How Task Interdependence and Homogeneity Affect Human-Robot Teaming

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ABSTRACT

The goal of this study is to understand how task and worker characteristics affect psychological outcomes of human-robot teaming for human workers. Collaborative robots are increasingly teamed up with humans to improve productivity and task ergonomics. To ensure that humans have a positive experience collaborating with robots, we need an understanding of how different task allocations affect their experience. In a laboratory study using a simulated manufacturing workcell, we manipulated the task characteristics of a manufacturing task, particularly task interdependence and homogeneity, creating four task-allocation strategies. Thirty-two participants collaborated with a robot arm to complete a manufacturing task following one of these strategies, and their perceptions of the robot and of the collaboration were measured through questionnaires. Our results showed that when human and robot workers performed the task interdependently, participants had a more positive attitude toward the robot and their collaboration. Working on tasks homogeneously with the robot reduced positive attitudes toward the robot and the collaboration. Task characteristics had differential effects on how men and women perceived the robot and the collaboration. Our findings highlight the need to consider task characteristics when allocating tasks to human-robot teams in close-proximity manufacturing environments and inform designers of collaborative robots and engineers engaged in task planning for human-robot teams.

KEYWORDS

Human-robot collaboration; human-robot teaming; task characteristics; task homogeneity; task interdependence; task allocation

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1 INTRODUCTION

Advanced robotic technology has opened up the possibility of integrating highly autonomous robots into shared workspaces with human teams. These *collaborative* robots are envisioned to increase productivity of human labor, allow greater flexibility in production, and improve ergonomics of manual tasks [29, 34]. However, this

Figure 1: In this paper, we investigate how task and worker characteristics affect participants' perceptions of a robotic collaborator and their work, using a simulated manufacturing workcell in which the human-robot team work together under different task allocations.

capability raises the question of how to best allocate work to maximize team efficiency and the experience of human team members working with robotic teammates.

While prior work on task allocation for teams of humans and robots, i.e., *human-robot teaming*, has explored methods for allocating work for minimizing makespan, or task completion time, and ergonomic impact [5, 31, 35], other factors exist that can affect worker experience with collaborating with robots, overall job satisfaction, and eventually the widespread adoption of collaborative robots. One such factor is *task homogeneity*—whether we assign tasks such that a robot and its human collaborator work on different, specialized set of tasks (i.e., non-homogeneous) or such that they work on the same set of non-specialized tasks (i.e., homogeneous). When task homogeneity is high, human and robot workers share workspace, tools, and supplies, which may increase the need for coordination. Another factor that may affect worker experience in task allocation is *task interdependence* [17]—whether tasks are allocated such that human and robot workers depend on each other for completing the task or work in parallel without any dependency. Higher task interdependence requires increased coordination between human and robot teammates.

While prior work on human-only teams has explored how job specialization and interdependence can affect workers' self-efficacy, job satisfaction, and team outcomes [11, 18, 21], how these factors translate to human-robot teams remains unknown. Furthermore, worker characteristics may add to this complexity. For example, human-robot interaction literature highlight stark differences in how men and women interact with robots [30], suggesting that

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worker sex may be one of the factors that shape worker experience with collaborative robots.

In this paper, we study how task interdependence, homogeneity, and worker characteristics, particularly sex, affect psychological outcomes of human-robot teaming for human workers, such as perceptions of robotic teammates, perceptions of collaboration, and perceptions of work using a simulated manufacturing workcell created in our laboratory (Figure 1). The results of this study can guide us in more effective task allocation for human-robot teams.

2 RELATED WORK

As collaborative-robot technology becomes more prevalent, work that was previously done by a *human-human* team is being reformulated for *human-robot* teams. Therefore, we draw on a strong body of literature that has studied human-human teams in various settings as well as more recent research on human-robot teaming. In particular, below we review literature on how structural properties of tasks can affect team outcomes, how humans perceive their collaborators in a team, and how individual differences can affect attitudes toward working with a collaborative robot.

2.1 Task Characteristics & Collaboration

Structural properties of tasks assigned to a person can affect the perceptions of that person of the task and or his collaboration with his/her team. Hackman and Oldham [6] developed a *Job Characteristics Model* consisting of five properties—task identity, task significance, skill variety, job feedback, and autonomy—and suggested that these properties can affect the workers in how much they learn, how responsible they feel for the outcomes of the work, and how much they care about the work outcome.

