Automation in Construction 164 (2024) 105455

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Understanding human-robot proxemic norms in construction: How do humans navigate around robots?

YeSeul Kim [a], Seongyong Kim [a], Yilong Chen [a], HyunJin Yang [b], Seungwoo Kim [c], Sehoon Ha [d], Matthew Gombolay [d], Yonghan Ahn [b], Yong Kwon Cho [a,*]

[a] School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr., Atlanta, Ga 30332, USA
[b] Dept. of SmartCity Engineering, Hanyang University, South Korea
[c] Dept. of Global Smart City Convergence, Sungkyunkwan University, South Korea
[d] School of Interactive Computing, Georgia Institute of Technology, 790 Atlantic Dr., Atlanta, GA 30332, USA

ARTICLE INFO

Keywords:
Proxemics
Human-robot interaction
Robotic spatial behavior
Human spatial preferences

ABSTRACT

As an increasing number of mobile robots are envisioned to work and interact with humans in construction workspaces, it becomes critical that robots' spatial behaviors align with the expectations of human coworkers to ensure safe and efficient co-navigation. Yet, we have a limited understanding of what robotic spatial behaviors are perceived as socially normative under different work contexts. This paper investigated perceived appropriate proxemic behaviors of robots by examining actual construction practitioners' spatial behaviors during interactions with robots. We developed a virtual environment of a typical indoor construction job site and explored the role of work conditions and human-robot relations on their proxemic behaviors. The findings reveal that participants tend to maintain a larger separation distance in more crowded work conditions compared to normal ones and when encountering a robot as a passerby compared to encountering a human. We further discuss the implications of our results for the development of robot path planning with appropriate distancing strategies.

1. Introduction

The construction industry is widely recognized as one of the most dangerous sectors largely because of its unstructured and congested work environment. Most construction practitioners describe their workplace as a place where constant interactions with others are inevitable [1]. In these settings, ensuring safe interactions with others is of utmost importance. They need to maneuver through the workspace without causing collisions or disrupting others. While the shortest path is usually preferred, safety becomes the primary consideration in selecting paths when construction activities are conducted simultaneously in close proximity [2]. In essence, keeping a sufficient distance from potential risks is a critical aspect of construction workplace conventions.

Recent advancements in mobile robots demonstrated the potential for applications in construction job sites performing simple, non-permanent construction tasks, such as data collection [3], reality capture [4,5], safety surveillance [6], and indoor environment monitoring [7,8]. The deployment of robots in human work environments can bring novel safety concerns for workers. With robots expected to encounter and interact with human workers while executing their tasks, the risks of collisions escalate with the robot's presence [9–12]. Although maintaining the maximum possible separation distance from humans or halting in front of them may improve safety, it may result in inefficient navigation [13]. Moreover, even when no physical risk is involved, people can still feel unsafe in proximity to robots as robots can be perceived as disruptive and even threatening in workplaces [14]. Such persistent undesired interactions can potentially demotivate workers since robots interact with human workers daily [15]. Thus, to ensure workers' physical and psychological safety and well-being, it became imperative to design robots to understand and conform to social norms of human spatial behaviors [16].

However, there remains a limited understanding of the appropriate spatial boundaries for robots that are designed to be operated in human workplaces. While a few studies have investigated human-robot proxemics in the construction domain, they primarily focused on direct

* Corresponding author.
E-mail addresses: ykim858@gatech.edu (Y. Kim), skim3310@gatech.edu (S. Kim), ychen3339@gatech.edu (Y. Chen), hyunjin29@hanyang.ac.kr (H. Yang), wow88131014@skku.edu (S. Kim), sehoonha@gatech.edu (S. Ha), matthew.gombolay@cc.gatech.edu (M. Gombolay), yhahn@hanyang.ac.kr (Y. Ahn), yong.cho@ce.gatech.edu (Y.K. Cho).

https://doi.org/10.1016/j.autcon.2024.105455
Received 30 October 2023; Received in revised form 16 March 2024; Accepted 5 May 2024
Available online 15 May 2024
0926-5805/

interactions [17], neglecting the nuanced intricacies of indirect interactions. Unlike the caged industrial work setting, construction job sites present various scenarios where workers may come into unplanned contact with mobile robots. Depending on the situations in which the interaction occurs, the same distance can be perceived as appropriate in one situation and inappropriate in another situation. As these unintended encounters represent a significant portion of interactions at construction workplaces, there is a need to study the underlying dynamics of unplanned, indirect human-robot interactions.

To this end, this study aims to investigate socially normative spatial behaviors for robots during indirect interactions. As spatial behaviors are often nuanced and contextualized, we propose to learn from actual construction workers' demonstrations to infer what robotic behaviors are deemed appropriate from their perspectives. To do so, we conducted experiments in a virtual environment where participants navigated and interacted with robots in different human-robot relationships under varying degrees of crowded work conditions. Our analysis revealed the impact of these contextual factors on participants' spatial behaviors, leading to differences in both proxemic adherence and navigation performances. The findings from this study can lay the groundwork for shaping new social norms addressing the challenges of ensuring safe and efficient robot path planning in human work environments.

The remainder of this paper is organized in the following structure. Section 2 presents the theoretical backgrounds of human-robot proxemics. The research method is detailed in Section 3, followed by the results in Section 4. Section 5 discusses the broader implications of our findings, and the conclusion is described in Section 6.

2. Theoretical background

This section presents the theoretical background of humans' distancing behaviors. We first introduce proxemic theories in human social interactions. We then describe the constructs of appropriate distancing in human-robot interactions and introduce various factors that affect human distancing behaviors. We finally present our research hypotheses.

2.1. Social spaces and proxemics

A fundamental aspect of social norms in crowd navigation is collision avoidance, which is highly related to the notion of personal space. People form social spaces and manage their space in response to others across various social and interpersonal situations. Proxemics is the study of the observed human spatial behaviors, or spatial proximity, during human-human interactions [18]. Comprehending the various social spaces within human-human proxemics is essential to exhibit more natural and effective collision-free path planning.

The most fundamental social space is individuals' personal space in interpersonal interactions. Proxemic theory identified four ranges of personal spaces (e.g., intimate (<45 cm), personal (45 cm – 1.2 m), social (1.2 m – 3.6 m), and public distances (>3.6 m)) for different social interactions [19]. They are usually represented in concentric circles [19], though several studies suggested other shapes, such as an ellipse [20]. Because people consider personal spaces as their private space, violating the individual's personal space can cause discomfort [21], even in short-term interactions.

Similarly, when people gather, they form ***a group space***. A group of people tends to arrange certain formations (e.g., F-formation [22], O-space [23]). The group space is bigger than a mere summation of the individual's personal space. Intruding on the group space will cause discomfort, though the individual's personal space is not intruded.

When individuals engage in an activity, they form an activity space related to the physical actions performed by the activity and related objects [24]. Based on the type of activities that a person performs, the body posture, positioning, and task boundary will vary, requiring different sizes of activity space [25]. In construction job sites, the activity space can be equated with work zones, which typically refer to areas for workers, materials, tools, and travel paths necessary for completing a construction task [26].

The different sizes of these spaces suggest that proxemic behaviors are more complicated than simple collision avoidance as they maintain a greater distance than merely preventing physical contact. These spaces indicate the distance at which people begin to feel uncomfortable by others' presence [27,28]. Thus, the principles of proxemics can be applied as a control mechanism in human-robot interactions to ensure safe proxemic behaviors, as illustrated in Fig. 1. Robots should understand the humans' proxemic norms and maintain a sufficient distance from workers concerning these social spaces.

2.2. Constructs of appropriate proxemics in human-robot interaction

With the increasing number of robot applications in human environments, a rich body of work has studied human-robot proxemics and has sought to identify appropriate distances for robots.

Traditionally, determining an appropriate distance has been centered on physical safety considerations. Regulations and standards, such as EN ISO 13482:2014, emphasize maintaining a specific safety distance from robots to minimize collision risks [29]. This safety-based proxemic preference is often employed in work environments where the risk of physical harm to humans is a prominent issue. This approach establishes the appropriate distance at which the robot poses no physical threat to humans, often achieved by segregating robot working areas from human workspaces [30].

More recently, perceived or psychological safety has gained prominence as a factor in determining the suitable distance between humans and robots. [31] showed that unfamiliar robots in work settings can be perceived as disruptive and potentially dangerous, inducing user anxiety. Such negative feelings can increase cognitive overload and lead to unsafe behaviors [32]. Consequently, maintaining a certain distance, irrespective of physical safety concerns, becomes imperative to mitigate perceived threats and ensure the psychological safety of workers.

Similarly, comfort serves as another psychological construct influencing the choice of separation distance between robots and humans. It is sometimes used interchangeably with perceived safety, as comfort essentially entails the absence of negative emotions such as feelings of unsafe. Comfort-based proxemic preference measures the optimal distance at which individuals do not feel uncomfortable with the proximity of a robot [33,34]. Increasing the distance from robots can mitigate discomfort caused by close interaction [14].

