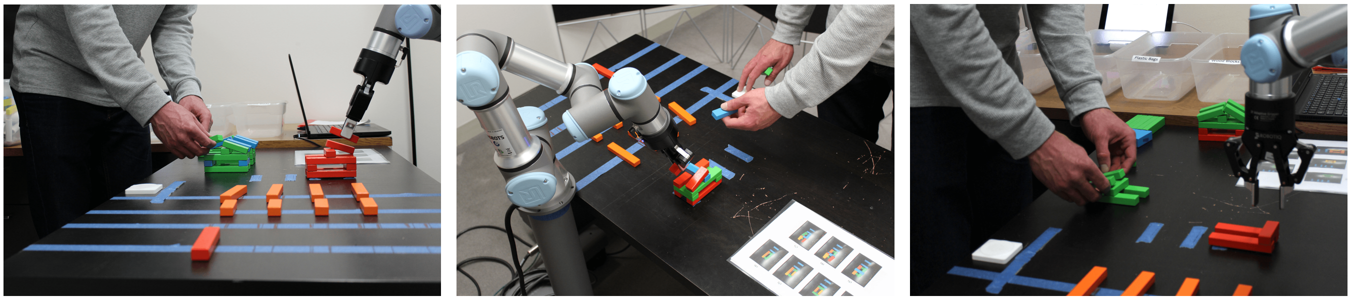


Fig. 3. The three task interdependence conditions (from left to right). In *pooled interdependence*, the participant and the robot constructed objects individually. In *sequential interdependence*, the participant and the robot took turns putting blocks on the object. In *reciprocal interdependence*, the participant and the robot each were in charge of one part of the object.

system (PNS) controls relaxation [20]. Heart rate variability (HRV), which captures changes in inter-beat interval, i.e., the time between heart beats [1], is a measure of ANS activation and the balance between SNS and PNS [19]. Reduced HRV reflects decreased sympathetic regulation, which is highly related to anxiety, stress, fear, and depression [27].

Psycho-physiology can adapt to technology use [6], allowing researchers to measure real-time affective responses. Kulic and Croft [16] conducted the first study of user affective states when facing a physical robotic arm using physiological response, particularly skin conductance. They found that users exhibited less anxiety when facing the robot planner designed to appear safer. Rani et al. [25] developed an online stress detection tool to evaluate human worker's stress in human-robot interaction. The tool takes HRV and interbeat interval as inputs and looks for stress signals. Although there is growing interest in utilizing pscho-physiological responses in HRI, few studies have utilized them in studying human-robot teaming in close proximity. In a study by Arai et al. [2], skin potential response (SPR) was employed as a measure of mental strain to investigate the relationship between industrial robots' motion and proximity and human worker's stress. They found that human operators were in high stress when working with an industrial robot within 2m or an arm that moves faster than 500mm/s. Dehais and colleagues [8] measured skin conductance from participants during a simple hand-over task and found different responses to robot motion with different levels of safety, comfort, and legibility.

In this study, we asked participants to wear an ambulatory heart rate monitor to collect HRV while collaborating with a Universal Robots UR3e collaborative robot.[1] In higher levels of task interdependence, participants are expected to have less task load, therefore relying more on the robot. Previous literature has suggested that higher stress is associated with decreased HRV [19], [27], informing our second hypothesis:

- **H.2a** *Participants in teams with higher task interdependence will feel less stressed than those in teams with lower interdependence, as measured by increased HRV.*
- **H.2b** *Participants will feel safer working with the robot in teams with higher task interdependence than in those with lower task interdependence.*

[1]https://www.universal-robots.com/products/ur3-robot/

III. METHOD

A. Participants

A total of 31 participants (25 male, 6 female)—aged 18–21 (M = 20.87 , SD = 2.42)—were recruited from a pool of students from the University of Wisconsin-Madison campus with manufacturing experience or majoring in mechanical or industrial engineering. Among all the participants, 21 were Caucasians, 8 Asians, 1 African American, and 1 Hispanic.

B. Study Design & Procedure

The study followed a between-participant design with three levels of task interdependence (*pooled, sequential, reciprocal*). This study was conducted as session two of a larger protocol. After obtaining informed consent, participants were instructed to wear an ambulatory heart rate monitor, which was fitted to the center of the participant's chest. To collect baseline heart rate data, participants were instructed to sit quietly for five minutes. After completing session one, which was part of a separate study, participants completed a questionnaire to assess their initial perceptions of the robot. After watching an instructional video on how to perform the task, participants completed an assembly task with the UR3e collaborative robot (Fig.3). After the task, participants completed a post-study questionnaire and a semi-structured interview aimed to measure their experience with the robot.