Task interdependence is one such key property of teamwork. Kiggundu [17] suggests that employees respond positively to task interdependence when the setup of the task involves providing resources to others that are necessary for others' success. This work found task interdependence to improve a sense of responsibility and personal work outcomes [36]. The *level* of task interdependence in a team has also been found to affect team outcomes [16, 19, 20]. As the level of interdependence changes, different methods of communication and coordination between members are needed for optimal team performance [2, 3].

Job specialization is another property that affects individual and consequently team performance. Traditionally, manufacturing facilities have employed *job rotation* as a means to mitigate feelings of monotony, boredom, and mental fatigue in workers [18, 21]. However, the emergence of advanced technology, including manufacturing robotics, has changed the relationship between job rotation and job burnout. Recent studies in the automotive industry suggest that workers no longer prefer job rotation, but they instead prefer to work on their own specialized tasks to increase their level of professional efficacy and lower feelings of replaceability [11].

The type and structure of the task, such as whether or not the task involves manual work and the roles that individual workers play, can also affect job outcomes. Stewart and Barrick [32] found that task interdependence can have a differential effect on team outcome when working on conceptual versus behavioral tasks. These factors also appear to affect human-robot teams. For example, when teaming with a subordinate robot, human collaborators feel more responsibility toward the outcome [9]. Furthermore, people prefer robots whose appearance matches the type of the task assigned to the robot [4].

The effects of task characteristics such as interdependence also determine the success of human-robot teams. Johnson et al. [15] argued that robots must be designed such that they can work interdependently with humans and that, otherwise, team performance would suffer under complex situations where dependencies exist. Hinds et al. [9] provide evidence that task interdependence affects the sense of responsibility that human workers feel toward collaborative work. Nikolaidis et al. [26, 27] have explored how interdependent work can be facilitated by enabling the development of shared mental models through human-robot cross-training.

2.2 Collaborator Perceptions

When people work in teams, they develop perceptions of the work and traits of their collaborators, such as their ability and integrity, and these perceptions can change over the course of their collaboration [14]. These perceptions extend to human-computer and human-robot teams. For example, when computers interdependently work on a task with humans, people view them as being more similar to themselves, more friendly, and more cooperative [25]. When collaborating with robots, the behavior of the robot, such as whether the robot makes anticipatory decisions, can affect perceived contribution of the robot to the team's success [10] and its awareness of its human counterpart [12, 13].

2.3 Individual Differences

Research in human-robot interaction and teaming has also shown that individual differences can affect people's attitudes towards robots. For example, people with backgrounds in science and technology were found to show a more positive attitude toward the robot compared to those with backgrounds in the social sciences [28]. Several other studies found differences in how men and women perceive robotic assistants, partners, and collaborators [22, 30, 33]. Among these studies, Mutlu et al. [23] investigated how men and women perceived a robotic partner under different task structures, comparing cooperative and competitive structures. They found significant differences in how socially desirable men found their robotic partner to be and their overall positive affect across different task structures. They found no effects of task structure on women's experiences and perceptions of the robot. These studies suggest fundamental differences in how men and women perceive teammates when task characteristics change and motivate further investigation in the context of task-based human interaction with collaborative robots.

3 HYPOTHESES

Based on previous research on the effects of task characteristics on collaboration, we formulated the following set of hypotheses on how task interdependence and homogeneity may affect worker attitudes toward robotic teammates and their work.

Hypothesis 1. When humans and robots work *inter*dependently, human workers' attitudes toward their robotic teammates and the resulting collaboration will be more positive than when their work is independent.

