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Assessing proxemics impact on Human-Robot collaboration safety in construction: A virtual reality study with four-legged robots

Gilles Albeaino [a,*], Idris Jeelani [b], Masoud Gheisari [b], Raja R.A. Issa [b]

[a] Department of Construction Science, Texas A&M University, 3137 TAMU, College Station, TX 77843, USA

[b] M.E. Rinker, Sr. School of Construction Management, University of Florida, 573 Newell Dr, Gainesville, FL 32603, USA

ABSTRACT

Recent advancements in four-legged robots have prompted their integration into the construction industry, yet the safety implications of their deployment remain inadequately explored. As such comprehensive investigations are required to ensure the safety of robot deployment and the well-being of construction professionals who work with and alongside these robots. This study addresses this gap by conducting a user-centered experiment employing virtual reality to assess human behavior and safety impacts in varying interaction spaces with four-legged robots within a simulated construction environment. By employing objective and subjective measures, including physiological and attentional responses, emotional reactions, situational awareness, risk perceptions, and attitudes towards robots, this study analyzes the impact of proxemics on construction individuals at two distinct interaction spaces: proximal (1.5 – 4 ft) and distal (12 – 25 ft) from the four-legged robots. The study found that while participants' physiological responses, emotional states, situational awareness, risk perceptions, and attitudes towards robots were not significantly influenced by four-legged robot interaction space, those in the distal group allocated significantly more attention to the robot, particularly in terms of fixation count, indicating a significant proxemics impact on attentional states. These findings shed light on the safety implications of human-robot collaboration on jobsites, contributing to the advancement of safe and efficient practices in construction settings.

1. Introduction

The construction industry has long been recognized as one of the most hazardous sectors to work in, characterized by a concerning prevalence of mental health issues among its workforce (Brown et al., 2022). It also accounts for some of the highest rates of injuries and deaths compared to other industries. In recent years, there has been a persistent and troubling trend of fatalities within the construction industry, with the sector consistently ranking among the highest in terms of occupational deaths in the US, accounting for 18 % of the total reported workplace fatalities in 2021, and rising to 19 % in 2022 (Bls, 2022). At the same time, in response to the stagnant productivity rates and skilled labor shortages within the sector (Hasan et al., 2018), there has been a growing trend towards integrating automation and robotics into daily construction operations. This integration was not achievable until recent years due to advancements in engineering, robotics, and sensor technology, which have enabled the deployment of automation and robotics within the dynamic environment of construction sites. Mobile collaborative robots, ranging from aerial vehicles such as drones to ground-based robots like wheeled vehicles, are currently becoming increasingly integrated into the industry. Among these, four-legged robots, also known as quadrupeds, have attracted attention for their suitability and versatility in the dynamic conditions characterizing construction environments. This type of robot offers several advantages, including the ability to navigate complex environments, traverse rough terrains, climb stairs, overcome onsite obstacles, and support a wide variety of sensors to accomplish various construction tasks (Halder et al., 2022). Four-legged robot applications range from progress monitoring (Halder et al., 2022; Afsari et al., 2022; Halder et al., 2021) and safety management (Kim et al., 2022) to material handling (Sustarevas et al., 2018) and the inspection of structures and infrastructure (Halder et al., 2023; Jang et al., 2022). Given the wide range of current and potential four-legged robot applications, their collaboration with human counterparts is anticipated to grow, leading to more frequent and intensive interactions on construction sites, where humans and robots are expected to work closely together to accomplish various tasks efficiently and safely.

A significant amount of research has explored the potential applications, benefits, and opportunities of deploying four-legged robots in construction processes to replace or complement traditional methods (Afsari et al., 2021; Sun et al., 2023). However, despite the increasing deployment of these robots on jobsites and their numerous advantages, the dynamic and unpredictable nature of these environments necessitates a thorough examination of safe coexistence and collaboration

* Corresponding author at: 3137 TAMU, College Station, TX 77843, USA.
E-mail addresses: gilles.albeaino@tamu.edu (G. Albeaino), idris.jeelani@ufl.edu (I. Jeelani), masoud@ufl.edu (M. Gheisari), raymond-issa@ufl.edu (R.R.A. Issa).

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between robots and humans. Interactions between construction individuals and mobile ground robots introduce new variables into the already complex, dynamic, and hazardous construction environment, with evidence suggesting that these interactions can lead to physical, psychological, and attentional risks that might result in hazardous situations (Sun et al., 2023). For effective integration into human environments, robots must adhere to societal norms of physical and psychological distancing to respect personal space (Takayama and Pantofaru, 2009; Mumm and Mutlu, 2011). On construction sites, where interactions between humans and robots are becoming more frequent and complex, maintaining appropriate proxemic behavior and following established human social interaction protocols is crucial for minimizing safety risks and ensuring effective collaboration. Since human-robot interactions vary on jobsites, understanding human spatial behavior around robots and its effects on individuals is vital for ensuring the safety of construction personnel. Four-legged robots are anticipated to operate in diverse interaction spaces, engaging in tasks that require both proximal (e.g., construction and material handling) and distal (e.g., progress monitoring) interactions. Consequently, construction individuals may have different proxemic preferences, which can influence and be influenced by the physical, psychological, and attentional risks associated with robot interactions at various distances. This highlights the need to study how human proxemic preferences affect and are affected by robots operating at different distances in construction environments, to better understand and mitigate these risks.

Acknowledging the importance of understanding and mitigating the safety risks associated with integrating mobile collaborative (i.e., aerial and ground) robots in construction, several studies have examined the integration of these robots in construction workplaces from a health and safety perspective (Sun et al., 2023; Jeelani and Gheisari, 2021; Zhu et al., 2023; Albeaino et al., 2023; Nassar et al., 2024; Albeaino et al., 2023). Very few other studies have also been conducted within the construction domain to understand how spatial relationships impact HRI safety. For example, Albeaino et al. relied upon VR to assess the health and safety challenges of construction professionals along with their proxemics preferences while working at different distances from drones (Albeaino et al., 2023). While this study revealed that drone presence affected physiological responses and task attention, with drones at greater distances causing more distraction than those in close proximity, it focused solely on aerial robots. The findings may not fully translate or be directly applicable to ground-based four-legged robots, as it is well-established in the Human-Robot Interaction (HRI) literature that differing robot characteristics – such as type (aerial vs. ground), appearance, and shape – can result in different interaction dynamics and proxemic behaviors (Samarakoon et al., 2022). In addition, Kim et al. investigated the perceived appropriate proxemic behaviors of robots by examining construction practitioners' spatial behaviors during interactions with ground robots in a screen-based virtual reality (VR) construction site environment (Kim et al., 2024a,b). The findings showed that subjects maintained larger separation distances in crowded work conditions, and when encountering robots as passersby as opposed to when encountering humans. However, the study relied only on simulation logs for proxemic behavior analysis, without assessing human psychophysiological states. The latter is crucial for understanding psychological and attentional impacts associated with interacting at different distances from four-legged robots on construction sites. A recent study analyzed trust dynamics in human–robot collaboration within a VR construction environment, considering factors such as workspace environment, level of interaction, proximity, speed, and angle of approach (Chauhan et al., 2024). While the study highlighted the impact of proximity on trust, the results might be influenced by the simultaneous examination of other variables, making it difficult to isolate the specific effects of proxemics on construction individuals. This underscores the need for focused research on ground-based robots' proxemics to better understand and mitigate construction safety risks.