In the assembly task, participants worked with the robot to complete the construction of three toy houses from magnetic blocks. Participants were randomly assigned to one of the three conditions: *pooled*, *sequential*, and *reciprocal*. In *pooled interdependence*, the participant and the robot worked independently, constructing two houses, and the robot was in charge of constructing one. Both the participant and the robot followed the same steps and needed to be familiar with the entire assembly process. In *sequential interdependence*, the participant and the robot took turns to place the blocks that made the toy house, following a pre-programmed order. One error on either worker could result in the failure of the construction. For example, failure to place the supporting block in the middle would cause failure in constructing the entire roof top. The participant still needed to be familiar with the entire assembly process to work with the robot in a particular order. In *reciprocal interdependence*, the participant was in charge of the construction of the roof top of the house, and the robot built the base of the house. At the end of the assembly, the participant also had to combine the two parts as the final step. The participant and the robot each specialized in one part of the process and did not necessarily need to be familiar with the entire process.

C. Measures

1) Physiological Measure: The heart rate data were collected using a Polar H10 Heart Rate sensor[2] in real time. The data was processed using the Elite HRV app[3]. The app generated measurements for mean HRV, mean heart rate, time-domain, and frequency-domain measures. Following recommendations by Shaffer and Ginsberg [27] on short-term heart rate measures, we utilized HRV and frequency-domain measurements including High-Frequency Power and LF/HF ratio to test our hypothesis.

2) Task & Perceptual Measures: Team-level time of completion served as the performance measure. Additionally, participants received two questionnaires. The pre-study questionnaire aimed to get and initial assessment of perceptions of the robot using the Godspeed Questionnaire [5] and the Inclusion of Other in the Self (IOS) Scale, a measure of interpersonal closeness [3]. The post-study questionnaire also included the Godspeed Questionnaire and the IOS Scale, but it also added the Situation Awareness Rating Technique (SART) [29], the NASA Task Load Index (TLX) [11], and perceptions of collaboration [23].

3) The Semi-structured Interview: A semi-structured interview was conducted at the end of the session. In the interview, we asked questions regarding the interaction flow, level of collaboration, robot contribution, and safety concerns during the task. We also asked participants questions regarding their manufacturing experience.

IV. DATA ANALYSIS & RESULTS

A. Analysis

We tested gender, age, ethnicity, height, weight, and time of completion as potential covariates and found none to have a significant effect ($p > .05$). A linear fixed-effects regression model was constructed with task interdependence and perceptions of the robot from the pre-experiment questionnaire as the input variables, controlling for initial impressions of the robot, and heart rate variability, anthropomorphism, animacy, likeability, intelligence, perceived safety, and closeness as response variables. An additional linear fixed effects regression analysis was conducted with task interdependence as the input variable and time of completion as response variable. We conducted *post hoc* contrast analysis to make comparisons indicated by our hypothesis. Situation awareness was not analyzable due to insufficient responses from the participants. All analyses were conducted in R. All statistics are shown in Fig. 5 and Fig. 4

[2]https://www.polar.com/
[3]https://www.elitehrv.com/

Semi-structured interviews were transcribed by four trained experimenters. All analyses were conducted following a Ground Theory Approach [10].

B. Quantitative Results

H.1a predicted that participants in teams with higher task interdependence would outperform participants in teams with lower task interdependence. Our analysis partially supported this hypothesis. As shown in Fig. 4, we found a main effect of task interdependence on the team-level time of completion. Participants in the teams with sequential interdependence completed the task the slowest.

H.1b predicted that participants in teams with higher task interdependence would view the robot more as a team member. Our analysis supported this hypothesis (Fig. 5). We found main effects of task interdependence on perceived anthropomorphism, perceived animacy, and perceived intelligence. Participants in the teams with sequential interdependence gave the lowest ratings on perceived anthropomorphism, and perceived animacy. Additionally, we found no main effect of task interdependence on likeability or interpersonal closeness.

There was no main effect of task interdependence on task load. However, contrast tests revealed that participants in the reciprocal interdependence condition rated their task load to be marginally lower than those in the pooled interdependence condition (Fig. 4).

