How Task Interdependece And Homogenity Affect Human-Robot Collaboration

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ABSTRACT

Objective: The goal of this study is to understand how task interdependence, homogeneity, and worker characteristics, particularly sex, affect psychological outcomes of human-robot teaming for human workers. Background: 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 to develop an understanding of how different task allocations based on task interdependence and homogeneity affect their experience.
Method: Thirty-two participants collaborated with a robotic arm on completing a manufacturing task. In a between-participants design, each participant was assigned to a task allocation strategy corresponding to one of four experimental conditions: (1) non-homogeneous, non-interdependent; (2) non-homogeneous, interdependent; (3) homogeneous, non-interdependent and (4) homogeneous, interdependent. Participants´ perception of the robot and the collaboration was measured through subjective questionnaires as well as an semi-structured interview conducted after each experiment.
Results: When human and robot worked interdependently towards completing a task, human had a more positive attitude towards the robot and their collaboration. Working on non-specialized, homogeneous tasks with the robot reduced humanś attitude towards the robot and the collaboration. Task characteristics had differential effects on how men and women perceived the robot and the collaboration. Conclusion: Task interdependence and homogeneity as well as human sex can play a major role in a human workerś experience collaborating with a robot on a manufacturing task.
Application: Our conclusion supports integrating task interdependence and homogeneity as variables when allocating tasks to human-robot teams in close-proximity manufacturing environments. These results could be used by designers of collaborative robots and engineers and/or software that plan and allocate tasks to human and robot.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability;

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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 [24, 28]. However, this capability raises the question of how to best allocate work to maximize team efficiency and the experience of human team members working with their robotic teammates.
While prior work on "task allocation" in human-robot teams, or "human-robot teaming", has explored methods for allocating work for minimizing task completion time (makespan) and ergonomic impact [4, 26, 29], other factors exist that can affect worker experience with collaborating with robots. Positive worker experience can in turn improve worker job satisfaction and lead to successful adoption of new technology. 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-homogenous) 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 [15] - whether we allocate tasks such that human and robot workers depend on each other for completing a task or work in parallel without any dependency. Higher task interdependence requires increased coordination between human-robot teammates. In this study, we test the main effects and the interaction effects of task homogeneity and interdependence on the human workersṕerception of the robot as well as the effectiveness of the team collaboration. While prior work on human-only teams has explored how job specialization and interdependence can affect workerś self-efficacy, job satisfaction, and team outcomes [10, 16, 19], it remains unclear how these factors translate when collaborating with a robot. 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 [25], suggesting that 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. The results of this study can guide us in more effective task allocation for human-robot teams.

2 RELATED WORK

As human-robot teams are becoming more prevalent, in some cases work that was previously done by a human-human team is assigned to these new 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 works that study human-robot teams. In particular, below we review literature on how structural properties of tasks can affect team outcome, how humans perceive their collaborators in a team, and how individual human differences can affect attitudes towards a collaborative robot.

2.1 Task Characteristics and Collaboration

Structural properties of tasks assigned to a person can affect perception of that person of the task and or his collaboration with the team. Hackman and Oldham [5] developed a Job Characteristics Model consisting of five principles: task identity, task significance, skill variety, job feedback, and autonomy. These principles can affect the psychological state of the workers in how much they learn, how much they feel responsible for the outcomes of the works, and how much they care about the work outcome.

Task interdependence is one such key property of teamwork. Kiggundu [15] found that employees respond positively to task interdependence when the setup of the task involve providing resources to others or necessary for othersśuccess. This work found no negative relationship between interdependence and job outcomes. In fact, interdependence appears to improve a sense of responsibility and personal work outcomes [30]. Furthermore, the level of task interdependence in a team can affect team outcomes [14, 17, 18]. As the level of interdependence changes, different methods of communication and coordination between members are needed for optimal team performance [1, 2].

Job specialization is another property that affects individual and consequently team performance. Traditionally, manufacturing industries have employed job rotation as a means to mitigate feelings of monotony, boredom, and mental fatigue in workers [16, 19]. However, the emergence of advanced technology and 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 [10].

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 et al. [27] find that task interdependence can have a very different 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 [8]. Furthermore, people prefer robots whose appearance matches the type of the task assigned to the robot [3].

The effects of task characteristics such as interdependence also determine the success of human-robot teams. Johnson et al. [13] argued that robots must be designed such that they can work interdependently with humans and that, otherwise, team performance will suffer under complex situations where dependencies exist. Hinds et al. [8] provide evidence that task interdependence affects a sense of responsibility human workers feel toward collaborative work. Nikolaidis et al. [21, 22] have explored how interdependent work can be facilitated by enabling the development of shared mental models through human-robot cross-training.

2.2 Perceptions of Collaborator

When people work in teams, they develop perceptions of the work and traits of their collaborators, such their ability and integrity, and these perceptions can change over the course of their collaboration [12]. 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 [20]. 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 teamś success [9] and its awareness of its human counterpart [11].