This user-centered experiment relied upon VR to empirically evaluate human behavior and safety impact at varying interaction distances (i.e., proxemics) from four-legged robots while performing a construction task in a simulated environment. This study focuses specifically on the attentional and psychological risks, two of the potential risks associated with four-legged robot deployment on construction sites. Specifically, the objective is to examine the safety implications of four-legged robots on construction sites by evaluating, through a between-subject experiment design, individuals' physiological, attentional, and emotional states, along with their situational awareness, risk perception, and attitudes towards robots when working at different interaction spaces from these robots. This comprehensive evaluation employs a combination of physiological monitoring sensors, eye-tracking enabled wearable devices, and validated survey questionnaires to provide both objective and subjective measures of participant responses. Given that the interaction dynamics between humans and robots vary depending on the application context, and considering the nature of the four-legged robot's movement, this study defines two interaction spaces based on Hall's human–human interaction distances (i.e., 1.5 ft, 4 ft, 12 ft, and 25 ft) (Hall, 1969). These distances have been widely utilized in Human-Robot Interaction (HRI) research when studying human proxemics preferences while interacting with robots (Samarakoon et al., 2022). The interaction spaces were defined as follows: (1) Proximal space (1.5 ft to 4 ft); and (2) Distal space (12 ft to 25 ft). The research seeks to answer the following questions:

- Does the four-legged robot interaction space (proximal and distal) have an impact on the physiological, attentional, and emotional states of construction individuals?
- Does the four-legged robot interaction space (proximal and distal) have an impact on construction individuals' risk perception, attitudes towards robots, and situational awareness?

VR was used in this study for several reasons, including the ability to simulate somehow futuristic HRI scenarios and conduct experiments in a controlled, repeatable, and safe manner (Bretin et al., 2022). First, conducting experiments in real-world construction environments presents numerous challenges. These challenges include the futuristic nature of human-robot interactions – as not all construction sites are adopting robots yet – and the relatively early stage of four-legged robot deployment in construction. Additionally, collecting data specific to the interaction between humans and robots while controlling for external factors typically present on site could be difficult, especially in a dynamically changing environment such as the construction jobsite. Moreover, conducting such experiments in real-world construction sites can pose safety hazards for human subjects, particularly when exploring the safety impacts of mobile collaborative robots interacting with them in the proximal (1.5 ft to 4 ft) space. This has been highlighted in previous studies exploring HRI proxemics, which have encountered limitations due to safety concerns and regulatory constraints, and had to employ various techniques, such as adding barriers between human subjects and the robots (Henkel et al., 2014), conducting laboratory experiments to control for external factors during the experiment (Takayama and Pantofaru, 2009), or did not test on specific distances due to their closeness to human subjects as mandated by Institutional Review Boards (Albeaino et al., 2023). Such constraints can influence participant behavior and compromise the validity of findings (Bretin et al., 2022). Utilizing VR circumvents these limitations by enabling safer and more controlled experiments without the need for artificial barriers, thereby ensuring the validity of the results. It should be also noted that that previous research showed that people elicit similar psychophysiological responses in VR compared to real-world experimentation (Simeonov et al., 2005). By studying the impact of four-legged robot proxemics in construction, this study helps advance the understanding and implementation of safe and efficient human-robot collaboration within the construction industry while offering insights that could ultimately inform and support future efforts focusing on proposing safety-related regulations for mobile collaborative robot deployment, identifying avenues for enhancing robot design, and recommending targeted training interventions for the workforce to ensure they are prepared for the rapid integration of mobile robots in construction. The rest of the paper is structured as follows. First, a background pertaining to the use of four-legged robots in construction is discussed, covering their applications, deployment challenges, and associated safety risks. This is followed by the adopted methodology, which includes scenario identification, VR development, and assessment. Subsequently, the results obtained from the study are presented and discussed. Finally, a conclusion is provided with a summary of the findings and their implications for the safe deployment of four-legged robots in construction.

2. Theoretical Underpinnings

In addition to Edward Hall's foundational work on proxemics (Hall, 1969), which has significantly influenced research in HRI proxemics (Samarakoon et al., 2022), the impact of four-legged robots on the health and safety of construction professionals is primarily examined through the lenses of System Safety Theory (Leveson, 2020) and Social Construction of Technology theory (Pinch and Bijker, 1984). A construction site can be considered an integrated system where various components such as individuals, robots, equipment, and management interact dynamically. According to System Safety Theory (Leveson, 2020), safety is an emergent property influenced primarily by the interactions and interdependencies among system components rather than solely by their individual characteristics (Larsson et al., 2010). This emergent safety property is shaped by a set of parameters related to the design, operation, and the behavior of different system components. This perspective challenges the notion that optimizing individual components in isolation will necessarily optimize overall system safety, underscoring the critical importance of understanding how these components interact and influence safety outcomes in complex environments like construction sites. Applying System Safety Theory to this user-centered experiment involves examining how interactions between humans and four-legged robots at different operational distances influence individuals' safety and well-being, ultimately helping to identify potential hazards and safety impacts arising from these interactions. The spatial dynamics between the four-legged robots and humans can significantly influence safety outcomes and cause accidents on construction sites, especially since individuals in close proximity to these robots may exhibit different behaviors compared to those farther away.

SCOT theory provides a lens through which to evaluate the integration of four-legged robots into the social environment of construction sites. The SCOT theory posits that technology is not developed in isolation but is deeply embedded in its social context (Pinch and Bijker, 1984). According to SCOT, the acceptance, use, and ultimate success or failure of a technology are shaped by the interactions and negotiations among various social groups, each with their own interests and perspectives. This theory argues that to understand technology acceptance (or rejection), it is important to evaluate its integration in the social world that includes all technology stakeholders. This theory argues that it is human action that shapes technology, rather than technology determining human behavior. The benefits of a technology, while often highlighted by its developers and promoters, must be examined from the standpoint of all affected groups to gain a comprehensive understanding of its impact. It is crucial to understand who defines the benefits of a technology and which groups participate in this process. For example, while construction managers and site owners may highlight the advantages of four-legged robots in terms of increased efficiency and cost savings, it is equally important to evaluate how these robots impact the workers who are in direct contact with them. Building upon the framework of the SCOT theory, this study emphasizes the necessity of considering the social context within which four-legged robots are integrated into construction environments. Human action and social dynamics significantly shape technology usage, thereby impacting its efficacy and safety on construction sites. This study aims to address potential biases by not only assessing the managerial viewpoint but also by investigating the proxemics-related behavioral and safety implications for construction personnel. By incorporating the insights of SCOT, the study acknowledges that understanding the real-world impacts of four-legged robots necessitates a holistic approach that considers the experiences of all stakeholders, particularly those who may not have a direct role in the development of these technologies but are significantly affected by their deployment.

3. Background

3.1. Applications of four-legged robots in construction

Despite the relatively recent deployment of four-legged robots in the construction industry (Fig. 1), their application is rapidly gaining traction, with more and more tasks emerging on jobsites. In the construction phase of a project, four-legged robots have been mainly used for progress monitoring, safety management, as well as construction and material handling. In the post-construction phase, four-legged robots have been used for structure and infrastructure inspection.