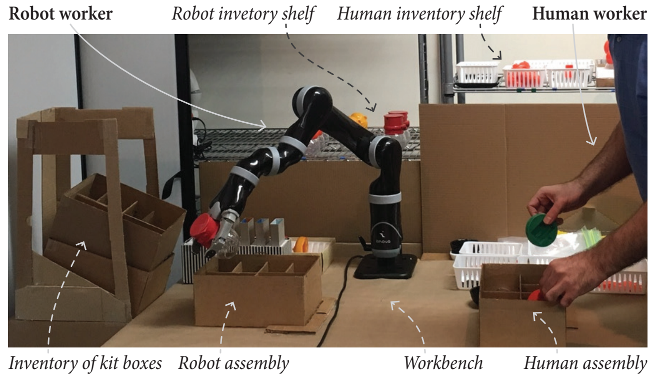
The basis of this hypothesis is findings from research on task interdependence that suggests that interdependent tasks may improve job outcomes and increase sense of responsibility for other's work [15, 36].

Hypothesis 2. Worker attitudes towards robotic teammates and the resulting collaboration will be more positive when collaboration involves specialized, non-homogeneous tasks compared to collaborating on non-specialized, homogeneous tasks.

While task homogeneity has not been extensively explored, prior research suggests that *task specialization* improves professional efficacy and thus promotes worker confidence [11], providing the basis for this hypothesis.

Additionally, while we did not posit specific hypotheses due to lack of prior evidence in the context of teaming in manufacturing settings, we expected individual differences, specifically worker sex, to affect attitudes toward robotic teammates and perceptions of collaborative work.

Figure 2: The physical layout of the simulated workcell. The human and robot workers had their own inventory shelves and shared the workbench to perform their respective tasks in configurations that depended on the study condition.



4 METHOD

To assess how task characteristics affect human experience with collaborating with a robot, we simulated a manufacturing workcell using a robotic arm and an experiment task inspired by real-world manufacturing operations. We asked participants to perform multiple rounds of the manufacturing task and measured their perceptions of the robot as well as the resulting collaboration.

4.1 Study Design

The study followed a 2×2 between-participants design involving two factors: *task homogeneity* and *task interdependence*. This manipulation resulted in four experimental conditions: (1) non-homogeneous, non-interdependent; (2) non-homogeneous, interdependent; (3) homogeneous, non-interdependent and (4) homogeneous, interdependent. These conditions are described in greater detail in the following paragraphs.

4.2 Experiment Setup, Materials, & Tasks

The paragraphs below describe the collaborative-robot platform used in the study, the setup of the workspace created for collaboration, and the manufacturing task performed by the participants in collaboration with the robot.

Collaborative-Robot Platform. To create a simulated hybrid, human-robot workcell, we utilized a Kinova Mico robotic arm[1], a lightweight under-actuated multipurpose robotic arm. The arm has six degrees of freedom with unlimited rotation on each axis and a gripper with two fingers that can be used to grasp, manipulate, transport, and release objects. We programmed the robot to perform a manufacturing task using the Robot Operating System (ROS) application programming interface (API). The robot's actions and behaviors in each experimental condition were pre-programmed, and the robot followed a specific schedule for that condition.

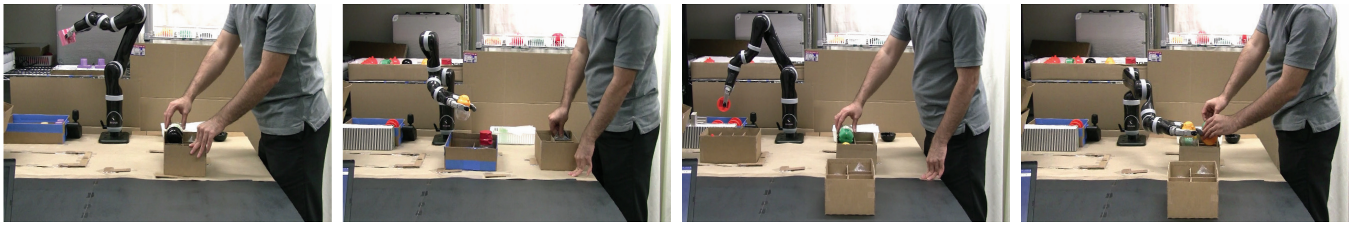
Workspace Setup. We simulated a single-station, hybrid manufacturing workcell in our laboratory. The robotic arm was installed on the workbench at a distance that allowed it to share a task with its human collaborator while minimizing any potential safety risks to the participant. The robot and human workers were each given an inventory shelf that contained parts that were required for the manufacturing tasks described below. The robotic arm could re-stock its shelf or take parts from it. The human worker could take parts from his/her shelf. The conveyor belt where the workers would place assembled materials to be delivered to the next hypothetical station was simulated using tapes placed on the workbench. Empty boxes required for the task were stacked on a pallet next to the workbench. The setup of the workcell and the collaborative robot are shown in Figure 2.

