But Where Are You Going?! Motion Is What Is Most Important for Real-World Co-Present Mobile Robots

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Abstract— **Mobile robots are being introduced to industrial workplaces in roles that require copresence with humans. To develop effective robots that do not negatively impact humans, including their subjective experience and ability to get their work done, we must understand humans' needs for working near these robots. In this paper, we examine what human workers need from copresent robots' motion during work at a large warehouse. To do so, report and synthesize findings about robot motion from across five studies (e.g., focus group, observation, experiment). Results indicate that workers were most focused on robot movement, including consistency, distance, prioritizing people, and indicating when it sensed people. Researchers and practitioners can use these findings to prioritize what aspects of mobile robots to develop to improve human worker experiences around robots and team efficiency.**

I. Introduction

Industry 4.0 heralds the introduction of highly automated robotic systems for applications like manufacturing and logistics [1], the industry that stores and transports goods. For established companies that have invested heavily in human processes, the transition to Industry 4.0 will be gradual; most companies only consider projects that realize a return on investment in three years or less. Thus, companies in the logistics industry, with annual expenditures of $8 trillion as of 2022 [2], are experimenting with introducing autonomous robots into existing human spaces. This paper evaluates Amazon's recent efforts to introduce autonomous mobile robots for moving warehouse items among human workers.

When humans and robots operate in shared spaces, it is important for people to be physically safe and to investigate people's other needs related to the robots, like perceived safety and perceived understanding of the robots [3]. Critical to this is motion. For example, robots that move faster than a person's comfort level or closer to them than they expect can be perceived as dangerous. Robots with erratic motion can be unpredictable and difficult to work around [4], [5]. In this paper, we explore what warehouse workers needs from robots regarding motion.

Because we ran these studies in industry, to meet immediate research needs, not all studies were about motion – rather, we extract and synthesize relevant findings about motion. Several studies have a low sample size; to make up for this, we report findings across five studies: one focus group, one observation, and three studies regarding workers' needs from robots' motion. In this paper, we contribute to the literature by synthesizing findings across studies with actual end users in different real-world contexts, with different robots, to learn what workers consistently need from robot motion.

II. Background

Work places with mixed human-robot workers are coming. Logistics industries operate at a large scale with many repetitive tasks, making automation a promising method of increasing efficiency [6], [7], [8], [9], [10]. Since 2012, many companies worldwide have been competing to develop autonomous mobile robots for e-commerce [11].

Much is known about the properties of robot motion that result in positive human interactions [12]; however, most studies examine robot motion in a lab setting or in public spaces (e.g., [13], [14], [15], [16], [17], [18]). When considering working with robots in industry, a different set of factors may dominate the human-robot interaction (HRI), particularly motion. Below, we review current knowledge about characteristics of good motion in HRI and how it affects people.

A. Good motion based on human factors

For collaboration with robots in shared spaces, the most important issues for humans depend on robot speed and proximity, predictability, and communication about motion (e.g., via legibility) [19]. These issues affect how people trust and behave around the robots.

Speed and proximity. Faster robot movements resulted in higher ratings of workload and anxiety [20], especially when they were closer to humans [4], [5], leading to proportionate levels of trust [21]. The exact speed profile may be less important to human observers than the overall time to execute the motion [22]. Collectively, the findings indicate that humans are sensitive to the speed of motion in their environment. Humans can be partially in control of these factors and increase their perceived safety, as they automatically vary their walking speed and direction to maintain a comfortable proximity from a moving robot [23].

Predictability. Motion predictability allows viewers who know a robot's goal to anticipate its motion. People both preferred more predictable robot behavior [22] and performed better when working near predictable robots [20].

Communication. Motion is a powerful communication channel. It influences perceived robot personality [24]. Expressive motion can convey ideas and moods to humans [25], [26]. The way a robot moves near a person affects humans' interaction, such as by going around a dyad in conversation versus between them [27].

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Legibility. Legible motion communicates a goal, creating intent-expressive motion. Note that "Predictability and legibility are fundamentally different and often contradictory properties of motion" [28]. For example, it would be predictable for a robot to go directly from point A to point B. However, to communicate that the robot is going to point B rather than point C, the robot may use legible motion, moving to disambiguate its destination such as by shifting toward B before it is necessary. A given motion's legibility depends on the role of the human who observes it, because their context depends on their role [29]. Legible motion can increase efficiency for robots working near people by easing coordination with them [30].