Construction phase: In the construction phase, four-legged robots are becoming widely used in construction progress monitoring tasks (Halder et al., 2022; Afsari et al., 2022; Halder et al., 2021). The use of small collaborative four-legged robots for construction progress monitoring tasks was explored by Afsari et al. (Afsari et al., 2021) who deployed a four-legged mobile robot equipped with a 360° camera to automate data collection process while monitoring construction progress. Despite highlighting different robot mobility-related onsite safety concerns, the authors indicated that the deployed robot has the advantages of providing accurate, consistent, and better-quality construction progress images while reducing labor and time. Four-legged robots have also been used for automated material tracking on construction jobsites (Wetzel et al., 2022). In terms of the use of four-legged robots for construction safety, and to eliminate the subjective scaffold inspection process that safety managers typically perform on site, Kim et al. (Kim et al., 2022) successfully relied upon four-legged robot-generated 3D point cloud data and semantic segmentation for the reconstruction of scaffolds. In addition, in jobsite locations where hazardous materials exist, four-legged robots can be deployed to identify and assess conditions and threats from a stand-off distance, ensuring construction individuals' safety (Boston Dynamics, 2021). Four-legged robots have also been assisting in construction type of tasks. Specifically, and although limited to trajectory-related performance tests, Sustarevas et al. (Sustarevas et al., 2018) relied upon an agile and independent four-legged robot that is potentially capable of 3D printing large structures. If equipped with robotic arms, four-legged robots could assist in material (e.g., bricks, CMUs, tools) pickup and handling (Bellicoso et al., 2019).

Post-construction phase: In the post-construction phase, four-legged robots have been relied upon for inspection tasks (Halder et al., 2023). For example, Bellicoso et al. (Bellicoso et al., 2018) successfully deployed and tested the capabilities of their four-legged robot in autonomously performing oil and gas site inspection tasks. Recent studies have successfully combined a 360° camera-equipped four-legged robot, Building Information Modeling (BIM), and a Unity® game engine to simultaneously visualize a 3D environment, plan missions, and digitally control the ground robot using Unity® to accomplish less labor-intensive and more efficient construction inspection tasks (Halder et al., 2021; Halder and Afsari, 2022). Kolvenbach et al. (2020) relied upon a four-legged robot to inspect concrete deterioration in sewer systems to improve sewer system inspection efficiency and prevent humans from manually walking through them. Results showed that the robot could accomplish high levels of concrete deterioration estimation accuracy. More recently, Jang et al. (2022) developed a four-legged

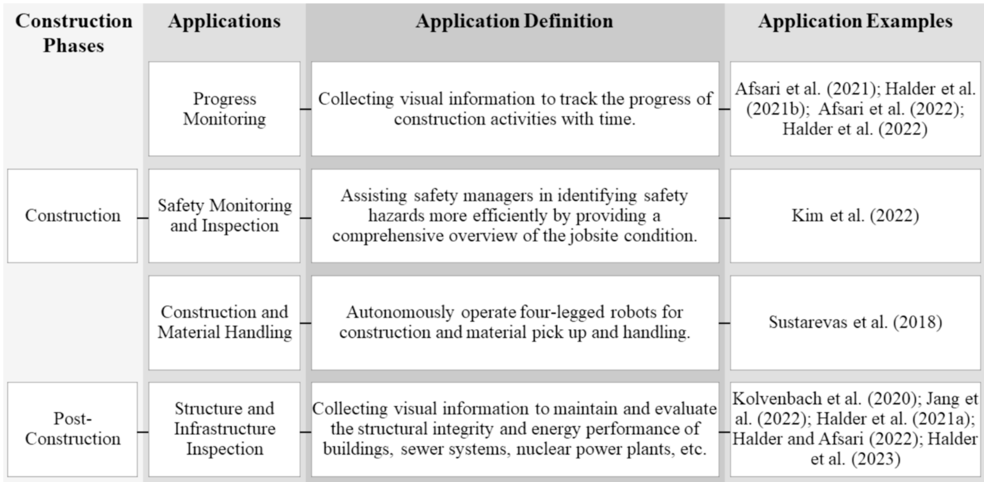


Fig. 1. Applications of four-legged robots in construction.

robot for nuclear power plant underground pipeline inspections and crack detection. Stated advantages over traditional and more manual inspection methods include overcoming safety limitations such as harmful gas emission, air quality deterioration, and preventing humans from working in dark and confined environments.

3.2. Deployment challenges of four-legged robots on construction sites

Challenges pertaining to four-legged robots have not been fully explored yet in construction, especially since this type of collaborative ground robot has just recently been started to be used on jobsites. Nevertheless, the deployment challenges of four-legged robots have been identified through an extensive literature review and categorized into four distinct groups: (1) robot-related, (2) regulations-related, (3) environment-related, and (4) human-related (Table 1).

Robot-related challenges: When deploying four-legged robots on jobsites, Afsari et al. (2021) indicated that these types of robots cannot be currently operated without human intervention and that they should always be accompanied by humans to ensure proper navigation and operation. This was even evidenced by the guidelines proposed by the manufacturer (Boston Dynamics, 2021), requiring all time human supervision during robot operation. This prevents four-legged robots from navigating and inspecting in a fully autonomous mode on jobsites. In this regard, the onboard and ground technologies need to be optimized to ensure proper and fully autonomous navigation without human intervention. This is an essential component to avoid robot collision with material, equipment, and people that could result in damage, injuries, or even fatalities. In addition, the onboard and ground sensors, hardware components, and technologies need to be optimized to overcome current robot-control station communication problems which constituted a challenge when deploying four-legged robots for construction progress monitoring tasks (Afsari et al., 2021). More simple ground control station and autonomous waypoint navigation, which currently cannot be modified once the autonomous path has been set pre-mission (Afsari et al., 2021), are also needed to reduce the complexity of four-legged robot operation.

Table 1
Challenges of four-legged robots in construction.

Categories	Challenges
Robot	• Restricted autonomous navigation. • Robot-control station signal loss or interference. • User interface/ground control station complexity.
Regulations	• Limited regulatory agency standards or guidelines. • Ethics and privacy concerns.
Environment	• Difficulty navigating environments with complex onsite conditions. • Limited field of view. • Inaccuracies detecting objects, edges, and navigating unguarded jobsite environments. • Presence of jobsite obstacles and crowded surroundings.
Human	• Lack of operator training and skills. • Negative psychophysiological and attentional effects.

Regulations-related challenges: Four-legged robots are also limited in terms of regulatory agency [i.e., Occupational Safety and Health Administration (OSHA)] standards or guidelines when being operated on jobsites (Afsari et al., 2021). There are unclear rules and regulations as to the use of four-legged robots near or around workers, preventing the autonomous operation of robots when workers are present on site. For example, the manufacturer's safety and compliance document of Spot® indicates that the four-legged robot should not be operating at distances that are closer than 1.98 m (6.5 ft) from humans (Boston Dynamics, 2021). If this requirement is to be maintained on jobsites, then the physical interaction and collaboration between humans and robots on site would be severely limited (Afsari et al., 2021). It is also expected that the onsite presence of four-legged robots might be associated with ethics- and privacy-related concerns, as well as potential civil liberty intrusions, caused by the continuous monitoring of jobsite individuals (Sun et al., 2023).

Environment-related challenges: Some environmental conditions may cause hazards on jobsites. The first environmental challenge is related to the four-legged robots' ability to accurately detect edges and successfully navigate unguarded environments. The second is related to the ability of the four-legged robots to detect objects of different size, height (i.e., hanging objects), thickness, material, color, and brightness, potentially affecting the jobsite navigation (Afsari et al., 2021; Boston Dynamics, 2021). Four-legged robots' navigation is also affected by the presence of onsite obstacles (e.g., cords, tripping hazards), high-riser stairs, surface inclinations, floor types (e.g., slippery surfaces, sand, dust, and liquids affect the robots' stability), lighting conditions, and limited field of view which could potentially create hazards on jobsites (Afsari et al., 2021; Boston Dynamics, 2021).

Human-related challenges: Due to the ground control station complexity and the need for continuous human intervention during the robot deployment (Afsari et al., 2021), humans should be well trained to be able to operate four-legged robots in dynamically changing and hazardous environments such as construction jobsites. In addition, the presence of four-legged robots on site could expose construction individuals to different human risks (Afsari et al., 2021), potentially causing hazardous situations (Sun et al., 2023). It should be noted that humans may develop automation anxiety, stemming from increasing concerns about job displacement, fear of being replaced by robots, and worries about future employment prospects (Navon et al., 1993).