Task. To achieve a realistic simulation of a manufacturing workcell in our laboratory, we developed a manufacturing task that subsequently integrated two real-world manual manufacturing operations: *kitting* and *stocking*. Kitting is a process in which several loose parts are placed in a box or container. In a complex workcell, the kit may be used to assemble parts in the next station or workcell or may be assembled into a final product that will be shipped to the customer. Stocking is a process by which parts or completed products are stocked, piled up, or put on a shelf for future use. For example, parts may be stocked on a shelf, and a different worker may pick them up to assemble a product or to produce a kit. Final products may also be stocked prior to the shipment to customers. Both operations were selected and integrated into a task that could be performed individually by a human or a robot worker or collaboratively by a human-robot team.

In the task, the robotic arm and/or the human worker assembled small toy lanterns shown in Figure 1. Each lantern was composed of a body, base, battery cap, light cover, and one screw. This product offered an appropriate level of complexity for individual and collaborative assembly and involved parts that can be manipulated by both human and robot workers given the state-of-the-art technology. The "kit" created in the kitting task included four lanterns placed in a cardboard box and securely fitted into an insert.

[1]Kinova Robotics: http://www.kinovarobotics.com/

Figure 3: The four versions of the assembly task created by manipulating task interdependence and homogeneity.



Non-homogeneous, non-interdependent task | *Non-homogeneous, interdependent* task | *Homogeneous, non-interdependent* task | *Homogeneous, interdependent* task

4.3 Experimental Conditions

We manipulated the manufacturing task described above to create the following four conditions that involved different levels of task interdependence and homogeneity for a human-robot team that involved a single human and a single robot worker. Snapshots of the four conditions are shown in Figure 3, and a sample portion of the task plans for condition 3 is provided in Figure 4.

1. Non-homogeneous, independent. In this condition, the robot and the participant worked on different tasks that did not depend on each other. Specifically, the robot performed stocking while the participant performed kitting, resulting in non-homogeneous tasks, and the robot stocked parts on the shelf that were not relevant to the kit that the participant was producing, resulting in non-interdependent tasks. In the task, the participant picked up a box, then picked up a lantern body, base, and battery cap from the shelf, and put these parts in the box. The task required the participant to place a screw and light bulb cover in a small plastic bag and to put the bag in the box. The box was then placed on the conveyor belt.

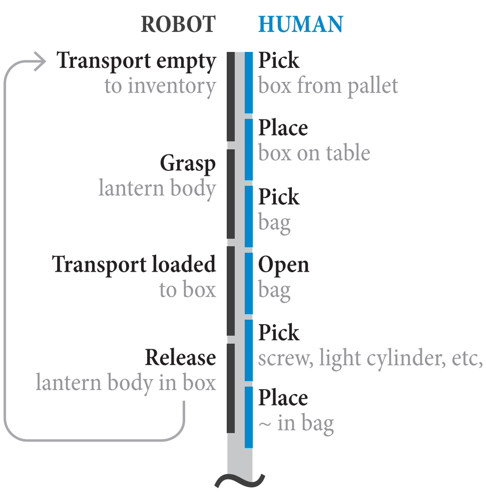
2. Non-homogeneous, interdependent. In this condition, the robot and the participant similarly worked on different tasks, stocking vs. kitting, resulting in a non-homogeneous task allocation. However, their tasks were dependent on each other such that the parts that the robot stocked would be used by the participant for producing the kit. Specifically, the robot took the lantern body from its own shelf and stocked it on the desk for the participant to retrieve. This process is similar to Condition 1 except that the participant manipulated the body from the pile that robot had stocked.

3. Homogeneous, independent. In this condition, both the robot and the participant performed kitting, resulting in homogeneous tasks for the two workers, in a non-interdependent fashion. Specifically, the robot produced a complete kit by itself, and the participant produced a complete kit by himself or herself. They both placed the boxes on the conveyor belt once kitting was complete.