Together, these constructs imply that the operationalization of appropriate proxemic behaviors centers on the protective function when threats are presented [31]. Maintaining greater distance mitigates perceived risks.

2.3. Attributes of human-robot proxemics

User studies exploring how people respond to a robot's spatial movement yielded varied assessments of appropriate distances between humans and robots, spanning from intimate to social distances, as summarized in Table 1. These studies identified and differed on the types of attributes and showed how these attributes to some degree explain the observed differences in proxemic behaviors.

2.3.1. Personal attributes

Among the most researched factors on human-robot proxemics are personal attributes such as age, gender, or personality. Despite the abundance of literature, the findings are inconsistent and less straightforward. For instance, studies on the effect of age presented varying conclusions. [35] observed that children generally maintained a greater physical distance from the robot compared to adults, while [36] found no significant age-related effect. Studies examining the impact of gender also have shown minimal or no significant effect on proxemic

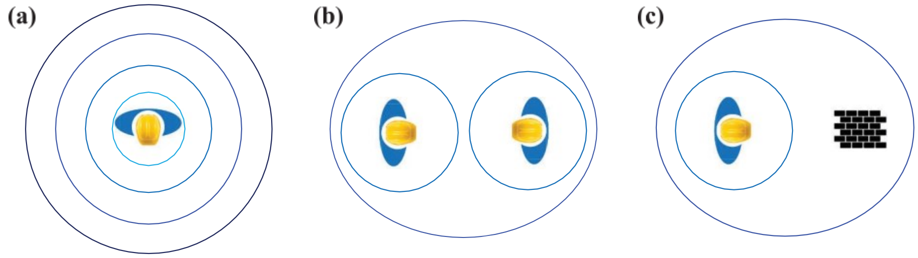

Fig. 1. Different social spaces: (a) personal space, (b) group space, and (c) activity space.

Table 1
Overview of Human-Robot Proxemic Studies.

		Interaction Context	Robot Features	Human-Robot Distance (cm)	Key variable	Size
1	Pacchierotti et al. [33]	Passing	Mechanic robot (PeopleBot-Minnie)	Not intimate	• Contextual (Passing distance)	*n* = 10
2	Neggers et al. [58]	Passing	Humanoid robot (Pepper robot)	Intimate (36)	• Contextual (Passing distance and side)	*n* = 32
3	Lo et al. [59]	Crossing	Inverted-pendulum robot (1 m tall)	Social (208)	• Robot (Crossing behavior – e.g., speed)	*n* = 98
4	Leichtmann et al. [60]	Approached by robot	Mobile robot w/ arm (185 cm tall)	Personal (51)	• Contextual (Room size, working memory load)	*n* = 72
5	Walters et al. [35]	Approaching & approached by robot	Mechanic robot (PeopleBot, 1.1.m tall)	Social (175) & Personal (84)	• Personal (Gender, age) • Contextual (Subject of approach)	*n* = 196 & *n* = 28
6	Walters et al. [39]	Approaching & approached by robot	Mechanic robot (PeopleBot, 1.1.m tall)	Personal to social	• Personal (Personality traits)	n = 28
7	Takayama and Pantofaru [41]	Approaching & approached by robot	Personal Robot 2 (1.35 m tall)	Intimate to personal	• Personal (Experience, pet ownership, gender) • Robot (Head direction) • Contextual (Subject of approach)	*n* = 30
8	Torta et al. [61]	Approached by robot	Humanoid robot (NAO)	Social (173–182)	• Contextual (Direction of approach, participant's body posture)	*n* = 18
9	Rossi et al. [40]	Approached by robot	Pioneer 3DX (1.3 m tall)	Personal (88)	• Contextual (Participant's activity) • Personal (Personality) • Robot (Speed)	*n* = 50
10	Lehmann et al. [43]	Approaching robot	Humanoid robot (NAO, 58 cm tall)	Personal (48)	• Robot (Head gaze movement, leaning back behavior)	*n* = 40

preferences [37], with conflicting results reported. It is suggested that gender requires more sophisticated examination due to its complex nature [38]. Regarding personality traits, [39] showed that proactive individuals had been observed to allow robots to approach closer, whereas those more neurotic kept a larger distance in human-robot interactions [40]. Though dispositional factors influence human-robot interaction behaviors, the overall effect remains inconclusive and inconsistent due to complex and multifaceted relationships among these factors. Another personal attribute potentially impacting human-robot proxemics is prior experience or familiarity with robotic technologies. Individuals with previous experience with robots may have different expectations and might not keep as much distance, feeling more in control during interactions with familiar technologies. Several studies [37,41] showed that people with prior experiences tend to maintain a shorter distance toward robots. In some studies, prior pet ownership is sometimes considered an indicator of prior experience with robots because both include interactions with non-human agents [42].

2.3.2. Robot-related attributes

Robot-related factors are also known to have some effect on proxemic preference. Studies have observed how various robotic attributes influence individuals' proxemic preferences. They revealed distinct proxemic expectations based on robot design attributes, such as size and anthropomorphism [43,44] as well as robot behaviors, including speed [45], sound [46], and gaze behaviors [42]. Nonetheless, the degree of robot design's effect on distancing behaviors requires further investigation, as the literature presents mixed outcomes. For instance, the robot's impact on size or height showed inconclusive results. Generally, individuals allow shorter robots to approach them more closely than large robots [47], but the relationship between robot size and preferred distance is inconsistent [48,49]. Similarly, a robot's speed has yielded divergent results regarding preferred distances. In different studies, increased robot speed has been associated with significantly larger distances [45] and smaller distances [40]. Regarding the appearance of robots, people hold higher expectations of proxemic social norm conformity when interacting with a humanoid robot. However, in certain instances, people maintained a greater distance toward robots with a mechanical appearance [50]. Because of the limited findings, it is difficult to deliver reliable conclusions on the effect of robotic factors on proxemic behaviors.

2.3.3. Context-related attributes

Contextual factors refer to temporary elements associated with the environment or situation in which the human-robot interaction occurs [51]. Several studies examined how individuals respond to these factors in terms of proxemic preferences. For example, the physical context of the environment, such as the size of the space, can impact users' comfort distance [52], particularly when their spatial movement is constrained in narrower areas compared to more open spaces. In confined spaces like narrow hallways [31] or when positioned close to a wall [53], individuals typically require a greater comfort distance from a robot.

Another aspect relates to user context. Depending on the specific activity a user is engaged in, the preferred distance may vary. For example, activities involving more static, lower posture positions (e.g., sitting) tend to favor a smaller distance compared to activities involving upstanding postures (e.g., standing, walking) [40]. [54] also showed that people tend to prefer shorter distances when approaching a robot themselves rather than when being approached by a robot, as they perceive a greater sense of control over the interaction.

Lastly, interaction context is also a vital aspect. The typical roles of humans in human-robot interactions are supervisor, operator, teammate, programmer, or bystander [55]. Studies explored how these interaction contexts affect the distance between the robot and the human. [56] used a concept of power distance for different relationships and showed that users prefer a closer distance for supervisor robots.

In the context of mobile construction robots, it is anticipated that most humans will primarily function as passersby or bystanders, with only a limited number of individuals operating the robot. However, indirect interactions such as coexistence in a workplace have not been sufficiently investigated. This gap highlights the need to investigate how workers in diverse work contexts [57] maintain distances from robots and how the nature of the human-robot relationship (e.g., operator vs. passersby) influences this behavior. Thus, this study explores indirect human-robot interactions under varied work conditions, focusing on human roles as operators and passersby navigating a workspace.

2.4. Research hypotheses

Although the previous literature identified factors affecting humans' preferred distance from robots, it is still unclear whether the effect of contextual factors will be observed in varied construction work contexts, especially when it involves more indirect interaction situations. This leads to the following questions: ***What human distancing behaviors will be observed under different work conditions? Will their proxemic behaviors be different when their roles in human-robot interactions are different?*** To this end, this study investigates the effect of 1) the work conditions (WC) of the job sites and 2) the human-robot relationship (HRR) on appropriate spatial behaviors during unintended encounters. We manipulated the crowdedness of simulation environments as well as the role of humans in human-robot relations, and we studied how they influence proxemic behaviors, as depicted in Fig. 2.