B. Motion for autonomous robots

Despite having the above recommendations on robot motion, they can be difficult to implement in autonomous robots. Mobile robots operating among humans require complex hardware and software systems [31]. Their safety systems can adversely impact robot performance, and the robots may need to employ additional navigation constraints to avoid inadvertently triggering the safety system [30]. Typically, a triggered safety system causes an emergency stop that overrides whatever carefully calibrated prosocial motion a mobile robot was intended to follow. Thus, practitioners may be constrained in implementing certain recommendations for autonomous robot motion.

C. Examining robot motion in industry

Before describing our studies, we indicate differences in our participants' experiences and the situations in industry compared to in lab or public spaces.

1) Participant differences: **Options.** In lab studies and public HRI, people often have more freedom to choose to interact with robots or not. In lab studies, people often know they will interact with robots going into the studies, and can leave at any time with minimal consequences. In public, people can easily leave the area if they do not like a nearby robot (e.g., that is on a sidewalk, in a restaurant) [32], [33]. In contrast, in industry, certain positions require that employees work near robots. Sometimes, people will begin a job that does not include robots, but as new technologies are introduced, they may later be required to work with robots.

Duration. Most HRI studies last less than an hour. Even longitudinal studies typically last several weeks or months. In contrast, workers may see robots often, if not constantly, over full workdays. They may work the job for years. This creates a different set of conditions in which people may engage in long-term learning and trust. Thus, it allows for different priorities. For example, people in HRI studies may simply disuse robots they do not like [34]. Conversely, in industry, if the managers have decided that the robots increase productivity, the robots may stay whether or not workers who interact with them day-to-day enjoy doing so.

Collaboration versus co-presence. Many HRI studies explore some levels of human-machine teaming (HMT), in which humans and robots actively collaborate with each other. In contrast, many industry employees may simply work alongside or be copresent with robots. For example, with Amazon's Proteus robot, humans and robots work together but with limited interdependence – that is, individual workers move their own carts around other humans and robots in the area, rather than interdependently collaborating with humans or robots. In this context, direct collaboration may be less important than simply not getting in each other's way or slowing each other down too much.

2) Study differences: This paper reports studies from industry. The studies are different from academic studies because working in industry creates different constraints and opportunities than in academia.

Robot ability. We were constrained to the ability of existing robots. This was a benefit in that we are certain that these robot motions are possible. It is a drawback that we cannot change the robot motion yet because within the team of engineers for the complex robots, changing motion for humans' comfort is prioritized along with many other considerations like reliability.

Study purpose In industry, we need to very quickly answer many functional questions about how to improve HRI. We must also collect data quickly because of the fast technology development and because taking workers away from their jobs can create congestion in workflows for fulfilling the company's responsibilities. Due to the need to quickly deliver for the customer, we do not have the time to run major research trajectories the way academia typically does. In this paper, we report 5 studies that had a variety of purposes. We make this paper cohesive by reporting specifically about findings that answer our research questions on robot motion and communication about motion (section III-A). This strategy includes both limitations (e.g., we did not manipulate main variables of interest) and strengths (e.g., we can examine how much participants care about motion and communication across many studies and contexts). This is a concept academics too can use to obtain more information from a study beyond the main study purpose.

Sample size. Because of industry's speed, our studies have small sample sizes. To combat this, we report multiple studies. A benefit of this is that we collect and synthesize data from multiple warehouses and related to multiple robots, extending the generalizability of our findings.

III. Present Studies

We present findings from one pre-study focus group about a robot, one observation of a facility, and 3 studies in which participants move around a space with actual robots. We used three robots (Experimental Platform A, Experimental Platform B, and Proteus), which were created to move carts of warehouse items at Amazon's facilities in in shared spaces where human workers did the same. The robots autonomously plan and execute motions through the warehouse and load and unload carts automatically. The robots are required to meet customer promises based on delivery-time guarantees. In this paper, we use "worker" to refer to people moving carts at the facility.

A. Main goals

Our main goals were to learn, in an industry context:

1) What elements of motion are most important in industry?

2) How do workers want robots to communicate about motion?

B. Details

In this section, we describe commonalities in participants, measures, and data processing. In the following sections, we first describe the methods and results for each study. Then we synthesize the findings into an overall discussion section.