4. Homogeneous, interdependent. In this condition, both the participant and the robot performed kitting in a homogeneous task setup. Their work depended on each other. In particular, the robot picked a body from its shelf and placed it inside the box that the participant was also filling with parts. Similar to the previous conditions, the participant picked up the remaining parts from the shelf and placed them in the box. The participant then placed the box on the conveyor belt.

We note that manipulating task characteristics necessarily results in tasks with significantly different allocations and outcomes while achieving the same production output, and thus no comparisons in task outcomes are made across these conditions.

Figure 4: A portion of the task plan for the *homogeneous, interdependent* task as allocated to human and robot workers.



4.4 Procedure

Following informed consent, a male experimenter led the participant to the simulated manufacturing workcell. The experimenter then showed the participant an instructional video that demonstrated a human and the robot collaboratively working according to the particular condition to which the participant was assigned in order to establish familiarity with the task. The experimenter then showed to the participant the different elements of the workcell, such as the robot, the shelves, the empty boxes, and the conveyor belt. The participant was then asked to assemble a single kit as a trial run. The experimenter then started the experiment and left the workcell. After assembling five kits, the participant was directed to a computer to complete the first questionnaire designed to measure participant demographics. After the first questionnaire, the participant was directed back to the workcell and asked to assemble five more kits, followed by a second questionnaire that measured subjective aspects of the participant's experience with the robot and the task. After the questionnaire, the experimenter administered a brief semi-structured interview, debriefed the participant, and provided compensation. The experiment was videotaped for future analysis. Each trial took approximately 30 minutes.

4.5 Participants

The study included 32 participants (16 males, 16 females) recruited from a university campus. Participant ages ranged from 18 to 35 ($M = 22.65$, $SD = 4.15$). All participants were native English speakers. Participants were from a variety of backgrounds, including geography, computer science, mathematics, and microbiology. They reported low familiarity with robots and manufacturing ($M = 3.06$, $SD = 1.66$; $M = 3.37$, $SD = 1.63$, respectively, on a seven-point rating scale). Participants also reported the frequency at which they play video games to be moderate ($M = 3.41$; $SD = 2.11$, on a seven-point scale, where 1 = "Never," and 7 = "Frequently, e.g., daily") and their level of comfort with assembly tasks (assembling, e.g., furniture, toys, models) to be high ($M = 5.03$, $SD = 1.66$, on a seven-point scale).

4.6 Measures & Analyses

In order to measure participant experience with human-robot collaboration under the four conditions described above, we used a self-report questionnaire and a semi-structured interview administered after the experiment.

Table 1: User-experience questionnaire consisting of five scales to measure participant experience: competence, task load, contribution, enjoyment, & willingness to collaborate.

Competence $\alpha = 0.76$	I trusted that the robot would perform its task correctly.
	I was confident about the robot's work.
	I thought that the robot was reliable.
	The robot knows what it is doing.
	The robot is smart.
	The robot was competent in performing the task it was assigned.
	The robot has a sophisticated program controlling its actions.
Task Load Index $\alpha = 0.85$	How mentally demanding was the task?
	How physically demanding was the task?
	How hurried or rushed was the pace of the task?
	How successful were you in accomplishing what you were asked to do?
	How hard did you have to work to accomplish your level of performance?
	How insecure, discouraged, irritated, stressed, and annoyed were you?
Contribution $\alpha = 0.90$	I found the robot to really contribute to the task.
	It would have been harder to do the task without the robot.
	Having the robot's contribution made the task easier.
	Working with the robot made my work easier.
Enjoyment $\alpha = 0.75$	I enjoyed working with the robot.
	Working with the robot made the task enjoyable.
Willingness to Collaborate $\alpha = 0.72$	I would prefer to perform this task without the robot.
	I prefer working with a human in this task instead of the robot.
	I enjoyed collaborating with the robot in this task.
	The robot and I make a good team.

User-Experience Questionnaire. We constructed rating scales to measure participant experience with the robot, including perceived competence of the robot, perceived contribution of the robot to teamwork, how the robot's presence affected participant work, perceived enjoyment of working with the robot, and willingness to collaborate with the robot. We refer to these scales as measures of *competence*, *contribution*, *presence*, *enjoyment*, and *willingness to collaborate*, respectively, hereafter. We also measured participants' physical and cognitive workload using the NASA Task Load Index (TLX) [8], which has been validated to provide consistent and reliable measurement of task load across various tasks [7]. Participant responses were measured using a seven-point rating scale for all scale items. Table 1 shows items included in all reliable scales.