3.3. Safety risks associated with the deployment of four-legged robots on construction sites

Currently, the robot-, regulation-, environmental-, and human-related challenges remain significant obstacles that could individually or collectively lead to negative human behaviors and perceptions toward the deployment of and interaction with four-legged robots, potentially resulting in adverse outcomes on construction sites. Therefore, there is a need to investigate the safety impacts of such collaborative robots in construction settings. Specifically, the deployment of four-legged robots on construction sites has been associated with three types of risks that were identified through inferential and VR visualization techniques based on the proximity of human-robot interactions, and subsequently validated and ranked by experts in construction safety and robotics. These risks include: (1) physical or contact risks; (2) attentional risks; and (3) psychological risks (Sun et al., 2023).

Physical or contact risks refer to hazards that can cause harm or injury to workers due to direct physical contact with objects, equipment, machinery, or other individuals. In the case of deploying four-legged robots, these risks could arise from various factors, such as software or hardware failures in the robots, close interactions with the robots, adverse weather and environmental conditions, and inadequate worker training leading to inefficient operation. These factors could in turn result in struck-by, caught-in, or caught-between injuries or fatalities on construction sites.

In addition, attentional risks constitute hazards that arise due to lapses in concentration, distractions, or lack of focus on the task at hand. For example, the onsite presence of mobile collaborative robots such as the four-legged robots may cause individuals to shift their attention from the task at hand and focus more on the robot, potentially causing distraction. Attentional allocation, the cognitive process by which individuals distribute their cognitive resources or focus their attention on particular stimuli or tasks, is integral to workplace safety and significantly influences occupational health outcomes. In fact, distraction, often referred to as attentional diversion, emerges as a significant factor contributing to workplace accidents and fatalities, thereby compromising safety performance and encouraging unsafe behaviors, particularly on construction sites (Cohen et al., 2017; Ke et al., 2021). This phenomenon undermines construction individuals' ability to recognize hazards and perceive risks, ultimately impacting safety performance by allowing many hazards to go unnoticed and associated risks unrecognized (Namian et al., 2018).

Finally, the deployment of four-legged robots could introduce additional psychological risks that impact the mental and emotional well-being of onsite individuals. These psychological risks are particularly critical within the current landscape of the construction industry, which is characterized by increasingly high and alarming rates of suicide and a pervasive atmosphere of anxiety, worry, and nervousness among its workforce (Brown et al., 2022; Sussell et al., 2021). Emotional states have been proven to have an impact on construction individuals' decision-making processes and cognitive abilities, potentially leading to a diminishment in their safety risk perception, hazard identification capabilities, awareness, and attitudes (Bhandari et al., 2016; Hwang et al., 2018; Wong et al., 2009; Xing et al., 2019), thereby increasing the potential for hazardous behaviors on the jobsites. In addition, construction is inherently stressful and demanding (Bowen et al., 2014). Prolonged exposure to high stress levels can induce mental fatigue and cognitive impairment, further exacerbating safety concerns (Langdon and Sawang, 2018; Leung et al., 2016; Wu et al., 2018). Excessive physiological demands on construction individuals have been linked to decreased levels of motivation, attentiveness, and overall well-being, hindering their ability to perform physically demanding tasks in a productive and safe manner (Abdelhamid and Everett, 2002; Abdelhamid and Everett, 1999). Furthermore, the introduction of four-legged robots on construction sites may induce anxiety and resistance, stemming from concerns about job displacement, fear of being replaced by robots, and uncertainties regarding future employment prospects (Navon et al., 1993). This anxiety could also be compounded by potential ethics- and privacy-related concerns, as well as civil liberty intrusions arising from four-legged robots continuously monitoring construction individuals (Sun et al., 2023). Collectively, these factors contribute to negative emotional states and attitudes towards the integration of robots in construction settings and pose a significant threat to onsite safety by increasing the likelihood of injuries or even fatalities. Therefore, and given the recent increase in automation on construction sites, studying the potential physical, attentional, and psychological risks associated with four-legged robot deployment on construction sites becomes a necessity.

3.4. Human-Robot interaction proxemics

For robots to be seamlessly integrated into dynamic and hazardous construction jobsites, they must adhere to societal expectations of physical and psychological distance to maintain personal space (Takayama and Pantofaru, 2009; Mumm and Mutlu, 2011). The use of four-legged robots in construction environments will require them to collaborate with construction individuals at varying interaction distances. For example, tasks such as construction and material handling will necessitate close interactions with humans, whereas tasks like progress monitoring may require more distant interactions. Consequently, human-robot collaborations at varying distances may elicit different psychophysiological responses from construction individuals. These individuals may have different proxemic preferences, influenced by the psychophysiological risks associated with robot interactions at various distances. This underscores the necessity of studying human proxemic preferences near four-legged robots in construction environments. Focusing on how these preferences affect and are affected by robots operating at different distances can help better understand and mitigate the associated risks.

Studying proxemics is a significant field of research, particularly in the areas of HRI. When studying HRI proxemics, researchers often rely on Anthropologist Edward Hall's definition of human–human social interaction distances (Samarakoon et al., 2022; Hall, 1969). These proxemic distances, along with their social implications and relevant application examples, are defined as follows (Samarakoon et al., 2022; Hall, 1969; Daza et al., 2021):

- *Intimate Distance:* Ranging from 0 to 1.5 feet, this space is reserved for close relationships, for comforting or protecting someone, and for loved ones, where physical contact is possible. This zone allows for touching, whispering, and embracing and is typically only entered with consent. An invasion of this space without justification can cause discomfort or be perceived as an attack. Exceptions occur in crowded environments like public transportation.
- *Personal Distance:* Spanning from 1.5 feet to 4 feet, this zone is used for interactions and conversations with friends, acquaintances, and family members. It allows for natural interactions where physical contact is possible but not as intimate as within the intimate distance. This space ensures that individuals can maintain a sense of personal control while limiting physical domination.
- *Social Distance:* Extending from 4 feet to 12 feet, this space is appropriate for interactions among strangers, colleagues, and other casual acquaintances, like in formal settings such as professional or business meetings. It allows for communication without physical contact.
- *Public Distance:* Ranging from 12 feet to 25 feet, this zone describes the distribution of people in urban spaces and is used for interactions in public spaces such as public speaking events, concert halls, parks, and museums. In these spaces, people are often unaware of others'

identities. In some situations (e.g., concerts or public transportation), social, personal, and even intimate zones can be temporarily invaded due to the circumstances.

Hall's proxemic distances are not only widely used but also particularly relevant for HRI studies, as they are grounded in fundamental principles of human interaction and societal norms. Hall's proxemic theory underscores the importance of respecting personal space (Takayama and Pantofaru, 2009; Hall, 1969), which is critical for the seamless integration of robots into human environments. By adhering to these proxemic norms, robots can navigate social interactions more naturally, aligning their behavior with human expectations and societal conventions (Takayama and Pantofaru, 2009; Mumm and Mutlu, 2011). This adherence mirrors the natural ways people interact with both other humans and technological entities, a concept supported by the media equation theory, which posits that people treat technology in a manner similar to their interactions with other humans (Takayama and Pantofaru, 2009). Consequently, incorporating Hall's proxemic distances into HRI studies facilitates a more natural and socially acceptable integration of robots into everyday settings.