H.2a predicted that participants would feel less stressed in the higher task interdependence condition, which would manifest itself as increased HRV. We did not find support for the prediction. When controlling for baseline HRV, there was only a marginal effect of task interdependence on HRV. Descriptively, participants in the sequential interdependence condition exhibited highest HRV. Participants in the reciprocal interdependence condition exhibited higher HRV than those in the pooled condition. None of the pairwise comparisons were significant ($p > .05$).

Finally, H.2b predicted that participants would feel safer in teams with higher task interdependence. We did not find

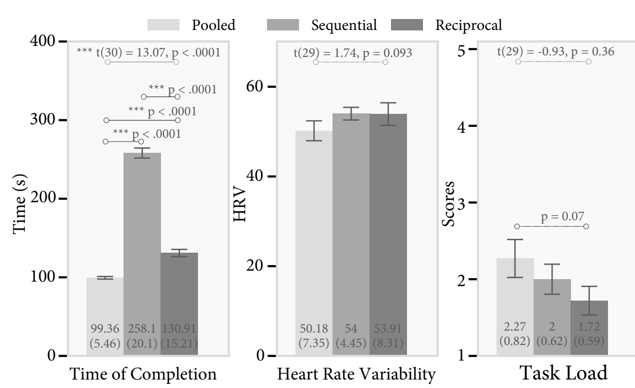


Fig. 4. Time of completion, HRV, and TLX across three levels of task interdependence. Main effects are shown on top of the graph; significant *post hoc* comparisons are shown on top of the bars; and descriptive statistics are shown as Mean(SD) for each bar. Significance levels denote *** $p < .0001$, ** $p < .01$, * $p < .05$.

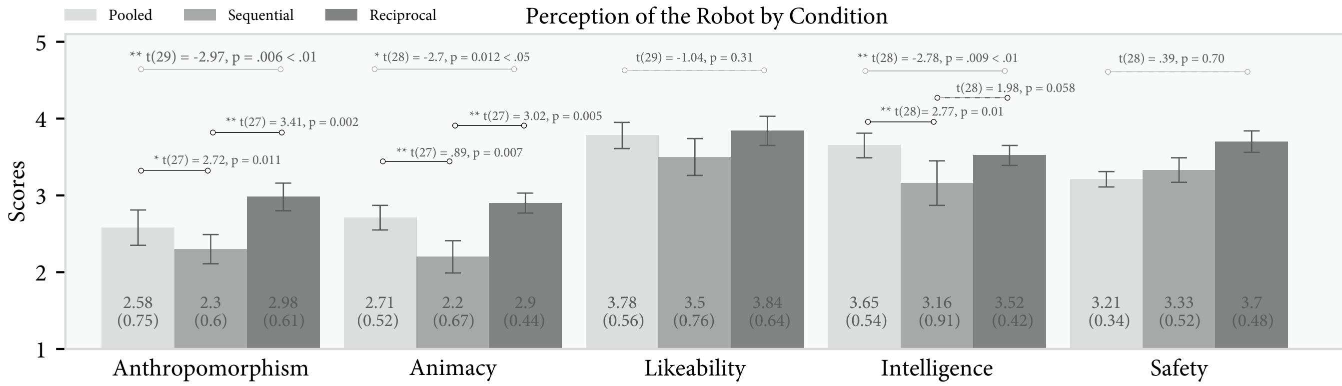


Fig. 5. Perceptions of the robot across the three levels of task interdependence. Main effects are shown on top of the graph; significant *post hoc* comparisons are shown on top of the bars; and descriptive statistics are shown as Mean(SD) for each bar. Significance levels denote *** $p < .0001$, ** $p < .01$, * $p < .05$.

support for the prediction. There was no main effect of task interdependence on perceived safety after the interaction.

C. Qualitative Results

Below, we report results from our analysis of the data from the semi-structured interview, which revealed two themes: *robot motion* and *self-efficacy*.

1) Robot Motion: In general, participants assessed the safety of the robot based on its motions. Specifically, they relied on the speed of the robot and area of movement to judge the safety of their work. In the study, the robot moved with default acceleration (1.4 rad/s^2) and velocity (1.05 rad/s). Across all conditions, participants stated that they felt safe working with the UR3e robot in close proximity for two reasons: (1) the robot moved slowly, and (2) participants had a clear sense of robot's workspace. For example, P09 in the reciprocal interdependence condition suggested, "*[The robot] is not really moving very quickly so that's not something where I am concerned if it messes something up that it would swing and hit me or its going to like widely miss the [block] even if there is a margin of error*." P35 in the sequential interdependence condition said, "*[The robot is] not intrusive in my space ... it has patterns so you knew where it was going to go. So you know what its going to act if its within its operations, its going to be moving in the right way.*" Participants started trusting the robot by learning about its motion. Instead of being concerned about their own safety, they reported being more worried about breaking the robot.