Analyses. To ensure the reliability of the user-experience questionnaire, we conducted a confirmatory factor analysis and eliminated items that showed poor consistency with the other items in each scale. This analysis resulted in a four-item scale of *competence* (Cronbach's $\alpha = 0.76$), a two-item scale of *contribution* (Cronbach's $\alpha = 0.9$), a two-item scale of *enjoyment* (Cronbach's $\alpha = 0.75$), a two-item scale of *willingness to collaborate* (Cronbach's $\alpha = 0.72$), and a five-item scale of *task load* (Cronbach's $\alpha = 0.85$). The analysis showed that the items of the *presence* scale did not form a reliable scale, and thus this scale was eliminated from analysis.

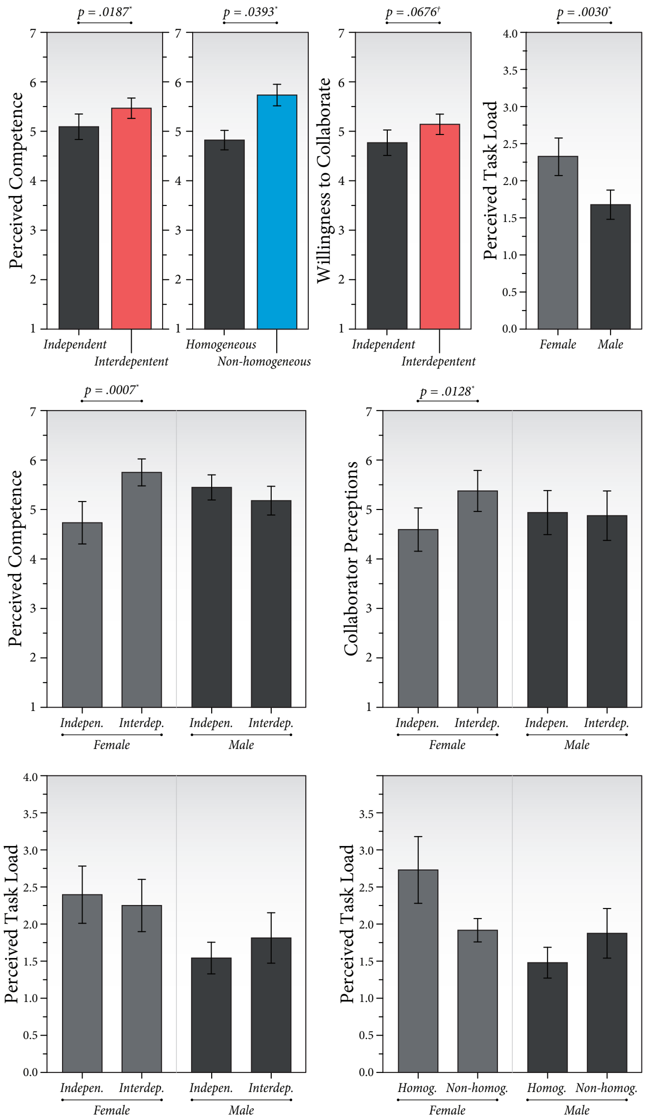
Data from each measure was analyzed using an analysis of covariance (ANCOVA), including task homogeneity, task interdependence, and their interaction as fixed effects and participant sex and other demographic factors we measured, including familiarity with robots, familiarity with manufacturing, video-gaming experience, and comfort with the assembly task, as covariates. To control for Type I errors in multiple comparisons involved in exploratory analyses, specifically comparisons for each gender, we applied a Bonferroni correction by adjusting the α-level for significance to the number of comparisons (e.g., $\alpha_{adj} = \alpha/2 = 0.05/2 = 0.025$ for two comparisons and an initial α-level of 0.05). Data on the main findings of our analysis are provided in Figure 5.