4. Methods

The aim of this study is to investigate human-robot proxemics in construction by examining the safety impacts associated with the four-legged robot interaction spaces on construction individuals. This was achieved by analyzing the effects of four-legged robots on construction individuals while they performed a task in a VR setting. The study utilizes both objective and subjective measures alongside VR to explore the impacts of four-legged robots on construction individuals. A three-step procedure was employed to accomplish the study's objectives (Fig. 2). In Step 1, an extensive literature search was conducted to identify a real-world construction scenario where ground robots are expected to collaborate with construction individuals. The identified scenario was then utilized in Step 2 to design and develop a VR-based construction environment featuring a four-legged robot positioned at various interaction spaces (i.e., proximal, distal) from users. This VR environment incorporated dynamic 3D models to simulate a real-world construction site with moving equipment and workers. Subsequently, in Step 3, construction individuals were recruited to participate in a between-subject experiment involving the designed VR environment, along with a series of objective (i.e., physiological monitoring sensors and eye tracking) and subjective (i.e., pre- and post-experiment surveys) measures. These were used to evaluate the effects of four-legged robot interaction space on participants' physiological, attentional, and emotional states, as well as their perception of risk, attitudes towards robots, and situational awareness. The subsections below discuss the adopted three-step procedure in more detail.

4.1. Step 1 – Scenario identification

A literature search was conducted to identify a real-world construction scenario where ground robots are expected to collaborate with construction individuals. Bricklaying task was identified to be a popular application of ground robots in construction. The nature of this type of task is laborious, repetitive, challenging, and hazardous (Dakhli and Lafhaj, 2017; Yu et al., 2009), and the use of ground robots such as the four-legged robot for such types of tasks has several advantages from a safety perspective. These advantages include: (1) reduced worker exposure to hazardous materials by preventing construction individuals from being exposed to and working with materials such as mortar and concrete which could be hazardous if inhaled or ingested; and (2) improved ergonomics by preventing individuals from repeatedly performing several movements such as bending, lifting, and twisting, which can result in musculoskeletal injuries (Dakhli and Lafhaj, 2017; Yu et al., 2009). In addition to improved productivity, the use of four-legged robots for this type of task can ensure greater accuracy and precision when compared to human workers, factors that reduce the risk of errors. Concrete placement and formwork installation activities were also part of the bricklaying scenario. These types were specifically selected to be part of the VR environment, especially since such activities are very common and could result in various accidents and injuries, including struck-by accidents, manual handling, slips, and trips (Lipscomb et al., 2006; Rozenfeld et al., 2010). In the developed VR scenario, users would take the role of a supervisor and monitor ongoing construction activities, including concrete placement (e.g., rebar tying), scaffold transportation,

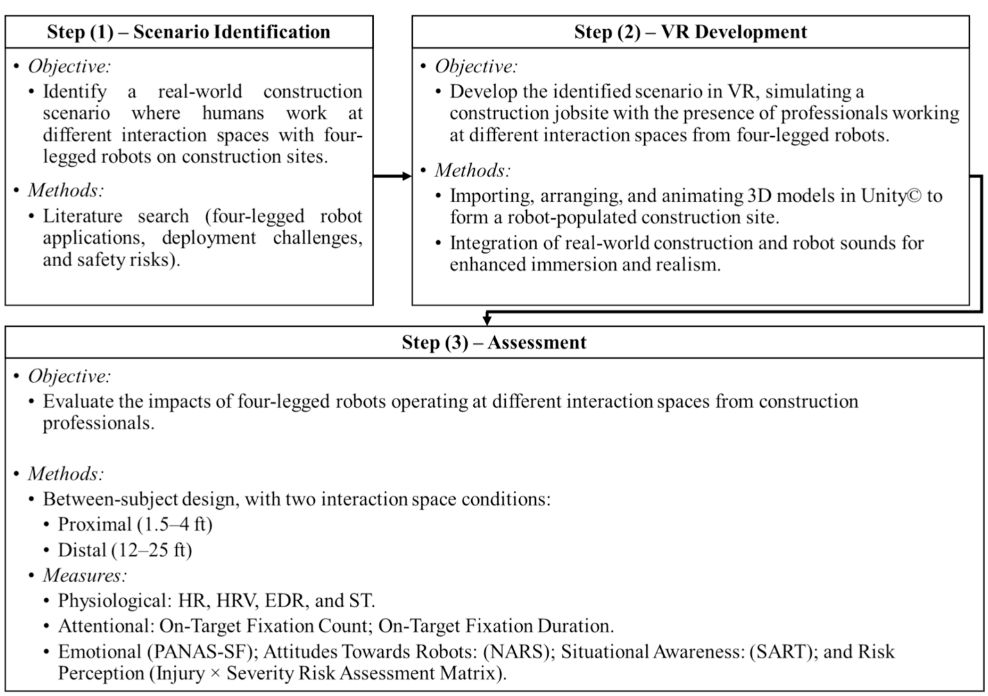


Fig. 2. Adopted Methodology.

bricklaying, in addition to other operations simulated by different virtual construction workers (Fig. 3).

4.2. Step 2 – VR development

The technical development of the VR environment involved multiple steps (Fig. 4). First, 3D models representing various construction jobsite components, such as cranes, machines, formwork, workers, and buildings, were imported into Unity©. These models were then arranged and animated to replicate slab preparation for concrete placement (e.g., rebar tying, hammering, and nailing) and formwork installation (e.g., scaffold transport by a virtual worker from one location to another for erection) activities. Additionally, a 3D model of the Boston Dynamics® Spot, a four-legged robot commonly used in construction tasks (Afsari et al., 2021; Halder et al., 2021), was integrated into the VR environment. These VR models were selected and animated to create a realistic and immersive construction site environment, ensuring that participants could easily identify and interact with the virtual objects. The selection was informed by the need to replicate common construction activities (i.e., crane operation, slab preparation, concrete placement, formwork installation) and the specific task (material handling and bricklaying) of the four-legged robot, thereby enhancing the ecological validity of the simulation. Storyboarding was also used at the early stage to outline the sequence of actions and interactions within the VR environment, ensuring a coherent and logical flow of activities similar to what would typically occur on construction sites. For the development of the VR environment, several assumptions were made. The physics engine in Unity© was configured to simulate realistic movement and interactions of the robot and other objects, assuming standard gravitational forces and material properties. The robot's movement and task execution were based on its actual capabilities and operational parameters as specified by the robot's manufacturer. In addition, it was assumed that the four-legged robot could pick up and transport concrete masonry units (CMUs) similar to its real-world functionality. This ensured that the simulated interactions were consistent with real-world scenarios.

Considering the nature of the four-legged robot's movement and the requirements of the bricklaying task, two scenes were developed to simulate different interaction spaces based on Hall's definition: (1) a proximal space ranging from 1.5 to 4 feet, and (2) a distal space ranging from 12 to 25 feet (Hall, 1969). In both scenes, the robot was programmed and animated to repetitively simulate bricklaying activity by picking up CMUs individually from a pile, transporting them, and progressively laying them layer by layer to construct a CMU wall, all while performing this task in a back-and-forth manner. All subjects experienced the same VR scenario, differing only in the interaction space (proximal – 1.5 – 4 ft; or distal – 12 – 25 ft) between them and the four-legged robot. In scene (1), the four-legged robot operated within a 1.5 – 4 ft space relative to the subjects. It repetitively moved back and forth within this range to pick up CMUs and then approached the subjects up to 1.5 feet to place the CMUs layer by layer to construct the wall. In scene (2), the four-legged robot operated within a 12 – 25 ft space relative to the subjects. It repetitively moved back and forth within this range to pick up CMUs and then approached the subjects up to 12 feet to place the CMUs layer by layer to construct the wall. This movement pattern was designed to reflect a realistic four-legged robot bricklaying work scenario, where the robot needs to move farther from construction individuals to pick up the CMUs and then closer to build the CMU wall as it performs its tasks. This approach aimed to eliminate potential biases by ensuring that the robot's animation, movements, and actions were identical across both proximal and distal scenes. Specifically, the robot's repetitive actions, such as picking up and placing the CMUs, were consistent in both interaction spaces. This design meant that the only variable was the interaction space (1.5 – 4 ft vs. 12 – 25 ft) between the robot and the human subjects, allowing for a clear analysis of the effects of proximity on user perception and responses. Real-world sounds associated with the robot's movements were incorporated for enhanced immersion.