We hypothesized that the appropriate distance between a robot and a human will vary depending on work conditions. In work environments with greater spatial constraints (e.g., crowded spaces), individuals tend to increase their distance to mitigate the risk of collisions, given their reduced control over spatial movement. Similarly, when co-present workers are engaged in high-workload tasks (e.g., physically demanding activities), people also tend to increase the separation distance because the capacity of other workers to avoid collisions decreases as they focus more on their tasks. Consequently, the desired safe distance will be higher in these complex work situations compared to normal conditions. This leads to the first set of hypotheses:

H1. *Participants will (a) have a smaller frequency of personal space intrusions, (b) have a longer navigation duration, and (c) cover a longer traveled path length (indicative of safer behaviors) in more crowded situations than in normal situations.*

Secondly, we posit that the type of HRR (e.g., a human's role in relation to a robot) affects the appropriate distance between them. People can feel uncomfortable working around robots [62]. This discomfort can be even more pronounced when they lack control over the robot. For example, the distance one maintains from an approaching autonomous robot as a passerby will be greater than the distance one keeps toward an approaching human as a robot operator, although both involve interactions between a human and a robot. This leads to the second hypothesis:

H2. *Participants will (a) have a smaller frequency of personal space intrusions, (b) have a longer navigation duration, and (c) cover a longer traveled path length (indicative of safer behaviors) when encountering a robot than when encountering a human.*

Lastly, we posit that work conditions and HRR influence proxemic behaviors, and the perceived risk level mediates the effect of work conditions and HRR. Perceived risk is known to trigger human cognitive factors that subsequently influence behaviors. In the construction work context, we assumed that people perceive a certain degree of danger from contextual risk elements in the workplace environment. Consequently, proxemic behaviors can be mediated by their perceived danger, as keeping a separation distance can reduce discomfort and safety risks arising from the situation. Thus, we assumed that people tend to increase their distance from others when they perceive a higher risk. This leads to the third hypothesis:

H3. *Perceived danger level will mediate the effects of the (a) work condition and (b) the human-robot relation on the minimum distance from others.*

3. Method

To investigate the effects of WC and HRR, we conducted human-subject experiments in which construction practitioners performed a navigation task in a virtual environment, followed up with post-trial surveys and semi-structured interviews. The detailed methods are described in this section.

3.1. Participants

The sample size was determined through a priori power analysis considering two main effects of work context and human-robot relationship [63]. Assuming a statistical power of 80% and medium effect size ($f = 0.22$) with α value of 0.05, we decided on the minimum sample size of 66 [63]. 78 participants from 8 construction projects, including commercial, residential building, and civil projects, participated in the experiments. By eliminating incomplete data, 71 participants (2 females and 69 males; average age: 44.3 & SD: 12.8) completed the study. All participants were practitioners in the construction industry with adequate work experience (average work experience: 13 years) and

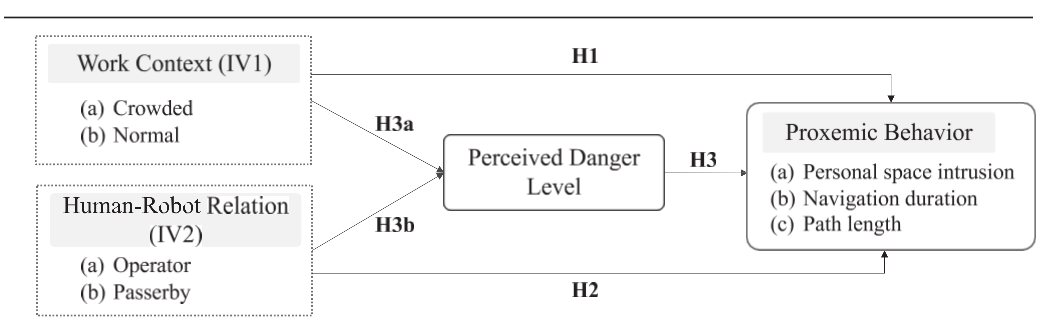

Fig. 2. Overview of research hypotheses with contextual factors as independent variables and perceived danger as a mediator.

domain knowledge. The detailed descriptions of the participants are summarized in Table 2.

3.2. Study design

3.2.1. Virtual environment design

We designed virtual simulation environments of a typical indoor construction workplace in Unity. As immediate or near-future robot applications are perceived to be quadruped robots or other mobile robot platforms carrying out temporary construction tasks such as data capture or safety monitoring [64] or simple single tasks [65,66], we incorporated quadruped and mobile robots to interact with the participants. Since most onsite mobile robots are configured as a mobile platform equipped with a robotic arm, our study also adopted this design. As the height of typical mobile robots with medium to large robotic arms ranges from 0.8 to 1.3 m, we designed our robot to be 1.3 m tall, reflecting the size of actual robots. Regarding robot speed, we programmed the robot NPCs to move at speeds equivalent to human NPCs to minimize any potential influence of speed on the participants' perception.

In the simulated work environment, we created four types of interactions that can occur from the indoor job site layout, as depicted in Fig. 3. We assumed the black paths represent more socially normative paths that comply with proxemic rules. In contrast, the red paths represent more efficient behaviors optimized by navigation performance (e.g., shortest paths). We extracted the participants' behavioral data related to these four interactions for data analysis.

We preprogrammed the movement of non-player characters (NPCs) to be initiated by a trigger. NPCs were set to begin to move toward the predefined waypoints once the distance between the NPC and an agent controlled by the participant gets smaller than a threshold. In this way, we ensured all participants had the same interactions during each experiment.

3.2.2. Experiment design

To explore the effect of contextual factors on the distance between a robot and a human, we employed a 2 (WC) x 2 (HRR) within-subject design. For the first independent variable, WC factor (IV1), we implemented normal and crowded conditions by varying the number of workers and objects as well as the intensity of the activities. Based on the feedback from a pilot test, we designed the crowded work conditions (IV1a) including 9 NPC workers, and added large-scale construction objects such as stocked wooden pallets and pipes. NPCs were executing high-workload tasks, such as carrying materials or working on a height. Combined, this condition was to represent a busy and congested work environment. On the other hand, the normal work conditions (IV1b) included 4 NPC workers, carrying out simple activities, such as walking or nailing a wall. The environment also included a smaller number of construction objects to represent less crowded ones. The manipulation check of the environment design is described in Section 4.1.

For the second independent variable, HRR factor (IV2), we created two human-interaction contexts by assigning the participants one of two roles: (a) a human worker teleoperating a legged robot, or (b) a human worker navigating the workplace. In both cases, the participant was approached by and interacted with other human and robot NPCs in the environment. For the teleoperator role (IV2a), the participant was approached by human NPCs (as depicted in Fig. 4(a)), while, for the passerby role (IV2b), the participant navigated as a human avatar and was approached by robot NPCs (as depicted in Fig. 4(b)).

Table 2
Overview of Participants.

Variable	Group	Sample Size
Work Experience	-10 years	31
	11–20 years	24
	21 – years	16
Role	Management	30
	Trade workers	41
Previous robot experience	Yes	16
	No	55

3.3. Experiment procedures

The experiment was conducted in accordance with the university's Institutional Review Board guidelines (H23040). In the first part of the experiment, participants were briefed about the overview and provided their informed consent. We presented a short video demonstrating potential applications of autonomous mobile and legged robots in construction settings. In the second part, each participant took a tutorial session to familiarize themselves with the navigation task in our simulation environment. The virtual environment was displayed on a large screen, and participants were instructed to sequentially navigate toward predetermined target positions using keyboard controls, simulating the way they would navigate in the actual job sites. If participants intruded into the personal spaces of other NPCs, the simulation environment generated a "collision" alert.

Once participants became familiar with the environment and the task, they were randomly assigned to one of the test conditions and conducted four experiments. The order of conditions was randomized and equally distributed across the possible combinations to mitigate the effects of the test order. After each experiment, participants completed a survey about how they perceived the simulation environments. Upon completing the entire set of experiments, we conducted a semi-structured interview regarding general demographic information, work experiences, and thoughts on expected social norms for onsite robots.

3.4. Data analysis and evaluation metrics

For evaluation measures, we employed both objective and subjective measures. Subjective measurements were obtained through self-report questionnaires, where participants shared their perceptions of the simulation environment using a series of 5-point Likert scale questions. For objective measurements, we assessed proxemic conformity (e.g., minimum distance from others and frequency of personal space intrusion) and general navigation performance (e.g., navigation duration and length of traveled path) because general navigation performance can also serve as an indicator of proxemic behaviors. The navigation path (in meters) can reveal patterns in proxemic behavior, such as maintaining a larger distance from others. Similarly, navigation duration (in seconds) can indicate collision avoidance behaviors. For instance, people may take longer if they slow down or pause to allow a passerby to cross when personal space cannot be upheld. To analyze individual navigation performance measures, we normalized each trial value by dividing it by the participant's average value. This normalization equalizing the average to 1 adjusts the value according to the average [67], which can account for the significant variations observed in participants' navigation performance.

For proximity conformity measures, we recorded the raw log files of each participant's simulation in Unity and extracted the states of all agents, such as position and velocity, to analyze specific proxemic behavior features. We counted an incident as a personal space violation whenever the shortest distance measured from the outer perimeter of the character played by the participants to the outer perimeter of any other characters in the simulation was less than the predetermined threshold at any given time. The threshold was set at 1.2 m, corresponding to the upper range of the personal spaces range [19].