1) Participants and IRB: For all three studies, we had IRB approval from WCG IRB[1]. For the pre-study and all studies, workers participated during regular work hours and received their regular work compensation for their time. Participation was voluntary. We emphasized that participants could leave at any time with no negative consequence and that their answers were anonymous. We specifically recruited participants from a variety of available ethnicities (e.g., African American, Latinx, Muslim, White, multiple) and genders for all studies to expand the generalizability of the findings.

2) Measures: We used semi-structured interviews to collect data. Where specified, we also used the think aloud method, in which participants say out loud what they thought about or noticed. Where specified, we asked participants to write their main comments on sticky notes to help the research team align with what participants thought was most important.

3) Data processing: One researcher coded participant interview and written responses using a thematic analysis technique to organize the data. The researcher obtained themes using a bottom-up approach, organizing participant responses as themes emerged from the data.

IV. Focus group

A. Participants

We recruited four groups of six participants for a total of 24 participants. Participants were workers in the West United States. Half of participants had experience with the robot, and the other half discussed what they would want from the robot. We did not collect further demographic information.

B. Procedure

The researcher provided an introduction, covered three different themes, and then debriefed participants:

a) Introduction (10min): The researcher shared the goal: To learn more about how to improve the robots. Then they demonstrated how to engage in the focus group.

b) Themes (15min per theme): For each theme, participants had three minutes to write down their own ideas. Then the researcher facilitated group discussion. Themes were:

1) **Human-human interaction:** How does human-human interaction work when navigating the warehouse (e.g., how do you navigate around people and objects)?
2) **Human-robot interaction:** What is going well with the robots, and how would you improve the robots? Or what would you want the robots to do to be successful?

c) Debriefing (5 min): The researcher answered participant questions, provided their own contact information in case of follow up questions later, and thanked participants.

[1]https://www.wcgclinical.com/

C. Robot: Experimental Platform A

Experimental Platform A robots had been moving around the facility for over two years before the study, which is when the participants with experience with the robots worked near them. The robot is approximately 1 m long, 0.6 m wide, and 1.8 m tall. Its form is a cage on wheels with doors that swing open. It moves at human walking speed and transports large and bulky items within the warehouse.

D. Results

Participants primarily discussed elements of the robots' motion and how the robots could communicate its intent.

1) Motion: Participants wanted robots to stay 10–15 ft from people, especially when moving quickly. They wanted robots to move at a slow walking pace when near people, and a brisk walking pace when distant: about 1.3 m/s.

When passing people, workers wanted robots to

1) give priority to
   a) whoever has the biggest/heaviest load,
   b) whoever has the most restricted line of vision,
   c) whoever has the least mobility,
2) behave predictably, like by continuing in a straight line,
3) stay out of the way by
   a) moving out of the people's trajectory or pulling over,
   b) turning around and going a different route if there is not enough space on the upcoming route,
   c) following at or below the human's pace, at a distance.

2) Communication: Participants wanted robots to communicate their intent when humans are near and when intent is ambiguous, in a simple manner (e.g., using blinkers). They also wanted training on the robots, especially when the robots' purpose or behavior changes.

V. Study: Observation

One of the authors cross-trained for a shift as a human worker, doing the job that the robots in this study are built to do, and which human workers currently do and will continue to do near the new robots: transporting carts. We describe here some observations from that experience. No robots were present during observation.

Navigation primarily takes place in walkways 1.2–1.8 m wide (although in other centers, these can be 2–3 times that width). Passing other workers with a full cart was challenging because carts are nearly the width of most walkways. Passing is therefore collaborative; employees work together to pass each other. Because passing is common, several well-understood principles guide it.

a) Responsibility: The responsibility for acting is shared by the parties in proportion to their level of mobility. An unencumbered worker will move out of the way to permit an encumbered worker to continue in a straight line. An unloaded pallet jack will get out of the way of a loaded pallet. A loaded pallet jack will get out of the way of a cart because they are harder to steer.

b) Collaboration: Collaboration to select a passing side depends on eye gaze and context. The distance at which the passing side becomes clear varies with the level of clutter from approximately 10 feet in the highest clutter to as much as 50 feet in open spaces.

c) Communication: When approaching an intersection, training dictates that workers should communicate with voice and hand signals. In practice though, they rarely use explicit communication. Instead, workers use context to understand where others are going. For example, people take empty pallet jacks towards the center of the facility and full pallet jacks toward the outbound dock doors.

d) Route planning: Workers use their knowledge of the network of the walkways to avoid needing to pass. When approaching an intersection with a choice of routes, they look for the direction that currently is less busy rather than the shortest path. They sometimes even make u-turns to avoid having to pass.

e) Passing side: The preferred passing side is highly contextual. It depends on the configuration of obstacles next to the walking aisle, like poles and pallets. Workers maneuver their load to wherever there is room to pass. Because passing side is dictated by the situation, there is very little bias towards passing on the right side.

f) Following: If one worker is following another, the follower must pass on the same side the leader to avoid creating a traffic jam.