4.3. Step 3 – Assessment

To investigate whether the interaction space of a four-legged robot impacts individuals' physiological, attentional, and emotional states, as well as their situational awareness, risk perception, and attitudes towards robots, a user-centered experiment was conducted. Construction workers were recruited to participate in one of two previously developed human-four-legged robot VR scene conditions: (1) Proximal Space: 1.5 – 4 ft; and (2) Distal Space: 12 – 25 ft.

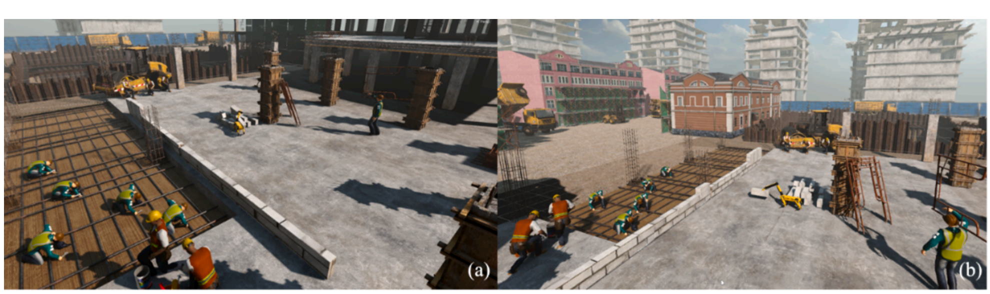
4.3.1. Measures and Metrics used for data collection and Processing

A set of objective and subjective measures were used to assess these physiological, attentional, and emotional states, as well as situational awareness, risk perception, and attitudes towards robots. This subsection discusses the measures and metrics used in detail.

Physiological Measures: The impact of four-legged robot proxemics on participants' physiological states was assessed by measuring their heart rate (HR), heart rate variability (HRV), and electrodermal response (EDR) using the Shimmer® GSR+, and their skin temperature (ST) using the Shimmer® Bridge Amplifier + throughout the experiment. Both monitoring sensors were set to collect physiological data synchronously, at a sampling frequency of 128 Hz, and the collected data was recorded, processed, and analyzed in the Shimmer® Consensys Pro software. Several filters were applied to process the collected physiological data as summarized in Table 2.

Attentional Measures: To measure the effect of four-legged robot proxemics on attention, individuals' eye movements were monitored throughout the experiment using the Tobii Pro® eye tracker integrated into the HTC Pro® head-mounted display (HMD). Two metrics were used to measure attentional state: (1) Fixation count on distractor, measuring how many times each subject directed their gaze towards the four-legged robot (i.e., total number of fixations) (Holmqvist et al., 2011); and (2) Total fixation duration on distractor, measuring the cumulative or total time (in milliseconds) each subject spent looking at the four-legged robot (Bednarik and Tukiainen, 2006).

Emotional Measures: Participants' emotional impact was assessed



Concrete placement activities: hammering and rebar tying — Scaffolds being transported for erection

Fig. 3. Four-legged robot bricklaying scenario.

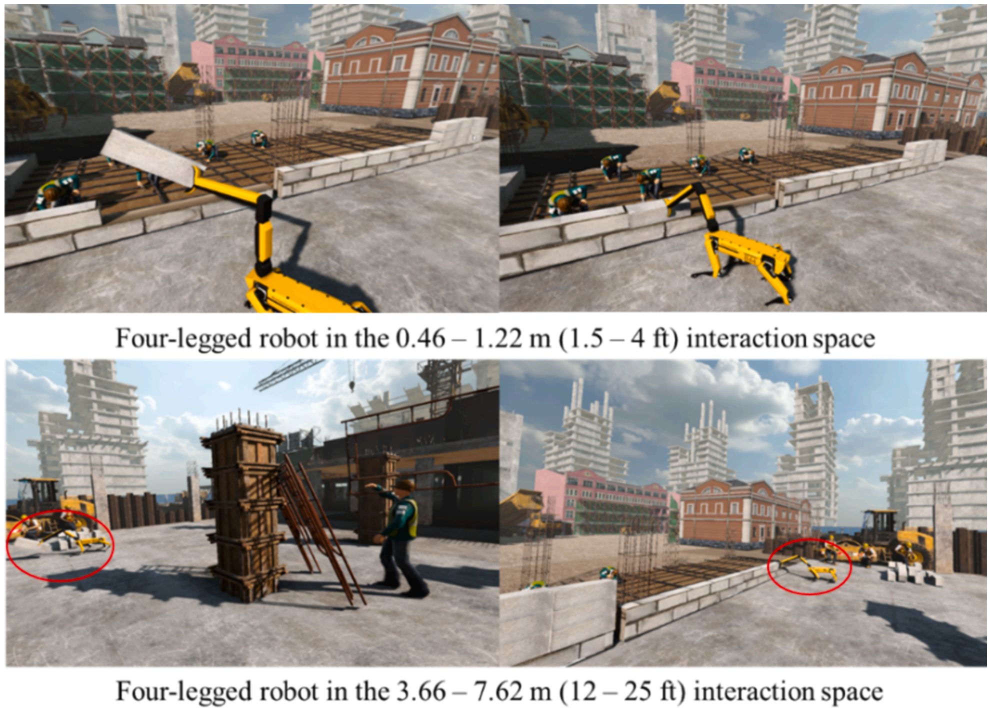


Fig. 4. VR Development Workflow.

subjectively using the validated Positive and Negative Affect Schedule (PANAS-SF) questionnaire (Watson et al., 1988). The questionnaire was used to evaluate the emotional states of participants both before and after the experiment (Table 3). Divided into two subscales, the questionnaire, consisting of 20 items, gauges emotional affect in terms of Positive Affect and Negative Affect. It has been used in this study to measure variations in participants' emotional responses while interacting at various interaction spaces from the four-legged robot.

Attitudes Measures: The validated Negative Attitudes towards Robots (NARS) subjective questionnaire was used to evaluate the impact of four-legged robot proxemics on individuals' attitudes (Nomura et al., 2006). NARS consists of three subscales and assesses negative attitudes towards (1) situations of interactions with robots; (2) social influence of robots; and (3) emotions in interaction with robots (Nomura et al., 2006). The questionnaire was administered at the end of the experiment to measure whether there were any differences in participants' attitudes while interacting at various interaction spaces from the four-legged robot (Table 3).