5 RESULTS

Our first hypothesis predicted that when human and robot work were interdependent, human workers would have a more positive attitude toward robots and the resulting collaboration than when their work were independent. Our analyses provided support for this hypothesis; we found that when human and robot work depended on each other, participants rated the robot as being significantly more competent, $F(1, 20) = 6.54$, $p = .0187$, and expressed marginally more willingness to collaborate with the robot, $F(1, 20) = 3.74$, $p = .0676$, compared to when there was no interdependency. We found no differences across different levels of task interdependence in other measures.

Our second hypothesis was that participant attitudes toward robotic teammates and the resulting collaboration would be more positive when collaborating on specialized, non-homogeneous tasks than in collaborations on non-specialized, homogeneous tasks. Consistent with our hypothesis, we found that when participants and the robot worked on non-homogeneous tasks, they rated the robot to be significantly more competent compared to when they worked on homogeneous tasks, $F(1, 20) = 4.86$, $p = .0393$. Data

Figure 5: Data from measures of perceived competence, willingness to collaborate, and perceived task load that highlight the main findings of our analyses. † and * denote significant and marginal differences, respectively.



from other measures provided did not vary across different levels of task homogeneity.

As noted in the Hypothesis Section, we also conducted an exploratory analysis of the effects of worker sex on worker experience, as prior work in human-robot collaboration point toward significant differences in the attitudes of men and women toward robots [22, 23, 30, 33], which we expected to observe in the manufacturing setting. This exploratory analysis revealed that task characteristics had a differential effect on how men and women perceived of the robot and the task. Specifically, we found an interaction effect between participant sex and task dependency over perceptions of the robot's competence, $F(1, 20) = 10.50$, $p = .0041$, and a marginal interaction between over participants' willingness to collaborate with the robot, $F(1, 20) = 4.18$, $p = .0543$. Comparisons across levels of task interdependence for each gender showed that female participants were significantly more willing to collaborate with the robot when their work depended on the robot's work than when it did not, $F(1, 20) = 7.4694$, $p = .0128$, $\alpha_{ajd} = 0.025$. They also found the robot to be significantly more competent when their work depended on that of the robot, $F(1, 20) = 15.91$, $p = .0007$, $\alpha_{ajd} = 0.025$. Data from male participants did not differ across different levels of task dependency. Our exploratory analysis also found a main effect of sex on perceived task load, women reporting their task load to be significantly higher than men, $F(1, 20) = 11.41$, $p = 0.0030$. We also found an interaction effect between participant sex and task homogeneity over perceptions of the task load, $F(1, 20) = 6.98$, $p = 0.0156$, although comparisons for each gender did not find significant differences in perceived task load across different levels of task homogeneity.

Finally, we also report on the effects of demographic factors on measured psychological outcomes of human-robot teaming in order to identify other individual differences future research might investigate. Our analyses showed that the frequency with which participants played computer games significantly predicted perceived competence of robot, $F(1, 20) = 7.83$, $p = 0.011$, willingness to collaborate with the robot, $F(1, 20) = 10.39$, $p = 0.004$, and perceived contribution of the robot, $F(1, 20) = 7.25$, $p = 0.014$, while negatively significantly predicting task load, $F(1, 20) = 7.69$, $p = 0.0117$. Participant comfort with assembly tasks significantly predicted perceived competence of the robot, $F(1, 20) = 7.54$, $p = 0.0124$, and familiarity with robots significantly predicted willingness to collaborate with the robot, $F(1, 20) = 5.27$, $p = 0.033$.

6 DISCUSSION

We hypothesized that when human and robot work were interdependent, human workers would show a more positive attitude toward robot and the resulting collaboration than when their work were independent. Consistent with our prediction and insights offered by recent literature (e.g., [15]), our results showed that task interdependence improved participant experience with the robot, particularly their perceptions of the robot's competence and the robot as a collaborator. When participant work depended on the robot's work, participants perceived the robot to be more competent and to be a more effective collaborator. We speculate that this effect is partly due to the interdependent task requiring participants to closely observe and analyze the robot's work and gain insight into the robot's operation. Furthermore, task interdependency might have resulted in a stronger affiliation between the participant and the robot, resulting in perceptions of the robot to be on a more equal footing and thus more positive. This explanation is also supported by prior work in human-computer and human-robot interaction that has suggested people perceive computers and robots that are similar to themselves more positively than those that are different from themselves [1, 24].