VI. Study 1. Experiment with Experimental Platform B

A. Participants

We recruited 16 participants. Eight participants had no experience with robots, 8 had experience with autonomous robots behind a cage, and 2 had experience with Experimental Platform A robot (the predecessor to Experimental Platform B robot).

B. Procedure

This was initially designed as a research study about robot communication methods (specifically using blinkers as turn signals), but through using the think aloud method and asking follow-up questions on participant comments, we obtained information about robot motion relevant to this paper; we therefore include this study. We introduced the study, asked participants to sign the consent document, and answered their questions. Participants completed a demographic survey.

We introduced participants to the Experimental Platform B robot and to the think aloud method, in which participants would describe what they saw and thought about during the study. The researcher prompted them when needed to gain more detail. The researcher accompanied each participant in three loops around an area. In each loop, they followed Platform B and later approached it from in front, to see it from the back and the front. The robot used lights on the bottom, top, neither, or both, as turn signals. During the study, participants walked carrying nothing, pushing a cart, or pulling a pallet jack. The purpose of the carts was for participants to experience the robot while moving carts like they would in their job. The study took 30 to 60 minutes.

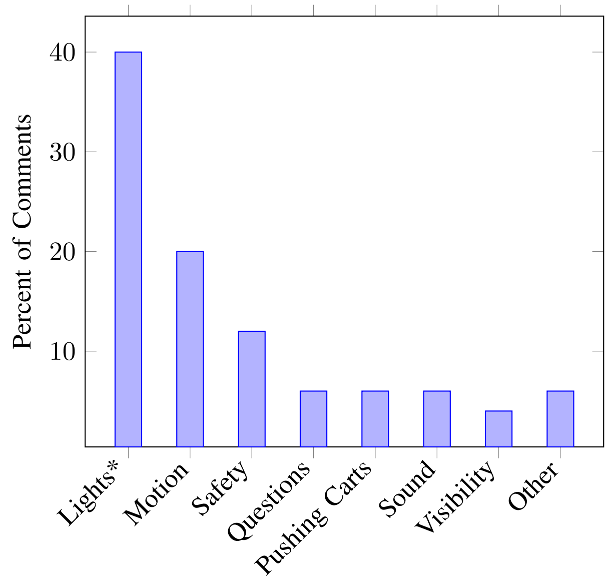

Fig. 1. Top topics workers brought up about Experimental Platform B. *Note that "Lights" is the most common category because it was the focus of the study.

C. Robot: Experimental Platform B

The robot was about 4' tall, 3' wide, and 4' long. It could drive forward and turn like a car, and it had an LED strip of lights on top and bottom, along with beacon lights on top.

D. Results

Besides commenting on the lights, which were the primary focus of the study and which researchers frequently prompted participants about, participants commented on motion twice as often as they commented on safety and four times as frequently as they commented on any other robot features (Figure 1).

1) Motion: Motion was critical; workers used it to make inferences about the robot's abilities and safety. For example, watching the robot avoid obstacles, one participant commented, "It knows where it is; safety is its concern." When the robot stopped for no apparent reason, a participant said, "It stopped abruptly, which means it has good braking... I think it could stop for a person."

However, their inferences were not always accurate or reliable. In the second example above, the participant inferred that the robot could stop for a person because of its motion, but they did not yet have information on the robot's sensing ability to notice people or objects. Workers tended to feel comfortable with the robots unless they thought it would stop quickly or back up quickly.

2) Communication: Some participants noticed that we used the LED lights "like a car; they show the direction it's going to go." They liked using lights for "knowing what the robot is going to... [The lights were] the main indicator I have been able to see." Some participants did not realize that the lights were meant to be like a car. One suggested, "you could put brake lights to make it clearer, [and] a real turn signal" rather than using the LEDs.