Situational Awareness Measures: The Situation Awareness Rating Technique (SART) was used to measure participants' situational awareness upon experiment completion (Table 3) (Taylor, 2017). SART is a validated survey consisting of a total of 10 seven-point rating questions (1 = Low; 7 = High) measuring three dimensions: (1) demands on attentional resources (D); (2) supply of attentional resources (S); and (3) understanding of the situation (U). The composite situational awareness score is then obtained using equation (1) below. SART has been used in this study to measure participants' situational awareness at both four-legged robot interaction spaces.

$$SA = U - (D - S) \quad (1)$$

Risk Perception Measures: A safety risk assessment matrix was used to measure participants' perceived risk at the end of the experiment (Table 3). The goal was to determine whether participants' perceived risk changes based on the two four-legged robot interaction spaces after completing the task in VR. Specifically, participants were asked to rate the likelihood of an injury occurring in the scenario they were presented with, using a severity scale. The scale was defined as follows (Namian et al., 2018; Namian et al., 2016; Tixier et al., 2014):

- Discomfort or pain: Incidents that result in temporary or persistent pain, but do not prevent workers from performing work in normal capacity.
- First aid: Incidents that require treatment for cases such as minor cuts, scratches, and sprains, where the worker is able to return to work immediately following treatment.
- Medical case: Work-related injuries or illnesses that require care or treatment from medical professionals beyond first aid, where the worker is able to return to regular work under normal capacity.
- Lost work time: Work-related injuries or illnesses that restrict workers from returning to work the following day.
- Permanent disability or fatality: Work-related injuries or illnesses that result in permanent disablement or death of worker.

The response options provided were not possible (0 %), unlikely but possible (25 %), likely (50 %), very likely (75 %), and certain (100 %). The validated severity scores adopted in this study have been successfully used in construction safety research (Namian et al., 2016; Tixier et al., 2014; Ibrahim et al., 2023). The severity scores are as follows: Discomfort/Pain (7.5), First aid (45.25), Medical case (128), Lost work time (256), and Permanent disablement or fatality (13,619). These severity scores were multiplied by the frequency ratings to calculate each individual's risk score.

4.3.2. *Assessment procedure*

The assessment procedure is illustrated in Fig. 5. Upon their approval to participate in the experiment, recruited construction individuals were asked to complete a demographics questionnaire which included questions about their gender, age, education level, construction experience, pet ownership, robot ownership, experience operating robots, familiarity with robots, familiarity with VR, emotional states, in addition to safety-related questions about Occupational Safety and Health Administration (OSHA) training and safety knowledge. They were also asked to fill out the PANAS-SF questionnaire. After completing the pre-experiment questionnaires, recruited individuals were randomly

Table 2
Physiological and Attentional Objective Metrics.

Measures	Metrics	Details
Physiological	HR	• **Measurement:** Determining the number of systolic peaks/min (Askarian et al., 2019). • **Processing:** Determined using the Shimmer® Consensys Pro PPGtoHR algorithm, which applies a low-pass filter with a corner frequency set at 5 Hz and a number of taps at 200. • **Impact:** Instances of acute stress typically result in a sudden elevation of HR (Dobkin and Pihl, 1992; Turner, 1994).
	HRV	• **Measurement:** Assessing the fluctuations in the time intervals between successive heartbeats (Shaffer and Ginsberg, 2017). • **Processing:** The inter-beat intervals (IBIs) were extracted using the Shimmer® Consensys Pro PPGtoHR algorithm, which employs a low-pass filter with a corner frequency set at 5 Hz and a number of taps at 200. The IBIs were then utilized in the calculation of HRV through the root mean square of successive differences (RMSSD) time-domain method (Shaffer and Ginsberg, 2017). • **Impact:** Individuals experiencing acute stress tend to exhibit low HRV (Lischke et al., 2018).
	ST	• **Measurement:** mounting a probe on individual's skin to monitor skin surface temperature. • **Processing:** Filters applied were high-pass filter (high cutoff frequency of 0.05 Hz) and Hampel (Jebelli et al., 2019a, 2019b). • **Impact:** Instances of acute stress tend to cause rapid and temporary declines in skin surface temperature (Herborn et al., 2015).
	EDR	• **Measurement:** The phasic component of electrodermal activity (EDA), also known as EDR, was used in this study, as it has been shown to reflect an immediate, short-term reaction to acute stressors or external stimuli (Boucsein, 2012; Greco et al., 2021; Lanatà et al., 2015). • **Processing:** Filters applied were low-pass (low-cutoff frequency of 1.5 Hz) and Hampel (Jebelli et al., 2019; Jebelli et al., 2019; Braithwaite et al., 2013). In addition, the convex optimization method was used to decompose the collected electrodermal activity (EDA) response into the phasic (EDR) and tonic (EDL) components (Greco et al., 2016). • **Impact:** Instances of stress augment perspiration levels and consequently alters the skin's electrical characteristics (Boucsein, 2012; Greco et al., 2021; Lanatà et al., 2015).
Attentional	Fixation Counts and Total Fixation Duration	• **Measurement**: tracking eye movements to determine the frequency of instances or number of times each subject looked at the four-legged robot (Fixation Counts), and the cumulative or total amount of time each subject spent fixating on it (i.e., Total Fixation Duration). • **Processing:** A fixation was recorded only if it lasted longer than 100 ms (Bednarik and Tukiainen, 2006; Negi and Mitra, 2020). • **Impact:** Both metrics are indicative of attentional diversion, reflecting the degree of distraction caused by four-legged robots and the level of attention they attract on jobsites.

Table 3
Emotional, Attitudes, Situational Awareness, and Risk Perception Subjective Metrics.

Measures	Metrics	Administration of Questionnaires
Emotional	PANAS-SF	Pre- and post-experiment
Attitudes towards Robots	NARS	Post-experiment
Situational Awareness	SART	Post-experiment
Risk Perception	Injury × Severity Risk Assessment Matrix	Post-experiment

assigned to one of the two developed interaction space conditions: (1) Proximal, simulating the four-legged robot operating in the 1.5 – 4 ft space; and (2) Distal, simulating the four-legged robot operating in the 12 – 25 ft. Subjects were equipped with the physiological monitoring sensors (i.e., Shimmer® GSR+and Shimmer® Bridge Amplifier +) along with the HTC Pro® HMD and eye tracking calibration was performed prior to the start of the experiment.

During the experiment, construction individuals were asked to remain stationary in the same location to be able to ensure consistent measurement across conditions and control for the distance between them and the four-legged robot. Participants were assigned the role of a jobsite supervisor, responsible for overseeing the activities of both construction workers (simulated virtual avatars) and the four-legged robot within the VR environment. This supervisory role required participants to monitor and assess the safety performance and productivity of the workers as they completed the slab preparation for concrete placement and the scaffold erection activities. They ensured that these construction workers adhered to safety protocols and completed their tasks effectively. In addition, participants supervised the four-legged robot as it performed the simulated bricklaying task and had to ensure that the robot operated safely while maintaining efficient task execution. To maintain participant engagement and simulate real-world supervisory duties, participants were regularly prompted with questions through the HMD headset audio. These prompts were designed to reflect the types of inquiries a jobsite supervisor might encounter from colleagues on a construction site. Participants were required to respond to these prompts to actively monitor and uphold safety and productivity standards within the VR environment. Collaboration was thus ensured by placing participants in a comprehensive supervisory role, necessitating interaction with both the virtual workers and the four-legged robot. This setup ensured that participants were engaged in a supervisory role that mirrored the complexities of modern construction sites, where coordination and communication with both human workers and robotic systems are essential. By incorporating this supervisory context, the study aimed to replicate the complexities and interactive nature of real-world construction sites. This approach contrasts with other HRI proxemics studies (Samarakoon et al., 2022), which often focus solely on human-robot interactions without considering the potential effects of the broader dynamic, hazardous, and collaborative work settings.