2.3 Individual Differences

Research in human-robot interaction and teaming also show that individual differences can affect peopleś attitudes towards robots. For example, people with natural science and technology backgrounds were found to show a more positive attitude towards the robot compared to those with backgrounds in the social sciences [23]. Another study found that, in an arithmetic task in the presence of a robot, males saw the robot more human-like and more socially-desirable than females did [25].

3 HYPOTHESES

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

Hypothesis 1. When a human and a robot work interdependently, the human worker will have more positive attitude toward robots and the resulting collaboration 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 otherś work [13, 30].

Hypothesis 2. Collaborating on non-specialized homogeneous tasks with robots will reduce attitudes towards robotic teammates and the resulting collaboration compared to collaborating on specialized non-homogenous tasks.

While task homogeneity has not been extensively explored, prior research suggests that task specialization improves professional efficacy and thus promotes worker confidence [10], providing the basis for this hypothesis.

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

4 METHOD

To assess how task homogeneity and interdependence 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 collaboration.

4.1 Study Design

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

4.2 Experiment Setup, Materials, and Tasks

4.2.1 Collaborative Robot Platform. To create a simulated hybrid, human-robot workcell, we utilized a Kinova Mico robotic arm-a lightweight underactuated multipurpose robotic arm (shown in Figure 1). 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.

4.2.2 Workspace Setup. We simulated a single-station hybrid manufacturing workcell in our laboratory (also shown in Figure 1). 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 will take parts from his 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.

4.2.3 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 be 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 given the state-of-the-art technology. The âĂIJkitâĂİ included four lanterns placed in a cardboard box and securely fitted into an insert.

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:
1. Non-homogeneous, non-interdependent. 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-homogenous 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 the body, base, and battery cap from the shelf, and put these parts in the box. The task required the participant to place the screw and light 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 and kitting, resulting in a non-homogenous task allocation. However, their tasks were dependent 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, non-interdependent. 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 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.

4.4 Procedure

After 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 participanté 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 video-taped for future analysis. Each participant trial took approximately 30 minutes.

4.5 Participants

The study included 32 participants (16 males, 16 females) recruited from the University of Wisconsin-Madison campus. Participant ages ranged from 18 to 35 ($M = 22.65$, $SD = 4.15$). Twenty-one participants were native English speakers. Participants were from a variety of backgrounds, including as Geography, Computer Sciences, Mathematics, and Microbiology. Participants 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).

4.6 Measures

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

4.7 User-Experience Questionnaire

We constructed Likert scales to measure participant experience with the robot, including perceived competence of the robot, perceived contribution of the robot, how the robot's presence affected participant work, perceived enjoyment of working with the robot, and perceived collaboration with the robot. We refer to these as competence, contribution, presence, enjoyment, and collaboration, respectively, hereafter. Items included in these measures are shown in Table 1. We also measured participantsṕhysical and cognitive workload using the NASA Task Load Index (TLX) [7], which has been validated to provide consistent and reliable measurement of task load across various tasks [6]. Participant responses were measured using a seven-point rating scale for all scale items.

5 RESULTS

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 (items 1, 4, 5, 7; Cronbachś $\alpha = 0.76$), a two-item scale of contribution (items 19, 21; Cronbachś $\alpha = 0.9$), a two-item scale of enjoyment (items 23, 24; Cronbachś $\alpha = 0.75$), a two-item scale of collaboration (items 23, 28; Cronbachś $\alpha = 0.72$), and a five-item scale of task load (items 8,9,10,12, 15; Cronbachś $\alpha = 0.85$). The analysis showed that the items of the presence scale did not form a reliable scale, and thus this scale was eliminated from analysis.
Following the reliability analysis, we conducted an analysis of covariance (ANCOVA), including task homogeneity and interdependence as fixed effects and participant sex as a covariate for each measure. Our first hypothesis was that when human and robotâĂŹs work is interdependent, human workers will have a more positive attitude toward robots and the resulting collaboration than when their work is independent. Our results confirmed this hypothesis. Our analysis showed that when human and robot work depended on each other, participants rated the robot as being more competent, $F(1, 28) = 6.54$, $p = 0.0187$, and perceived it more as a collaborator, $F(1, 28) = 3.73$, $p = 0.067$, compared to when there was no interdependency.

Our second hypothesis was that collaborating on non-specialized homogeneous tasks with robots will reduce attitudes towards robotic teammates and the resulting collaboration compared to collaborating on specialized non-homogeneous tasks. Confirming our hypothesis, we found that when participants and the robot worked on homogeneous tasks, they rated the robotś competence lower compared to when they worked on non-homogeneous tasks, $F(1, 28) = 9.74$, $p = 0.0042$. As noted above, 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 [25], which we suspect to observe in the manufacturing setting. Our analysis revealed that task characteristics had a differential effect on how men and women perceived of the robot and the task. For example, female participants found the robot to be more cooperative than male participants did and were more willing to collaborate with the robot than males were, under the condition when their task depended on the robotś, $F(1,28) = 4.18$, $p = 0.054$. Similarly, female participants found the robot to be more competent when their work depended on that of the robot, $F(1,28) = 5.16$, $p = 0.032$. We also found an interaction effect between participant sex and task homogeneity over perceptions of the task: male participants found the task to be more mentally and physically demanding when task allocation was homogeneous whereas female participants found it to be more demanding when it was not homogeneous, $F(1,28) = 6.98$, $p = 0.0156$.
Finally, we conducted additional exploratory analyses, replacing participant sex with other demographic factors, in order to identify other individual differences future research might investigate. Results from this analysis showed that the frequency with which participants played computer games predicted perceived competence of robot, $F(1,28) = 7.83$, $p = 0.011$), willingness to collaborate with the robot, $F(1,28) = 10.39$, $p = 0.004$, and perceived contribution of the robot, $F(1,28) = 7.25$, $p = 0.014$ negatively predicted task load, $F(1,28) = 7.69$, $p = 0.0117$. Participant familiarity with manufacturing predicted perceived competence of the robot, $F(1,28) = 7.54$,