1) ***re uenc o ersonal s ace intrusions***: the number of when the distance between the robot and the human is $<$1.2 m.
2) ***Average minimum distance to the nearest agent***: the average distance from the boundary of the encountering robot/human to the

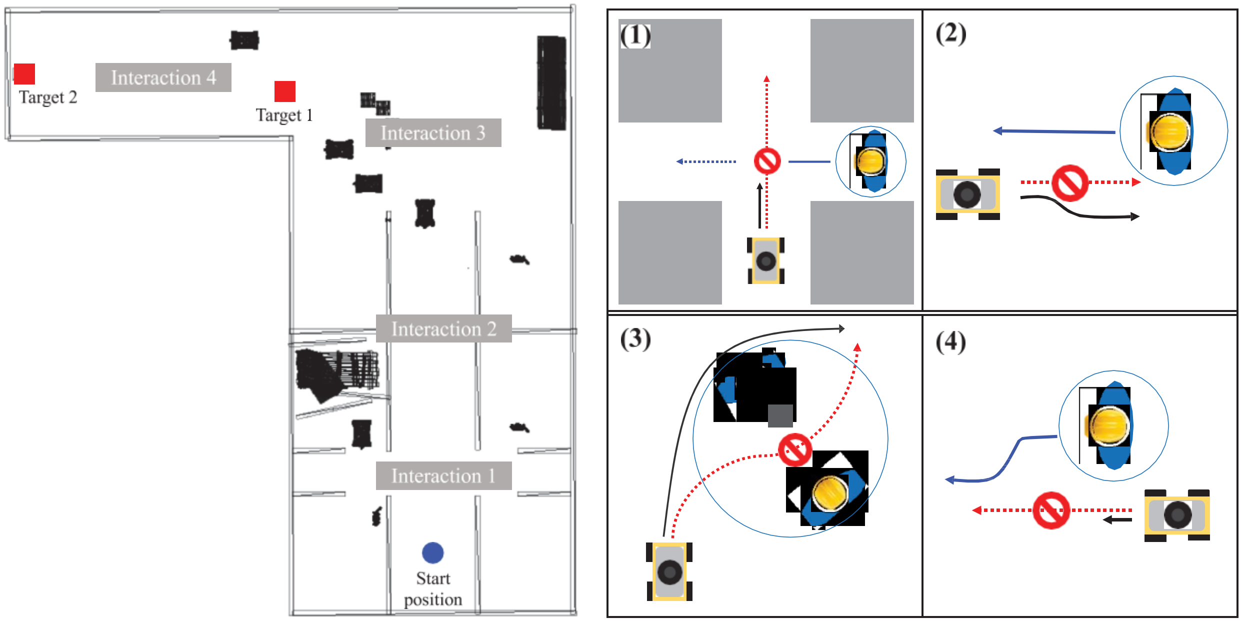

Fig. 3. Illustration of the simulation environment layout and the human-robot interactions: 1) Crossing, 2) Passing, 3) Group Interaction, and 4) Merging.

Fig. 4. Virtual construction site environment in Unity. Fig. 4(a) illustrates a trial when participants take a teleoperator role and navigate from a robot's point of view while encountering human NPCs. Fig. 4(b) illustrates a trial when participants take a human worker role and navigate from a human avatar's point of view while encountering robot NPCs.

boundary of the human/robot that a participant maintained during the interactions.

3) ***Total distance traveled***: the total navigation length a participant took during the interactions divided by the participant's average value.
4) ***Total navigation duration***: the total time (in seconds) a participant took to travel from the initial position to the end position divided by the participant's average value.

For data analysis, we conducted statistical tests to test the research hypotheses. First, we tested for normality using the Shapiro-Wilk test and homogeneity of variance using Levene's test. When normality and homoscedasticity assumptions are met, we performed a two-way Analysis of Variance (ANOVA) with a Tukey post hoc to examine the main and interaction effects of the WC and HRR. Otherwise, we performed the Wilcoxon Sign-Rank Test, which is a non-parametric version of the statistical test.

4. Results

4.1. Simulation environments manipulation test

To ensure the efficacy of our method, the immersiveness of the simulation environment is critical. To check whether participants perceived the simulation environment as we designed, we first measured participants' evaluation of the simulation environment using five 5-point Likert scale questionnaires. We asked about the perceived crowdedness of work conditions (Cronbach's alpha = 0.87). The ANOVA indicated that the participants' perceived work conditions were significantly different between the simulation environments ($F(1, 282) = 24.73$, $p < 0.001$, $\eta^2=0.08$) as illustrated in Fig. 5. This supports the hypothesis that we designed our simulation environment as intended, and the manipulation of work conditions did affect the participant's perception.

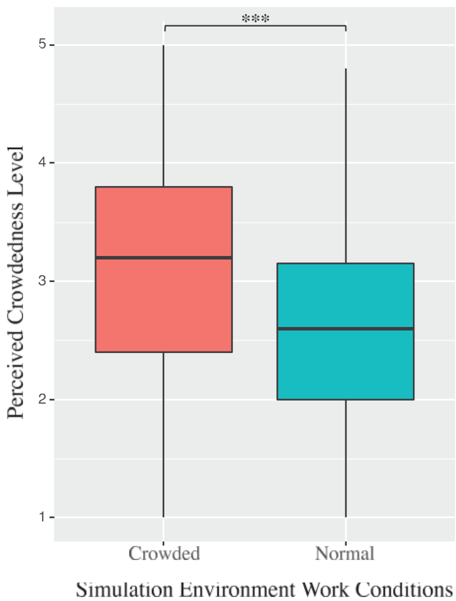

Fig. 5. The differences in participants' perceived crowdedness level for simulation environments, indicating a statistically significant difference in the perceived crowdedness for (1) crowded and (2) normal work conditions. ⋯ $p < 0.001$.

4.2. Analysis of proxemic behaviors

For H1a and H2a, we employed a Wilcoxon Sign-Rank Test because of the unmet homoscedasticity assumption. We found a significant effect of WC and HRR on the frequency of personal space intrusion, though the effect size was small, as summarized in Table 3, supporting H1a and H2a.

People more frequently intruded into the personal spaces of the human NPCs compared to robot NPCs, as illustrated in Fig. 6. The significant difference in the frequency of violation instances for different HRRs was corroborated by the differences in the minimum distance for different HRRs. For example, a greater distance was maintained from the robot NPCs (M = 1.65, SD = 0.61) compared to human NPCs (M = 1.49, SD = 0.61) while participants were passing their work zone ($F(3, 280) = 1.87$, $p = 0.02$). In the narrow corridors, there was also a significant increase in the lateral offset distance away from the approaching robot (M = 0.88, SD = 0.95) compared to human (M = 0.71, SD = 0.75), ($F(3, 280) = 1.21$, $p = 0.09$). During the post-interviews, several participants expressed their mistrust of robots, which led to a larger separation distance from robots. Unlike humans, who have an innate ability to sense the presence of others and swiftly react to their movement, robots were perceived as unsafe, struggling with collision avoidance, and prone to malfunctions. Due to the perceived incapabilities of robots, they opted for increased safety distances to avoid potential accidents.

> *"… robots are still not as agile as humans in adapting to unexpected situations."*

Regarding the WC, people were less likely to intrude into the personal spaces of others in crowded environments. While the average minimum distance people keep from others in the crowded environment was higher (M = 0.83, SD = 0.93) than in the normal environment (M =

Table 3
Wilcoxon Signed Rank test results on personal space intrusions. Results showed significant main effects of HRR and WC. · $p < 0.05$.

Measure	V	Effect size	p-value
HRR	4976	0.217	0.010 ·
WC	2885	0.172	0.037 ·

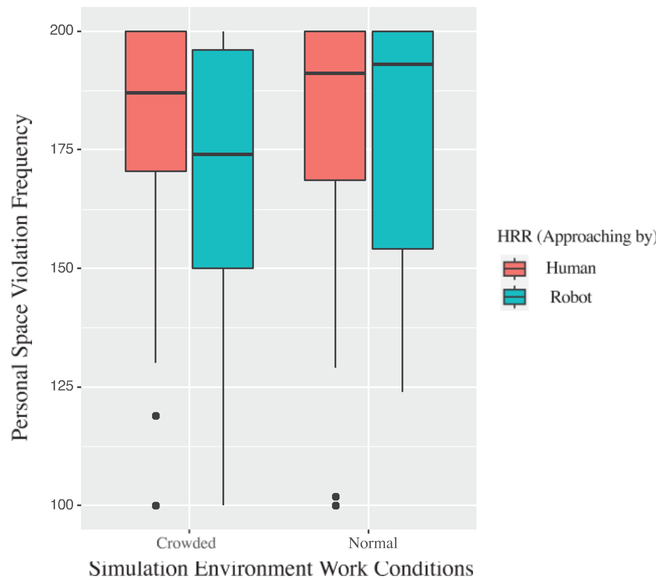

Fig. 6. The difference in frequency of personal space intrusion for each experiment condition.