2) Self-efficacy: With different levels of task interdependence, participants viewed contribution and robot role differently. Overall, eight out of 11 participants in the pooled interdependence condition considered the robot as a machine or tool; four out of 10 participants in the sequential interdependence condition considered the robot as a machine or tool; and none of the participants in the reciprocal condition considered the robot as a machine or tool.

In the *pooled interdependence* condition, participants expressed that they lacked feelings of teamwork. Participants described the session as "*working alone, there is no interaction*" [P30] or "*both working on [their] own things*" [P28]. Working with a robot in pooled interdependence added additional responsibilities to their work, instead of easing their workload. Participants rarely paid attention to the robot, stating that they "*didn't even notice the robot moving*" [P13]. Yet, they still felt the need to check on the robot's progress "*separate from [their own] work*" [P21]. Thus, they felt that the allocation of responsibilities were unfair, as their performance counted as a team. Two participants [P28, P26] in the pooled interdependence condition reported that they felt that they were "*competing*" with the robot.

In the *sequential interdependence* condition, participants felt more engaged with the robot although reported spending most of their time waiting and watching the robot to finish its work. They elaborated that their work heavily relied on the robot's outcome, so there was not much freedom. P35 said, "*It's important that the robot is doing its job well, like in this task, the quality of your work is dependent on the quality of the robot's a lot more ... if the robot makes a bunch of mistakes, it is also on me directly, there would be no product.*" Although the robot was there to ease workload, these participants felt that they were given additional responsibilities to check and control the robot. They viewed the robot as "*just programmed to do its task*" [P32] and viewed themselves as a monitor for the robot. Moreover, this mixture of responsibilities led to confusion during the task; participants suggested that they would like an error-detection or feedback system to ease the workload. In addition, P03 said, "*I feel like maybe if [the robot] could build the base and then I'd finish the top, I could start on the base for the next one. So something to just improve the efficiency.*" Participants expressed a need for a more reciprocal *allocation* of task.

In the *reciprocal interdependence* condition, all participants felt that they were working with the robot toward a shared goal. Participants stated, "*The robot was actively contributing to the success of building the house*" [P18] and "*I don't feel any differently than working that close to a human*" [P14]. P05 stated, "*It feels like [the robot] has a task and [the robot] has a motive even though it doesn't.*" These participants perceived the robot as a collaborator or teammate. In this condition, participants had freedom to pace their work as they liked while still felt collaborating with the robot. Participants felt "*connected*" to the robot, and the task allocation was efficient, as they "*[did not] have to wait [for the robot to finish]*" [P04]. In addition to the sense of team contribution, participants reported a mixed preference toward the task allocation. P05 suggested that the human should be in charge of the foundation of the object, so "*it would be less stressful, because there is less dependence on the robot's mistakes ... less snowballing.*" However, others preferred to be in charge of the final steps, e.g., because "*the robot maybe not stable ... so have the last human overlook on it and put the [final] touches on it*" [P09].

V. DISCUSSION

Our analysis showed that teams in sequential interdependence took the longest to complete the task, and those in pooled and reciprocal interdependence spent significantly less. Our findings align with those by Langfred [17] on the interaction between task interdependence and team-level autonomy. Team-level autonomy refers to a team's freedom to decide on how to carry out the task. In teams with high levels of task interdependence, team performance is positively related to team-level autonomy; whereas it is negatively related to team-level autonomy in low task interdependence [17]. Participants in the reciprocal interdependence condition reported having freedom to control the pace of their work, while participants in the sequential interdependence condition did not. Participants in the pooled interdependence condition felt no sense of team and felt that they were working alone, indicating minimal team-level autonomy. Similarly, participants in the sequential interdependence condition followed pre-defined actions with no autonomy.