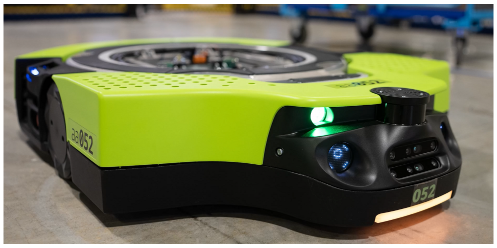

Fig. 2. Proteus robot

VII. Study 2. Exploratory study on Proteus

A. Participants

Participants were 8 workers from a center in South United States, and 3 General Managers (GMs) from a center in the Midwest. Workers had worked at the company between 5 weeks and 4 years, and had worked moving carts near Proteus between 2 weeks and eight months. Most were familiar with different autonomous robots from other areas in the center. GMs had been a GM between two weeks and two months.

B. Procedure

We ran worker participants one at a time. We introduced participants to the study. They signed the informed consent document and completed a demographic questionnaire.

We brought participants to an area where 3 to 6 Proteus drive units were active at a time, moving through two aisles and the mezzanine. Participants walked through the area multiple times, with and without moving a cart, to simulate working conditions, while using the think aloud method.

For GMs, the researcher introduced the robots and their functions and ran a semi-formal focus group with them.

C. Robot

We used the Proteus robot (Figure 2, Figure 3). This robot is 1 x .8 x .2 meters (3.3 x 2.6 x .7 ft). It is being designed to pick up and transport carts with warehouse items. During this study, the robots were in alpha testing and were confined to two aisles on the warehouse floor. Each robot had two robot chaperones nearby to stop the robot if it did something unexpected. Up to 6 robots were active at once.

D. Results

Participants discussed robots' motion and communication.

1) Motion: To create positive interactions with robots, workers wanted the robots to have **consistent motion** (few jerks), **path** (e.g., straight lines, consistent distance from walls), and **behavior** (e.g., the robots should not respond differently, like if workers are in a hurry or not).

2) Communication: To understand the robots, workers chose which robot signals to pay attention to (motion, lights, sounds, eyes) based on what made more intuitive sense to them individually, but they felt uncomfortable not knowing what all the signals meant. Workers wanted more certainty about the robots' behaviors and signals, such as through training - or, presumably, more intuitive interfaces.

Workers wanted the robots to provide specific information, including their **immediate direction** (e.g., with a light shining in front of it), **alterations to that path** (e.g., blinker, an eye wink to indicate they saw and will adjust to a person), and their **destination** (e.g., which cart drop-off point). Workers had concerns about not noticing robots soon enough as they **exit aisles or come around corners**.

Fig. 3. Proteus robot lifting a cart

VIII. Study 3. Bodystorming Proteus

Next, we ran a bodystorming study to gain more specific details about the motion workers wanted, especially related to immediate direction when passing the robot and exiting aisles or coming around corners.

A. Participants

Participants were 18 workers and 3 managers from a center in the South United States. One participant dropped out, not wanting to act out bodystorming scenarios, leaving 20 participants. Ten workers had experience with Proteus because they typically worked on a shift during which up to ten Proteus units were active and escorted by chaperones. Two of these workers had participated in Study 2. The other participants had minimal familiarity with Proteus. We ran 6 bodystorming sessions with 2 to 4 participants per session.

B. Procedure

Researcher introduced bodystorming and its purpose (10 min). Bodystorming is a research and design technique in which participants act out the part of the robots and humans. In this way, they can directly demonstrate, through their own body actions, what they want the robots to do. The researchers introduced Proteus and its capabilities (VII-C; 5 minutes) through description and direct observation of the robots, or images and videos when the robots were not available (i.e., for half of the sessions). Researchers ran warm up improv games (as recommended in bodystorming literature; 10 min), bodystorming activities (about robot behaviors exiting aisles and passing workers; 50 min), and a discussion session (15 min) to learn more about what participants wanted from Proteus, in which workers wrote main user needs on sticky notes and discussed them. Sessions lasted about 90 minutes.

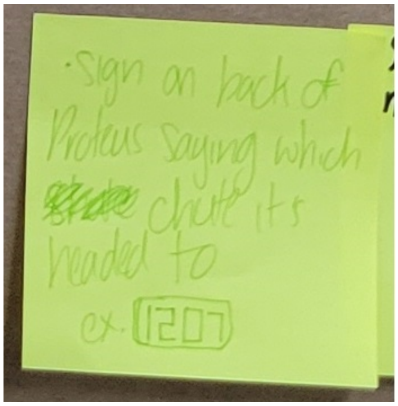

Fig. 4. Sticky note from participant: "sign on back of Proteus stating which chute [location] it's headed to; Example: 1207"

C. Results

The results confirmed prior findings of desire for motion predictability and communication about motion.