0.74, SD = 0.77), the difference was not significant. In post-interview sessions, however, participants still conveyed their tendency to maintain a greater distance from those engaged in strenuous activities, such as carrying materials.

> *"If I'm just walking around, a robot walking close to me is okay. But if I'm working on something, I might need more space; so I'd say it's better to keep extra distance."*

4.3. Analysis of total navigation duration and path length

To test H1bc and H2bc, we conducted a two-way ANOVA to test the main and interaction effects of WC and HRR on navigation performances.

As for total navigation duration, a significant main effect of HRR on navigation duration was found ($F(3, 271) = 5.06$, $p = 0.001$), as

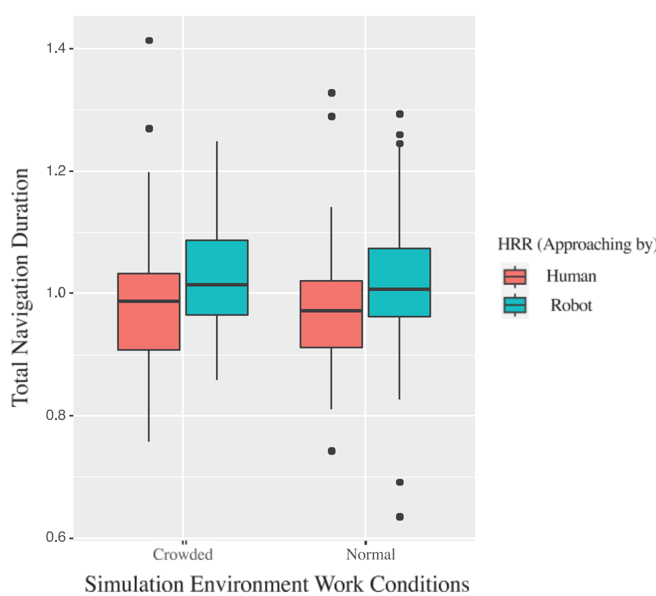

Fig. .. The difference in total navigation duration for each experiment condition.

illustrated in Fig. 7. This finding suggests that people tend to spend more time reaching target locations when encountering robot NPCs as opposed to human NPCs. This behavior was evident in intersection scenarios ($F(3, 271) = 8.94$, $p < 0.001$) and merging scenarios ($F(3, 271) = 5.24$, $p = 0.001$). At the intersection, participants generally yielded and waited for the robot passerby NPC to cross the intersection. The frequency of overtaking was significantly lower when approached by robots ($X^2(1) = 9.87$, $p = 0.001$). Similarly, in the merging case, they often waited until the robot NPC had overtaken and reached the target position first, resulting in fewer overtaking instances ($X^2(1) = 13.02$, $p < 0.001$). WC, however, did not have a significant effect of WC on the traveled duration, thus not supporting H1b. During the post-interview session, a participant explained that he was trying to "*get out of there as soon as possible"* in the crowded environment because he "*didn't want to get in anybody's way.*"

Regarding total navigation path length, a significant main effect was observed for HRR in support of H2c ($F(3, 271) = 18.28$, $p < 0.001$), and no significant main effect for WC or an interaction effect was found. As described in 4.2, participants tended to navigate around the work zone when they were approached by robots, leading to a significant increase in the path length in the group interaction scenario ($F(3, 271)$, $p < 0.001$). Similarly, in the passing scenario, a significant difference in the path length was also found for HRR ($F(3, 271) = 3.21, p = 0.02$) as well as for WC ($F(3, 271) = 3.21, p = 0.04$), indicating that people take larger lateral offset to the side when encountering a robot and in crowded environments. (See Fig. 8.)

4.4. *Mediation effect of perceived danger level*

For H3, we conducted a mediation analysis on the relation between proxemic behaviors and contextual factors with the perceived danger level as a mediator, using Baron and Kenny's approach [68]. We measured the participants' perceived danger level of the simulated job sites (Cronbach's alpha = 0.751) using four 5-point Likert scale questionnaires. To have a significant mediation effect, the effect of WC and HRR on proxemic behaviors should be decreased because the explained variance is lowered due to the perceived risks variance. Against our H3, perceived safety risk did not have a significant mediation effect, as depicted in Fig. 9.

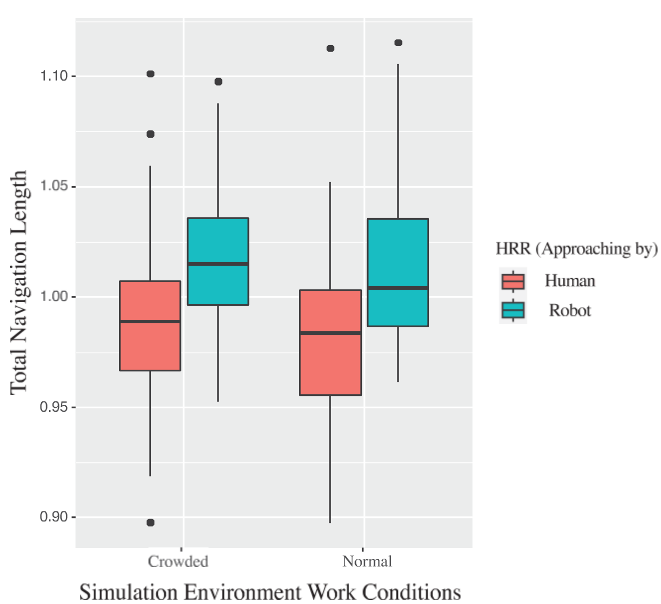

Fig. 8. The difference in total navigation path length for each experiment condition.

5. Discussions

5.1. *Considerations for new social norms for co-navigation*

The success of robot application in human-populated environments depends on the robot's ability to behave congruently with social expectations. The initial step toward developing socially appropriate robot behaviors involves understanding how human coworkers expect robots to behave in various work contexts. Our results suggested that the personal spaces imposed by proxemic rules are not fixed and the appropriate spatial behaviors of robots can and should be adaptable based on the contexts of the interaction. In crowded environments, people tend to prefer more passive spatial behaviors. A similar trend was observed when people interact with robots acting as passersby. The most conservative spatial behaviors were exhibited when they encountered robots in a crowded work environment. This suggests that people's perceptions of robot behavior appropriateness vary with context, and there is a need to explore the influence of other contextual factors on spatial behaviors.

Another noteworthy finding is that the perceived danger did not have a significant impact on governing spatial behaviors, though it was identified as an important factor in the human-robot proxemics literature [29]. Post-interview data suggests that one possible alternative explanation is the mistrust of robots. The trust level appears to be related to the perceived robot's capabilities. As described in Section 4.2, participants expressed their concerns about the robot's incapacity to detect and avoid collision quickly, which led them to take an extra safety buffer distance. They noted that enhancing the reliability and sensitivity of robots' onboard sensors to ensure robust collision prevention could foster trust.

"If a strong sense of trust is established between humans and robots, we might not need such a wide distance."

This finding offers practical implications for designing robot motion behaviors in workplaces. The *appropriate* distance is a dynamic concept, evolving as people interact with and acclimate to robots' behaviors. Consequently, the spatial strategies for robots should be constantly adjusted in response to shifts in users' trust levels. In the early phases, robot behaviors should be designed with safer proxemic strategies.

5.2. *Need for communicating navigational intents*

When navigating in a crowd, humans communicate their navigational intents through various means, including eye gaze, body postures, gestures, and verbal cues. These social cues are fundamental elements of proxemic behaviors, assisting people in coordinating with others. In construction work environments, practitioners often leverage both verbal and nonverbal social cues to communicate their navigational intent and to avoid potential collision risks. Thus, communicating intent to nearby workers is paramount in managing unforeseen changes and disruptions to ensure safety.

During the experiments, participants complained that the robots lacked such social cues and communication abilities, which made robot motions ununderstandable and unpredictable. Considering previous research, which highlighted that the lack of predictability can diminish trust levels [69], it is plausible that this unpredictability contributed to participants' low trust levels, provoking a larger separation distance. Overall, participants highlighted the importance of robots' communication functions to convey their navigational intent, which would enhance their understanding of robots' behaviors.

"If the robot can communicate like a human, then it's fine to keep a distance like with people. However, if it can't communicate, I believe it's better to keep a greater distance."