User Experience Questionnaire	
Competence	1. I trusted that the robot would perform its task correctly. 2. I was confident about the robotâĂŹs work. 3. I thought that the robot was reliable. 4. The robot knows what it is doing. 5. The robot is smart. 6. The robot was competent in performing the task it was assigned. 7. The robot has a sophisticated program controlling its actions.
Task Load Index	8. How mentally demanding was the task? 9. How physically demanding was the task? 10. How hurried or rushed was the pace of the task? 11. How successful were you in accomplishing what you were asked to do? 12. How hard did you have to work to accomplish your level of performance? 13. How insecure, discouraged, irritated, stressed, and annoyed were you?
Presence	14. I could easily predict the next movement of robot. 15. Trying to pay attention to the robotâĂŹs movements was stressful. 16. I found myself being distracted by the robotâĂŹs movements. 17.The robot got in my way while I did my work. 18. The robotâĂŹs presence did not affect my work at all.
Contribution	19. I found the robot to really contribute to the task. 20. It would have been harder to do the task without the robot. 21. Having the robotâĂŹs contribution made the task easier. 22. Working with the robot made my work easier.
Enjoyment	23. I enjoyed working with the robot. 24. Working with the robot made the task enjoyable.
Collaboration	25. I would prefer to perform this task without the robot. 26. I prefer working with a human in this task instead of the robot. 27. I enjoyed collaborating with the robot in this task. 28. The robot and I make a good team.

Table 1: User experience questionnaire that consisted of five scales to measure participant experience with the robot: Competence, Task Load Index, Presence, Contribution, Enjoyment, and Collaboration.

$p = 0.0124$, and familiarity with robots predicted willingness to collaborate with the robot, $F(1,28) = 5.27$, $p = 0.032$.

6 DISCUSSION

We hypothesized that when human and robotś work is interdependent, human workers will have a more positive attitude toward robots and the resulting collaboration than when their work is independent. Consistent with our prediction and that offered in recent literature (e.g., Johnson et al., 2012), our results showed that task interdependence improved participant experience with the robot, particularly their perceptions of the robotś competence and the robot as a collaborator. When participant work depended on the robotś 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 robotś work and gain insight into the robotś 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.

We also hypothesized that collaborating on non-specialized homogeneous tasks with robots will reduce attitudes towards robotic teammates and the resulting collaboration compared to collaborating on specialized non-homogeneous tasks. Our results indicated that task homogeneity affects participantsṕerceptions of the robot. Specifically, when participants worked on different tasks than those of the robot, they perceived the robot as more competent. This finding is consistent with results reported by research on job design on the effects of task specialization on worker satisfaction, suggesting that human workers may perceive robotic collaborators to be more competent when task allocation requires each worker to provide unique 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, homogeneity decreased task load among women but increased it among men. One potential explanation of this interaction is that task homogeneity was be perceived to create competition between the participant and the robot. 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 (Mutlu et al., 2006). In the current study, men might have perceived homogenous 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.

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.

7 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 collaborator 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 short time-scale 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.

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 arm to be integrated into day-to-day human environments, and thus collaborative robots designed for large-scale industrial environments might elicit different perceptions.

8 CONCLUSIONS

Collaborative robots are increasingly teamed up with humans to complete a variety of tasks. Given the diverse capabilities of these robots, we need to study how to best allocate tasks between human and the robot co-worker. In this paper, we study two variables for task allocation, task interdependence and task homogeneity, and investigate how these two properties affect human experience with the robot and with the collaboration. We also analyze how worker sex interacts with these properties. We conducted a 2×2 between-participants study where we 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 formulated two hypotheses: 1) When human and robot work is interdependent, human workers will have a more positive attitude toward robots and the resulting collaboration than when their work is independent. and 2) Collaborating on non-specialized homogeneous tasks with robots will reduce attitudes towards robotic teammates and the resulting collaboration compared to collaborating on specialized non-homogeneous tasks. Consistent with our hypothesis, we found that participants perceived the robot more competent and were willing to collaborate more with the robot when task interdependence existed. We also found that they rated the robot less competent when working on a 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 interdependence and homogeneity as well as worker sex for task allocation in human-robot teams.

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