Our findings can also be interpreted through the lens of human-robot collaborative fluency defined as a "well-synchronized meshing of actions" without necessarily "exchanging much verbal information," as suggested by Hoffman [13]. According to Hoffman [13], the objective fluency measure of human idle time is positively correlated with perception of team fluency by the human and negatively correlated with functional delay, a measure of switching delay experienced by team members [13]. In our study we observed that human idle time and functional delay varied under the three types of task interdependence. In teams with pooled interdependence, as the team members work independently, there was minimal idle time for the human, and idle time only occurs after they complete their individual task goal. Assigning one unit to the robot minimized functional delay. We chose to assign a single unit to the robot, because assignment multiple units to the robot would require the human to remove the assembled object as in the other conditions, which could cause delays. In teams with sequential interdependence, the human worker and the robot worker both followed strict turn-taking, resulting in frequent breaks in action and thus higher human idle time and higher functional delay. In teams with reciprocal interdependence, the motions and idle time were dynamic as the team members have freedom to adjust behaviors. Due to the ability to more flexibly order task actions, functional delay can be mitigated by working ahead on the next component or voluntarily opting to take a break. These findings suggest that reciprocal interdependence offers the ideal level of task interdependence for subjective fluency, although future work is necessary to further substantiate this implication.

The results from questionnaire measures of perceptions of the robot and from the interview demonstrated that participants perceived the robot as a human teammate in the *reciprocal* interdependence condition. These participants rated the robot as being more animated, more anthropomorphic, and more intelligent than those in the sequential condition did. They also recognized the robot's contributions to teamwork, as the allocation of task duties based on skills induced a sense of contribution and teamwork. Participants in the *pooled* interdependence condition also rated the robot to be higher in anthropomorphism, animacy, and intelligence than those in the sequential condition did. These participants believed that they were working alone in their own zone. Instead of working as teammates, some participants even developed a sense of competition with the robot. However, the lack of team perception did not necessarily prevent the participants from viewing the robot to be a smart and animate assistant, as the robot was capable of completing the task alone.

Participants' perceptions of the robot's safety did not change after the work session or across conditions. This finding implies that task interdependence may not affect perceived safety in human-robot collaboration. However, as previous literature and our interview data suggest, robot speed and range of movements played a large role in their feelings of safety. In our study, the robot moved at its default speed. One participant expressed that they might have felt anxious or rushed if the robot moved faster. Additionally, participants expressed that they would like the robot to adapt to the pace of their work in real time to make the human-robot teaming more dynamic and fluid. Future work should further explore the effect of robot motion in human-robot teaming and the possibilities surrounding adaptive collaborative robot systems.

In this study, we explored the use of HRV as a measure of real-time stress and anxiety. Although participants in the pooled interdependence condition showed slightly lower HRV and higher task load than those in the other two task interdependence conditions, we did not find conclusive evidence of the effects of task interdependence on stress from the HRV data, likely due to the short and easy task. Data from our interviews reveal that participants felt additional responsibility in the pooled condition. Due to the lack of teamwork, they might have been concerned or simply curious about the robot's progress, which might have added to their cognitive load, resulting in increased anxiety and stress. HRV has also been found to be highly correlated with long-term mental well-being and mortality [27]. Future research should also investigate manufacturing workers' long-term well-being in more complex human-robot teaming scenarios.

A. Limitations

We identified two main limitations to this study. First, because the data was collected as study session two in a larger protocol on human-robot collaboration, it is possible that participants had been habituated to the human-robot environment. Habituation refers to decreased responses due to repetitive exposure to stimuli. Previous literature has suggested that people quickly adjust their physiological and emotional responses after repetitive exposure [6], [28]. Given that the previous session was 45-minute long, experience with the robot in the previous session could have diminished the effects, particularly for HRV and perceived safety. However, habituation and acclamation could also result in a more realistic experimental setting to study human-robot collaboration. Thus, it is also possible that human workers experience less stress and less concern for safety over long-term collaborations with robot partners.

Second, a key goal of this study was to investigate the effects of task structure on worker experience in manufacturing settings. It is possible that the study task did not represent real-life manufacturing settings. Additionally, although we recruited participants who had some manufacturing background or relevant training, our study sample may not be representative of the population of workers in the manufacturing industry. Future research should examine the effects of task interdependence in more realistic manufacturing settings.

VI. CONCLUSION

In this study, we explored the effects of three forms of task interdependence on the outcomes of human-robot teaming, including team performance, perceptions of the robot, and worker experience. We found that in teams with sequential interdependence, participants showed lowest task performance and lower ratings on perceptions of the robot; while in teams with reciprocal interdependence, participants perceived the robot more as a teammate and completed the task more efficiently. Our findings highlight the importance of considering how tasks are structured for human-robot teams and offer practical and research implications for task allocation in manufacturing.

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