Regarding the potential communication interfaces, construction practitioners perceived direct and explicit methods, such as visual or

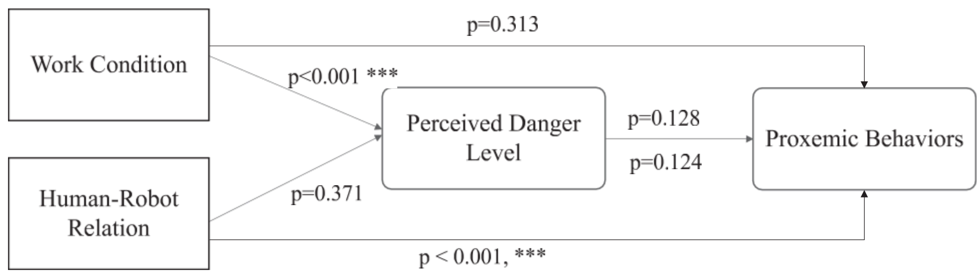

Fig. 9. Mediation analysis with perceived danger level as proposed mediators.

audio inputs, to be more effective than natural, subtle social signals like eye gaze although previous studies showed that social cues are more legible and thus more effective in communicating robots' intents to novice users [13,70]. For example, they found the projection of robot trajectories on the floor or a display screen useful, as these are already employed in current construction practices. Warning sounds were also deemed effective, especially when people have reduced visibility or attention level (e.g. when people accidentally get in the way while engaged in their tasks). Nonetheless, participants emphasized that both methods are limited and ineffective in certain situations. This implies that future research should examine the efficacy of various human-robot interface combinations within a specific work context.

5.3. Implications for worker's perception of robots as coworkers

Our findings revealed that participants suggested robots should operate and behave similarly to humans, and the same proxemic rules governing spatial movement in human-human interactions can and should be applied to human-robot interactions. This includes contextually appropriate distancing behaviors. This finding is significant because it indicates a shift in construction practitioners' perception of robots: they no longer perceive robots as threats but as potential future coworkers. In terms of proxemic rules, they held the same expectations for robots that mirror those they had for human coworkers in similar circumstances [67].

"It's like how people get trained on safety rules before they start working onsite. Robots should also made aware of human norms and rules."

This perspective aligns with the principles of The Media Equation [71] and findings from other research in HRI, which explain that people often perceive and respond to technology in ways similar to their interactions with humans. Participants also suggested that socially appropriate behaviors can foster more efficient co-navigation because they can make a better sense of human-like behaviors. Socially appropriate behaviors will enhance workers' ability to predict robot behaviors, and, in turn, people can incorporate the anticipated motions of robots into their path planning to achieve more fluent coordination.

"If the robot follows human norms, its behavior should be predictable like a human, so there may not be a need for a safety buffer."

6. Conclusion

The integration of robots at workplaces can transform traditional work conventions. In this study, we aimed to understand socially normative robot behaviors in future human-robot shared workplaces. We presented a human-subject study to analyze the effect of contextual factors on perceived appropriate proxemic behaviors during indirect human-robot interactions. The results revealed a tendency among construction practitioners to adopt safer proxemic behaviors when interacting with robots, while there was an implication that this perception may evolve as people gain more trust in robots.

From this study, we can derive practical recommendations on how to design natural, human-centric proxemic behaviors for autonomous robots working alongside humans. Such guidelines can improve the physical and psychological safety of workers. Moreover, our study contributes to the HRI domain by shedding light on the socially normative proxemic behaviors in indirect human-robot interactions, which were previously underexplored.

Nevertheless, our findings are subject to several limitations. First, the study was conducted within a virtual simulation environment displayed on a large screen. While studies suggest that a screen-based VR environment can offer a sense of immersion and is preferred by inexperienced users, the fidelity of the simulation environment could benefit from more advanced, high-fidelity virtual simulators. For instance, incorporating audio features in the VR simulation [72] or using head-mounted displays (HMDs) [73] could augment the participants' experience. These enriched experiences might lead to greater immersion, potentially yielding different findings, especially for experienced users. Secondly, we did not exhaustively investigate the impact of personal and robot-related factors, which could have a more pronounced influence on proxemic behaviors within the construction domain. For example, robot design aspects such as size or speed may affect human proxemic behaviors in safety-critical work environments although prior studies conducted in social settings did not find consistent significant effects of these factors [48,49]. In addition, individual attributes, such as prior experience or familiarity with robotic technologies, could also influence the outcomes in the construction work environments. While our study could not produce meaningful outcome findings regarding these factors, due to the imbalance in our dataset, future studies can elucidate the influence of these factors.

Lastly, our study primarily focused on initial interactions with autonomous mobile robots, considering that the majority of the current construction workforce has limited exposure to robotic technologies. We cannot ensure that our findings will be generalizable to future HRI scenarios in which people gain more experience and become more familiar with the capabilities and limitations of robots. Future research will investigate how human behaviors evolve with increased experience with robotic technologies in the real world.

CRediT authorship contribution statement

YeSeul Kim: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yilong Chen:** Visualization, Software. **HyunJin Yang:** Data curation. **Seungwoo Kim:** Data curation. **Sehoon Ha:** Conceptualization, Funding acquisition. **Matthew Gombolay:** Methodology, Funding acquisition, Conceptualization. **Yonghan Ahn:** Data curation, Funding acquisition. **Yong Kwon Cho:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

This material is based upon work supported by the U.S. National Science Foundation under Grant No. 2222723 and and the Ministry of Science and ICT through the National Research Foundation of Korea (NRF-2022H1D3A2A01093584). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the U.S. National Science Foundation and the National Research Foundation of Korea.

References

[1] Summary Report for Construction Laborers, ONet Online. https://www.onetonline.org/link/summary/47-2061.00 (accessed February 18, 2022).

[2] M. Kim, Y. Ham, C. Koo, T.W. Kim, Simulating travel paths of construction site workers via deep reinforcement learning considering their spatial cognition and wayfinding behavior, Autom. Constr. 147 (2023) 104715, https://doi.org/10.1016/j.autcon.2022.104715.

[3] P. Kim, J. Chen, J. Kim, Y.K. Cho, SLAM-driven intelligent autonomous mobile robot navigation for construction applications, in: I.F.C. Smith, B. Domer (Eds.), Advanced Computing Strategies for Engineering, Springer International Publishing, Cham, 2018, pp. 254–269, https://doi.org/10.1007/978-3-319-91635-4_14.

[4] K. Afsari, S. Halder, M. Ensafi, S. DeVito, J. Serdakowski, Fundamentals and prospects of four-legged robot application in construction progress monitoring, in: EPiC Series in Built Environment, EasyChair, 2021, pp. 274–283, https://doi.org/10.29007/cdpd.

[5] J.M. Davila Delgado, L. Oyedele, A. Ajayi, L. Akanbi, O. Akinade, M. Bilal, H. Owolabi, Robotics and automated systems in construction: understanding industry-specific challenges for adoption, J. Build. Eng. 26 (2019) 100868, https://doi.org/10.1016/j.jobe.2019.100868.

[6] M.-F.R. Lee, T.-W. Chien, Intelligent robot for worker safety surveillance: deep learning perception and visual navigation, in: 2020 International Conference on Advanced Robotics and Intelligent Systems (ARIS), 2020, pp. 1–6, https://doi.org/10.1109/ARIS50834.2020.9205772.

[7] R. Inoue, T. Arai, Y. Toda, M. Tsujimoto, K. Taniguchi, N. Kubota, Intelligent control for illuminance measurement by an autonomous mobile robot, in: 2019 IEEE International Conference on Advanced Robotics and Its Social Impacts (ARSO), 2019, pp. 270–274, https://doi.org/10.1109/ARSO46408.2019.8948806.

[8] M. Jin, S. Liu, S. Schiavon, C. Spanos, Automated mobile sensing: towards high-granularity agile indoor environmental quality monitoring, Build. Environ. 127 (2018) 268–276, https://doi.org/10.1016/j.buildenv.2017.11.003.

[9] D. Kim, S. Lee, V.R. Kamat, Proximity prediction of mobile objects to prevent contact-driven accidents in co-robotic construction, J. Comput. Civ. Eng. 34 (2020) 04020022, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000899.

[10] H. Izadi Moud, I. Flood, X. Zhang, B. Abbasnejad, P. Rahgozar, M. McIntyre, Quantitative assessment of proximity risks associated with unmanned aerial vehicles in construction, J. Manag. Eng. 37 (2021) 04020095, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000852.

[11] H.I. Moud, I. Flood, A. Shojaei, Y. Zhang, X. Zhang, M. Tadayon, M. Hatami, Qualitative Assessment of Indirect Risks Associated with Unmanned Aerial Vehicle Flights over Construction Job Sites, 2019, pp. 83–89, https://doi.org/10.1061/9780784482445.011.

[12] H.I. Moud, I. Flood, C. Capano, Y. Zhang, B. Abbasnejad, Safety of ground robot operations in construction job sites: A qualitative approach, in: Construction Research Congress 2020, American Society of Civil Engineers, Tempe, Arizona, 2020, pp. 1327–1335, https://doi.org/10.1061/9780784482865.140.