1) Motion:

a) Destination: Participants wanted to know the destination for each robot so they could better adjust their own route accordingly. (Figure 4). They wanted to know which aisle the robot would enter and if the robot would turn away before reaching them or if they would have to pass.

b) Location in aisles: Participants recommended that the robots stay off-center in aisles, which would make it simple to tell which side to pass the robot on (the side that the human is already on in comparison to the robot). When asked what they would want to do if they happened to come head-on toward the robot, participants acting as robots did not use legible motion, but they provided a visual signal (e.g., blinker) to show which side they would pass on. They tended to use cars as the metaphor and flash blinkers or wave in the direction they were going to pass.

c) Aisles and corners: Participants recommended that environmental features queue them about where robots are, including indicating which aisles the robots are in (e.g., with a beacon light at the end of the aisle), and to notify them when a robot was about to exit an aisle.

Around intersections and corners, people wanted the robots to slow down, or even stop, especially at blind corners. This is critical in this context in which many workers are moving quickly with heavy carts; because of the carts' weight and momentum, they take time to slow down. Therefore, some workers also recommended that the robots make sounds at these corners before proceeding, to alert workers to slow down or proceed with caution.

d) Adaptability: Participants were specific about who should adapt to whom. Most participants initially assumed that the robots would be simple and unable to take them into account. If so, they suggested the robots be predictable and dependable in their motion behaviors, and they indicated that they would be satisfied adjusting their motions to the robots'.

After we suggested that the robots may become smarter and asked them what to do in the best-case scenario, people requested that the robots give them the right of way (6 foot distance). They also wanted robots to detect if the robot and a worker were approaching a tight passage and proactively get out of the way to let the person go through first. However, they also indicated that if the robots were not that smart, they would appreciate training on what they should do around the robots so they would not confuse the robots.

2) Communication:

a) Notify if nearby: Many participants wanted the robots to notify workers of their presence if the people got too close because workers may be busy or distracted with their work tasks and not notice the robots. If robots beeped when people got too close, this could help prevent people from running into them. It could also prompt people to get out of the robot's way when stationary people are accidentally blocking the path.

b) Robot sensing: They wanted more transparency about what the robot was sensing. Some suggested that the robots physically turn their bodies to "look both ways" before emerging into an intersection. Many wanted more indication when the robot noticed humans. Most groups requested that the robot at least briefly stop to indicate that it had seen a human nearby. Some suggested that the robots beep or use their eyes, or otherwise acknowledged noticing a person. They indicated that this would help them feel safer with robots moving around them, at least in the beginning.

IX. Discussion

In this paper, we report one pre-study focus group in which industry workers expressed what they wanted from robots, one observational study in which a researcher took training for the job the workers were doing, and three full studies in which workers moved around robots and expressed what they wanted from robots. For these mobile robots, their motion was the most important feature, especially because it related to workers feeling safe and understanding what the robots would do next and how to interact around them. Below, we report main recommendations and which studies we obtained them from (Focus group: FG, Observation: O, and Studies (S) 1–3). Because it can be difficult to program a robot to follow certain recommendations II-B, we hope that practitioners can choose recommendations that are feasible in their system, and that future researchers further explore how these recommendations can be incorporated into mobile robotic systems that have various motion constraints. Please note that these recommendations are based on user suggestions and have not yet been tested in the field. People may suggest behaviors which, after experiencing, they find they do not like. Our next step is to empirically test these recommendations on the robot.

A. Recommendations

1) Consistency: Foremost, workers wanted predictable motion. This means having **consistent motion** (few jerks, no sudden reverses), **consistent path** (e.g., straight lines, consistent distance from chutes or walls), and **consistent behavior** (e.g., not changing their behavior based on the context, like if a person is in a rush; FG, S 1, 2, 3). This is similar to prior work indicating the importance of predictability [22], [20] *2) Speed and proximity:* Robots need to maintain a speed and proximity from people that allows them to stop in a way that people are comfortable with. In this study, participants requested that the robots maintain a distance from humans and speed similar to that which humans use – in this case, about 6 to 10 feet, especially because they are pulling heavy carts that can take longer to stop (FG, S 2, 3). This extends prior work showing that proximity and speed affect human trust of robots [4], [5].