We also hypothesized that collaborating on specialized, non-homogeneous tasks with robots would improve attitudes toward robotic teammates and the resulting collaboration compared to collaborating on non-specialized, homogeneous tasks. Our results indicated that task homogeneity affects participants' perceptions of the robot. Specifically, when participants worked on different tasks than those of the robot, they perceived the robot as being more competent. This finding is consistent with results reported by research on job design on the effects of task specialization on worker satisfaction [11], suggesting that human workers may perceive robotic collaborators to be more competent when task allocation requires each worker to specialize and offer unique contributions aligned with their specialization.

Our exploratory analysis highlighted effects of worker sex on worker perceptions of the task and complex ways in which worker sex interacted with task characteristics. In particular, task homogeneity decreased perceived task load among women but increased it among men. One potential explanation of this interaction is that task homogeneity was perceived to create competition between the participant and the robot. As discussed in the Background Section, prior work in human-robot interaction suggest differential perceptions of robotic partners among men and women under competitive and cooperative task structures, such that women report a more positive experience when they cooperate with a robot while men report a more positive experience when they compete with the robot [23]. In the current study, men might have perceived homogeneous tasks to be more competitive and thus to involve higher task load, and task homogeneity might have promoted a more collaborative environment and thus reduced task load for women.

We also found that previous familiarity with gaming, robots, and manufacturing positively predicted participant experience and negatively predicted task load. This finding suggests that individuals with greater experience with interacting with advanced technology and with manufacturing might be more open and adept to collaborating with robots.

6.1 Limitations

In this paper, we investigated the effects of task homogeneity and interdependence on human perceptions of a robotic collaborator in a manufacturing task. Other task characteristics, such as the relative social statuses of the human and robot workers or inherent differences in performance or competence between the human and robot workers, might shape worker experience and can be studied in future research. In our experiments, participants collaborated with a robot in a relatively simple manufacturing task that did not involve complex dependencies in tool or workspace use between the workers. Understanding how the studied task characteristics affect human-robot collaboration under different levels of task complexity requires further investigation. Additionally, participants in our study were engaged in a brief manufacturing task that was simulated in a laboratory environment, and establishing the generalizability of our findings to real-world manufacturing settings and long-term human-robot collaborations requires further research. Furthermore, the manipulations in task characteristics resulted in different task allocations for the human and the robot worker, which prevented us from making meaningful comparisons of task performance and behavior across conditions. Finally, we expect the design of the specific robot platform used to have an effect on worker perceptions. The Kinova Mico arm was designed as a lightweight multipurpose arm to be integrated into day-to-day human environments, and thus collaborative robots designed for industrial environments might elicit different perceptions.

7 CONCLUSION

Collaborative robots are increasingly teamed up with humans in a wide-range of settings including shop floors and small-batch-manufacturing facilities. To ensure their successful integration into these environments and their acceptance by human workers, we must develop a better understanding of how to best allocate tasks between human and robot co-workers and how the characteristics of resulting tasks affect worker experience, satisfaction, and perceptions of robotic collaborators. In this paper, we studied two variables for task allocation, *task interdependence* and *task homogeneity*, and investigate how these two characteristics affect human experience with robots and with collaborating with robotic workers. We also analyzed how worker sex interacted with these characteristics. We conducted a 2×2 between-participants study that manipulated task interdependence and task homogeneity, which resulted in four unique experimental conditions. Based on previous work that studied task interdependence and job specialization in human-human teams as well as human-robot teams, we predicted human workers to have a more positive attitude toward their robotic collaborators and toward their work (1) when human and robot work were interdependent than when their work were independent and (2) when they worked in specialized, non-homogeneous tasks than when they collaborated over non-specialized, homogeneous tasks. Consistent with these hypothesis, we found that participants perceived the robot to be more competent and were more willing to collaborate with the robot when their tasks were interdependent. We also found that they rated the robot to be more competent when working on a specialized, non-homogeneous task with the robot. Furthermore, worker sex interacted with task homogeneity and interdependence in complex ways. The findings of this study illustrate the significance of considering task and worker characteristics for task allocation in human-robot teams.

8 ACKNOWLEDGEMENTS

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