[13] G. Angelopoulos, A. Rossi, C.D. Napoli, S. Rossi, You are in my way: non-verbal social cues for legible robot navigation behaviors, in: 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, Kyoto, Japan, 2022, pp. 657–662, https://doi.org/10.1109/IROS47612.2022.9981754.

[14] B. Mutlu, J. Forlizzi, Robots in organizations: The role of workflow, social, and environmental factors in human-robot interaction, in: 2008 3rd ACM/IEEE International Conference on Human-Robot Interaction (HRI), 2008, pp. 287–294, https://doi.org/10.1145/1349822.1349860.

[15] D. Gallo, S. Gonzalez-Jimenez, M.A. Grasso, C. Boulard, T. Colombino, Exploring machine-like behaviors for socially acceptable robot navigation in elevators, in: 2022 17th ACM/IEEE International Conference on Human-Robot Interaction (HRI), 2022, pp. 130–138, https://doi.org/10.1109/HRI53351.2022.9889412.

[16] Y.S. Kim, B. Lee, R. Murphy, C.R. Ahn, Context-appropriate social navigation in various density construction environment using reinforcement learning, in: ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, IAARC Publications, Waterloo, Canada, 2021, pp. 505–512. https://www.proquest.com/docview/2642454765/abstract/429F86B75A734E60PQ/1 (accessed May 28, 2022).

[17] Y. Sun, I. Jeelani, M. Gheisari, Safe human-robot collaboration in construction: a conceptual perspective, J. Saf. Res. (2023), https://doi.org/10.1016/j.jsr.2023.06.006. S0022437523000804.

[18] L.A. Hayduk, Personal space: an evaluative and orienting overview, Psychol. Bull. 85 (1978) 117–134, https://doi.org/10.1037/0033-2909.85.1.117.

[19] Edward T. Hall, 1914–2009., The hidden dimension, 1st ed., Doubleday, Garden City, N.Y., 1966.

[20] D. Helbing, P. Moln´ar, Social force model for pedestrian dynamics, Phys. Rev. E 51 (1995) 4282–4286, https://doi.org/10.1103/PhysRevE.51.4282.

[21] J.R. Aiello, D.T. DeRisi, Y.M. Epstein, R.A. Karlin, Crowding and the role of interpersonal distance preference, Sociometry 40 (1977) 271–282, https://doi.org/10.2307/3033534.

[22] T.M. Ciolek, A. Kendon, Environment and the spatial arrangement of conversational encounters, Sociol. Inq. 50 (1980) 237–271, https://doi.org/10.1111/j.1475-682X.1980.tb00022.x.

[23] A. Kendon, Spacing and orientation in co-present interaction, in: A. Esposito, N. Campbell, C. Vogel, A. Hussain, A. Nijholt (Eds.), Development of Multimodal Interfaces: Active Listening and Synchrony: Second COST 2102 International Training School, Dublin, Ireland, March 23–27, 2009, Revised Selected Papers, Springer, Berlin, Heidelberg, 2010, pp. 1–15, https://doi.org/10.1007/978-3-642-12397-9_1.

[24] F. Lindner, C. Eschenbach, Towards a formalization of social spaces for socially aware robots, in: M. Egenhofer, N. Giudice, R. Moratz, M. Worboys (Eds.), Spatial Information Theory, Springer, Berlin, Heidelberg, 2011, pp. 283–303, https://doi.org/10.1007/978-3-642-23196-4_16.

[25] C. Sirithunge, H.M.R.T. Bandara, A.G.B.P. Jayasekara, D.P. Chandima, A probabilistic evaluation of human activity space for proactive approach behavior of a social robot, Paladyn, J. Behav. Robot. 12 (2021) 102–114, https://doi.org/10.1515/pjbr-2021-0006.

[26] S.-J. Guo, Identification and resolution of work space conflicts in building construction, J. Constr. Eng. Manag. 128 (2002) 287–295, https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(287).

[27] N.E. Neef, S. Zabel, M. Lauckner, S. Otto, What is Appropriate? On the Assessment of Human-Robot Proxemics for Casual Encounters in Closed Environment, 2022, https://doi.org/10.21203/rs.3.rs-2329385/v1.

[28] A. Sorokowska, P. Sorokowski, P. Hilpert, K. Cantarero, T. Frackowiak, K. Ahmadi, A.M. Alghraibeh, R. Aryeetey, A. Bertoni, K. Bettache, S. Blumen, M. Błaz˙ejewska, T. Bortolini, M. Butovskaya, F.N. Castro, H. Cetinkaya, D. Cunha, D. David, O. A. David, F.A. Dileym, A.C. del DomRnguez Espinosa, S. Donato, D. Dronova, S. Dural, J. Fialova´, M. Fisher, E. Gulbetekin, A. Hamamc1ogˇlu Akkaya, I. Hromatko, R. Iafrate, M. Iesyp, B. James, J. Jaranovic, F. Jiang, C.O. Kimamo, G. Kjelvik, F. KoT, A. Laar, F. de AraUjo Lopes, G. Macbeth, N.M. Marcano, R. Martinez, N. Mesko, N. Molodovskaya, K. Moradi, Z. Motahari, A. MVhlhauser, J.C. Natividade, J. Ntayi, E. Oberzaucher, O. Ojedokun, M.S.B. Omar-Fauzee, I. E. Onyishi, A. Paluszak, A. Portugal, E. Razumiejczyk, A. Realo, A.P. Relvas, M. Rivas, M. Rizwan, S. Salkiˇcevi´c, I. Sarma´ny-Schuller, S. Schmehl, O. Senyk, C. Sinding, E. Stamkou, S. Stoyanova, D. Sˇukolov´a, N. Sutresna, M. Tadinac, A. Teras, E.L. Tinoco Ponciano, R. Tripathi, N. Tripathi, M. Tripathi, O. Uhryn, M. E. Yamamoto, G. Yoo, J.D. Pierce, Preferred interpersonal distances: a global comparison, J. Cross-Cult. Psychol. 48 (2017) 577–592, https://doi.org/10.1177/0022022117698039.

[29] P. Salvini, D. Paez-Granados, A. Billard, On the Safety of Mobile Robots Serving in Public Spaces: Identifying gaps in EN ISO 13482:2014 and calling for a new standard, J. Hum.-Robot Interact 10 (2021), https://doi.org/10.1145/3442678, 19:1–19:27.

[30] J.T. Chuan Tan, F. Duan, Y. Zhang, R. Kato, T. Arai, Safety design and development of human-robot collaboration in cellular manufacturing, in: 2009 IEEE International Conference on Automation Science and Engineering, 2009, pp. 537–542, https://doi.org/10.1109/COASE.2009.5234120.

[31] B. Leichtmann, V. Nitsch, How much distance do humans keep toward robots? Literature review, meta-analysis, and theoretical considerations on personal space in human-robot interaction, J. Environ. Psychol. 68 (2020) 101386, https://doi.org/10.1016/j.jenvp.2019.101386.

[32] V. Villani, F. Pini, F. Leali, C. Secchi, Survey on human–robot collaboration in industrial settings: safety, intuitive interfaces and applications, Mechatronics 55 (2018) 248–266, https://doi.org/10.1016/j.mechatronics.2018.02.009.

[33] E. Pacchierotti, H.I. Christensen, P. Jensfelt, Evaluation of passing distance for social robots, in: ROMAN 2006 - The 15th IEEE International Symposium on Robot and Human Interactive Communication, 2006, pp. 315–320, https://doi.org/10.1109/ROMAN.2006.314436.

[34] E. Pacchierotti, H.I. Christensen, P. Jensfelt, Human-robot embodied interaction in hallway settings: a pilot user study, in: ROMAN 2005. IEEE International Workshop on Robot and Human Interactive Communication 2005, 2005, pp. 164–171, https://doi.org/10.1109/ROMAN.2005.1513774.

[35] M.L. Walters, K. Dautenhahn, K.L. Koay, C. Kaouri, R. Boekhorst, C. Nehaniv, I. Werry, D. Lee, Close encounters: spatial distances between people and a robot of

mechanistic appearance, in: 5th IEEE-RAS International Conference on Humanoid Robots, 2005, 2005, pp. 450–455, https://doi.org/10.1109/ICHR.2005.1573608.

[36] Human-Robot Interaction in Assisted Personal Services: Factors Influencing Distances That Humans Will Accept between Themselves and an Approaching Service Robot: Human Factors in Ergonomics & Manufacturing Vol 26, 2023, https://doi.org/10.1002/hfm.20675. No 6. (accessed May 6, 2024).

[37] M. Obaid, E.B. Sandoval, J. Złotowski, E. Moltchanova, C.A. Basedow, C. Bartneck, StopW That is close enough. How body postures influence human-robot proximity, in: 2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), 2016, pp. 354–361, https://doi.org/10.1109/ROMAN.2016.7745155.