3) Priority: If possible, robots should give priority to people – without negatively affecting perceived consistency (FG, O, S 1, 3). If the robots were advanced enough, workers also wanted them to give priority based on people's needs, such as to people with a heavy load, restricted line of sight, and decreased mobility, or who are faster than the robots - and to look ahead and get out of the way if need be (O, S 3). This was not discussed in prior work we found on robot motion. We recommend that future research explore when it is important to give people the priority for passing, and how to do so without negatively affecting consistency.

4) Indication of Sensing: At least for early robots, participants wanted indication of what they were sensing and if the robots were sensing people (S 2, 3). They also wanted this in potentially dangerous zones like at intersections or around blind corners.

5) Communication: Participants requested, especially when it was ambiguous, that the robots communicate what they needed next (FG, S 1, 2, 3). Interestingly, participants did not suggest anything related to legible motion (e.g., turning earlier than it needs to), which prior research shows can be useful [28]. Instead, they focused on more explicit signals from robots (e.g., blinkers to indicate intended direction). We do not think that this precludes legible motion as being a useful tool in HRI in industry, and we suggest that future research examine it during actual interaction with robots to test its efficacy.

6) Training: When working with actual robots and with workers who are required to work with these robots, some of the above features will be easier to program than others. Until motion is improved for the above purpose, we recommend training workers on if and how they affect the robot, especially as it pertains to understanding the robots' motion. This is especially important when updating the motion or making changes to how the robot moves (FG, S 2, 3).

B. Mobile robots in industry settings

In the warehouse, workers can assume that anyone they encounter shares crucial common ground. They share a goal of moving warehouse items quickly and efficiently. They share common training and culture, especially concerning safety practices. And they can assume that most others are familiar with the building layout.

Although the company recruits workers from all walks of life, this common ground sets a company warehouse apart from a public area like a sidewalk or academic hallway. It enables an implicit contract: workers realize certain optimizations or efficiencies in how they collaboratively navigate their shared space, and can expect these same efficiencies in others. This resembles the *pedestrian bargain* of [35], which observes that humans in pedestrian spaces must behave competently and trust others to behave competently. Many such efficiencies were noted in the observation study, including prosocial navigation behaviors for communication, passing, and following effectively.

Across studies, we see repeated emphasis on the importance of characteristics of robot motion. Workers in multiple studies stated desires for robots to move predictably and to get out of the way of workers. We interpret these desires as an expectation for robots to uphold the implicit contract. Ideally, robots would follow many similar social navigation behaviors, but this is a subject of ongoing research. At the least, robot motion should be predictable. If the robots can do neither, the workers felt that the robots should get out of the way to restore the contract. This finding highlights another avenue for research: how can robots move efficiently while minimizing being in the way of humans' motion?

C. Limitations and future directions

Because these robots were driving in incredibly complex environments, with a variety of lights and sounds, reflective floor surfaces (which the robot sometimes mistook as objects), and moving humans and carts, the robots' safety features cause the robots to slow and stop. Therefore, the robots' motion was sometimes unexpected. But it was also motion that may exist in the real world.

An interesting challenge of these studies was that most participants expected the robots to have very limited abilities. It was common for participants to first suggest that the robots move in a straight line from their current point to the destination and let humans figure out how to get around them. It was only after much encouraging participants to think about what they wanted if the robots were more intelligent that participants came up with more creative and human-friendly solutions like having robots prioritize people and get out of their way when need be. This may be because participants were in a work environment and accustomed to working near machines that are not intelligent enough to adjust to people. It would be interesting to study newer workers to the area to see if they have more creative and human-centric solutions, or to compare industry workers' ideas directly with another population like white-collar workers or children.

Because we ran these studies in industry, they have a different set of strengths and limitations compared to many academic studies. We could not calculate inter-rater reliability because only one researcher was available to code the data. However, we ran these studies with people who would actually interact with autonomous robots in real work setting. This increases the external validity of the study results in a way many academic studies do not. Because our studies had a low sample size, we relied on qualitative results, which give a broader picture, and we ran multiple studies to increase our confidence of the recommendations. We also included participants who worked alongside the robots for up to several months, showing some results well past the novelty effect. Although this paper is not typical of most HRI studies, we believe that the multiple methods we employed and the specific applied context provide unique insights. By doing so, we hope that this work can help bridge the gap between research in academia and industry.

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