[38] J.S. Hyde, The gender similarities hypothesis, Am. Psychol. 60 (2005) 581–592, https://doi.org/10.1037/0003-066X.60.6.581.

[39] M.L. Walters, K. Dautenhahn, R. te Boekhorst, K.L. Koay, C. Kaouri, S. Woods, C. Nehaniv, D. Lee, I. Werry, The influence of subjects' personality traits on personal spatial zones in a human-robot interaction experiment, in: ROMAN 2005. IEEE International Workshop on Robot and Human Interactive Communication 2005, 2005, pp. 347–352, https://doi.org/10.1109/ROMAN.2005.1513803.

[40] S. Rossi, M. Staffa, L. Bove, R. Capasso, G. Ercolano, in: A. Kheddar, E. Yoshida, S. S. Ge, K. Suzuki, J.-J. Cabibihan, F. Eyssel, H. He (Eds.), User's personality and Activity Influence on HRI Comfortable Distances, Springer International Publishing, Cham, 2017, pp. 167–177, https://doi.org/10.1007/978-3-319-70022-9_17.

[41] L. Takayama, C. Pantofaru, Influences on proxemic behaviors in human-robot interaction, in: 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2009, pp. 5495–5502, https://doi.org/10.1109/IROS.2009.5354145.

[42] J. Mumm, B. Mutlu, Human-robot proxemics: Physical and psychological distancing in human-robot interaction, in: 2011 6th ACM/IEEE International Conference on Human-Robot Interaction (HRI), 2011, pp. 331–338, https://doi.org/10.1145/1957656.1957786.

[43] H. Lehmann, A. Rojik, M. Hoffmann, Should a small robot have a small personal space? Investigating personal spatial zones and proxemic behavior in human-robot interaction, 2020.

[44] M.L. Walters, D.S. Syrdal, K. Dautenhahn, R. te Boekhorst, K.L. Koay, Avoiding the uncanny valley: robot appearance, personality and consistency of behavior in an attention-seeking home scenario for a robot companion, Auton. Robot. 24 (2008) 159–178, https://doi.org/10.1007/s10514-007-9058-3.

[45] C. Brandl, A. Mertens, C.M. Schlick, Human-robot interaction in assisted personal services: factors influencing distances that humans will accept between themselves and an approaching service robot, Human Factors Ergon. Manuf. Service Industr. 26 (2016) 713–727, https://doi.org/10.1002/hfm.20675.

[46] G. Trovato, R. Paredes, J. Balvin, F. Cuellar, N.B. Thomsen, S. Bech, Z. Tan, The sound or silence: investigating the influence of robot noise on proxemics, in: 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), 2018, pp. 713–718, https://doi.org/10.1109/ROMAN.2018.8525795.

[47] J.T. Butler, A. Agah, Psychological effects of behavior patterns of a mobile personal robot, Auton. Robot. 10 (2001) 185–202, https://doi.org/10.1023/A:1008986004181.

[48] D.S. Syrdal, K. Lee Koay, M.L. Walters, K. Dautenhahn, A personalized robot companion? - The role of individual differences on spatial preferences in HRI scenarios, in: RO-MAN 2007 - The 16th IEEE International Symposium on Robot and Human Interactive Communication, 2007, pp. 1143–1148, https://doi.org/10.1109/ROMAN.2007.4415252.

[49] M. Walters, The Design Space for Robot Appearance and Behaviour for Social Robot Companions, Doctoral dissertation, University of Hertfordshire Research Archive, 2008.

[50] D.S. Syrdal, K. Dautenhahn, M.L. Walters, K.L. Koay, Sharing spaces with robots in a home scenario - Anthropomorphic attributions and their effect on proxemic expectations and evaluations in a live HRI trial, 2008, pp. 116–123.

[51] S. Worchel, The influence of contextual variables on interpersonal spacing, J. Nonverbal Behav. 10 (1986) 230–254, https://doi.org/10.1007/BF00987482.

[52] B. Leichtmann, A. Lottermoser, J. Berger, V. Nitsch, Personal space in human-robot interaction at work: effect of room size and working memory load, J. Hum.-Robot Interact. (2022) 3536167, https://doi.org/10.1145/3536167.

[53] M.L. Walters, Robot to Human Approaches: Preliminary Results on Comfortable Distances and Preferences, 2007.

[54] T. Iachini, Y. Coello, F. Frassinetti, G. Ruggiero, Body space in social interactions: a comparison of reaching and comfort distance in immersive virtual reality, PLoS One 9 (2014) e111511, https://doi.org/10.1371/journal.pone.0111511.

[55] H.A. Yanco, J. Drury, Classifying human-robot interaction: an updated taxonomy, in: 2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No.04CH37583) vol.3, 2004, pp. 2841–2846, https://doi.org/10.1109/ICSMC.2004.1400763.

[56] Y. Kim, B. Mutlu, How social distance shapes human–robot interaction, Int. J. Human-Comput. Stud. 72 (2014) 783–795, https://doi.org/10.1016/j.ijhcs.2014.05.005.

[57] M. To¨rner, A. Pousette, Safety in construction – a comprehensive description of the characteristics of high safety standards in construction work, from the combined perspective of supervisors and experienced workers, J. Saf. Res. 40 (2009) 399–409, https://doi.org/10.1016/j.jsr.2009.09.005.

[58] M.M.E. Neggers, R.H. Cuijpers, P.A.M. Ruijten, Comfortable passing distances for robots, in: S.S. Ge, J.-J. Cabibihan, M.A. Salichs, E. Broadbent, H. He, A.R. Wagner, A´. Castro-Gonz´alez (Eds.), Social Robotics, Springer International Publishing, Cham, 2018, pp. 431–440, https://doi.org/10.1007/978-3-030-05204-1_42.

[59] S.-Y. Lo, K. Yamane, K. Sugiyama, Perception of pedestrian avoidance strategies of a self-balancing mobile robot, in: 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2019, pp. 1243–1250, https://doi.org/10.1109/IROS40897.2019.8968191.

[60] B. Leichtmann, A. Lottermoser, J. Berger, V. Nitsch, Personal space in human-robot interaction at work: effect of room size and working memory load, J. Hum.-Robot Interact. 11 (2022) 1–19, https://doi.org/10.1145/3536167.

[61] E. Torta, R.H. Cuijpers, J.F. Juola, Design of a parametric model of personal space for robotic social navigation, Int. J. Soc. Robot. 5 (2013) 357–365, https://doi.org/10.1007/s12369-013-0188-9.

[62] C. Bartneck, D. Kuli´c, E. Croft, S. Zoghbi, Measurement instruments for the anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety of robots, Int. J. Soc. Robot. 1 (2009) 71–81, https://doi.org/10.1007/s12369-008-0001-3.

[63] J. Cohen, Statistical Power Analysis for the Behavioral Sciences /, Second edition, L. Erlbaum Associates, Hillsdale, N.J, 1988.

[64] Y. Kim, H. Kim, R. Murphy, S. Lee, C.R. Ahn, Delegation or collaboration: understanding different construction Stakeholders' perceptions of robotization, J. Manag. Eng. 38 (2022) 04021084, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000994.

[65] H. USA, Jaibot Drilling Robot. https://www.hilti.com/content/hilti/W1/US/en/business/business/trends/jaibot.html (accessed December 21, 2023).

[66] Canvas I The Future of Construction. https://www.canvas.build/, 2020 (accessed June 3, 2021).

[67] R.M. Baron, D.A. Kenny, The moderator-mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations, J. Pers. Soc. Psychol. 51 (1986) 1173–1182, https://doi.org/10.1037//0022-3514.51.6.1173.

[68] S. Nikolaidis, D. Hsu, S. Srinivasa, Human-robot mutual adaptation in collaborative tasks: models and experiments, Int. J. Robot. Res. 36 (2017) 618–634, https://doi.org/10.1177/0278364917690593.

[69] R. Fernandez, N. John, S. Kirmani, J. Hart, J. Sinapov, P. Stone, Passive demonstrations of light-based robot signals for improved human interpretability, in: 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), IEEE, Nanjing, 2018, pp. 234–239, https://doi.org/10.1109/ROMAN.2018.8525728.

[70] B. Reeves, The Media Equation: How People Treat Computers, Television, and New Media like Real People and Places /, CSLI Publications, Stanford, Calif, 1996.

[71] How sounds influence user safety decisions in a virtual construction simulator, Saf. Sci. 86 (2016) 184–194, https://doi.org/10.1016/j.ssci.2016.02.018.

[72] T. Iachini, Y. Coello, F. Frassinetti, V.P. Senese, F. Galante, G. Ruggiero, Peripersonal and interpersonal space in virtual and real environments: effects of gender and age, J. Environ. Psychol. 45 (2016) 154–164, https://doi.org/10.1016/j.jenvp.2016.01.004.