The total duration of the VR experiment was set at 3 min to mitigate subject fatigue and adhere to recommended VR exposure durations (less than 10 min) that prevent subjects from exhibiting sickness symptoms

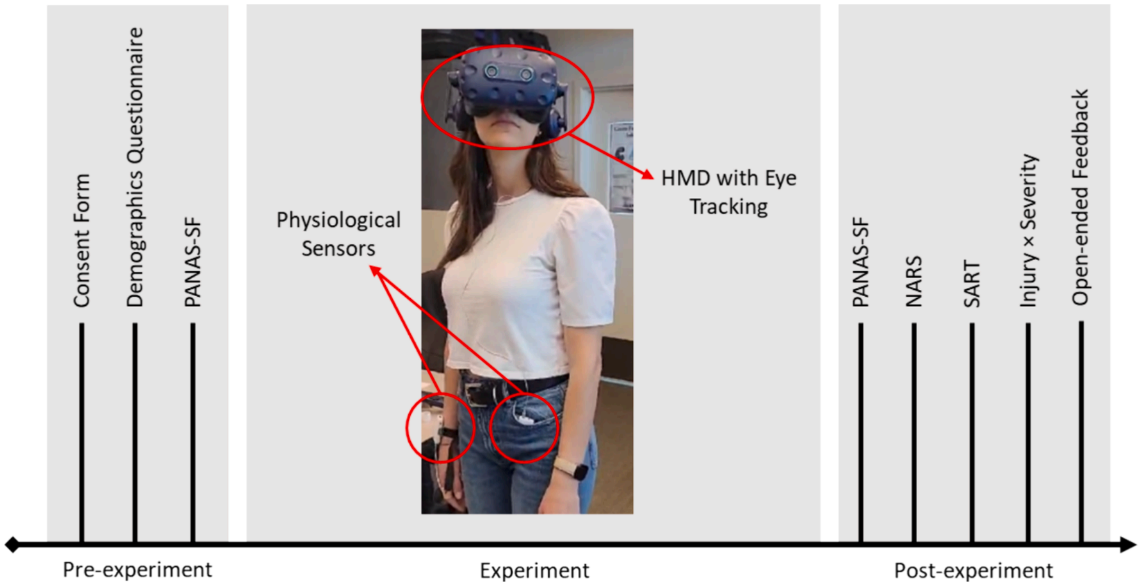


Fig. 5. Assessment Procedure.

often caused by lengthy exposure to VR (Chang et al., 2020; Munafo et al., 2017). Of these 3 min, 2 min were dedicated to psychophysiological and attentional data collection. During this period, the physiological sensors operating at a frequency of 128 Hz collected approximately 15,360 data points for each measure (HR, HRV, ST, and EDR). This timeframe was chosen to balance data collection needs with participant comfort and to ensure that sufficient data was captured. The 3-minute duration was divided as follows:

- Minutes 0–1: No data was collected during the first minute to allow participants to adjust to the VR scene and the HMD.
- Minutes 1–3: Physiological and attentional data collection began at the start of the second minute and continued until the end of the trial.

After completing the experiment, construction individuals were asked to fill out the PANAS-SF questionnaire once again to measure any emotional state changes resulting from the experiment itself. They were also asked to fill out the NARS, the SART, as well as to rate the likelihood of an injury occurring in the VR scenario they were presented with, using the injury frequency-severity scale. As previously indicated, these surveys measured individuals' attitudes towards robots, situational awareness, and perceived risk after completing the VR-based experiment. Individuals were also asked to provide, through an open-ended type of question, their feedback about the VR experiment and the presence of four-legged robots on jobsites. All questionnaires were distributed using Qualtrics, and the assessment protocol (IRB202202631) was also approved by the University's Institutional Review Board. No prior training was provided to the recruited construction individuals on the topic of four-legged robots and their potential impacts in construction. The differences in means across all measured physiological (HR, HRV, ST, and EDR), attentional (fixation count and total fixation duration), emotional (positive affect and negative affect), situational awareness (SART subscales scores), risk perception (risk scores), and attitudes (NARS subscale scores) variables between the proximal (1.5 – 4 ft) and distal (12 – 25 ft) interaction space groups were analyzed using independent samples t-tests. Assumptions of normality and equal variances were assessed, and a significance level of $\alpha = 0.05$ was applied for all statistical tests.

5. Results and Discussion

5.1. Demographics

A total of 72 individuals with an average age of 23.75 ± 4.91 years participated in the experiment (Table 4). The studied population was equally divided between the 1.5 – 4 ft and the 12 – 25 ft interaction space groups. Overall, more than half of the participants were undergraduate construction students (N=43, 60 %), aged between 18 and 24 years (N=47, 65.3 %), males (N=47, 65.3 %), and had less than 1 year (N=52, 72.2 %) of construction experience. Most of the participants indicated that they had received the OSHA 10-hour or 30-hour training (N=52, 72.2 %), and that they had fair to competent (N=58, 80.6 %) knowledge level in construction safety. The majority were pet owners (N=51, 70.8 %) and around half of them were robot owners (N=37, 51.4 %). The majority indicated that they have some experience operating robots (N=55, 76.4 %) as well as some level of familiarity with robots (N=64, 88.9 %) and VR (N=64, 88.9 %). None of the participants indicated being angry or sad, and most of them were either satisfied (N=39, 54.2 %) or happy (N=25, 34.7 %).

5.2. Impact of four-legged robot interaction space on physiological state

Participants' average HR, HRV, ST, and EDR were calculated for both four-legged robot interaction distance groups (Table 5). The proximal (1.5 – 4 ft) group had slightly higher HR and ST, and lower HRV and EDR when completing their task during the VR experiment when compared to the distal (12 – 25 ft) group. However, these differences were not found to be statistically significant ($p \geq 0.247$). In addition, all of the measured HR, HRV, ST, and EDR values fell within the typical normal range for a resting and healthy person (Dawson et al., 2016; Jose and Collison, 1970; Lenhardt and Sessler, 2006; Nunan et al., 2010; Sund-Levander et al., 2002). Therefore, the results do not provide enough evidence supporting the fact the four-legged robot interaction distance significantly affects participants' physiological states.

The obtained findings are consistent with some observations in the HRI literature across various fields. In construction, Chauhan et al. (2024) found that closer proximity to robots in open jobsite environments with low-level of HRI was associated with a significant decrease in EDA and a decrease in HRV, though the latter was not statistically significant (Chauhan et al., 2024). These results align with the current study, which also observed that proximity to a four-legged robot, while

Table 4
Participant demographics.

Parameter	Proximal (1.5 – 4 ft) N=36	Distal (12 – 25 ft) N=36
Gender		
Male	25 (69.4 %)	22 (61.1 %)
Female	11 (30.6 %)	14 (38.9 %)
Age		
18 to 24 years	25 (69.4 %)	22 (61.1 %)
25 to 31 years	8 (22.2 %)	12 (33.3 %)
More than 31 years	3 (8.3 %)	2 (5.6 %)
Education Level		
Undergraduate	26 (72.2 %)	17 (47.2 %)
Graduate	10 (27.8 %)	19 (52.8 %)
Construction Experience		
0 to 1 year	28 (77.8 %)	24 (66.7 %)
1 to 5 years	7 (19.4 %)	9 (25.0 %)
More than 5 years	1 (2.8 %)	3 (8.3 %)
OSHA Training		
Yes, OSHA 10 or 30	26 (72.2 %)	26 (72.2 %)
No	10 (27.8 %)	10 (27.8 %)
Construction Safety Knowledge		
No knowledge	0 (0.0 %)	0 (0.0 %)
Some knowledge	5 (13.9 %)	9 (25.0 %)
Fair knowledge	22 (61.1 %)	19 (52.8 %)
Competent knowledge	9 (25.0 %)	8 (22.2 %)
Pet ownership		
Yes	27 (75.0 %)	24 (66.7 %)
No	9 (25.0 %)	12 (33.3 %)
Robot Ownership		
Yes	21 (58.3 %)	16 (44.4 %)
No	15 (41.7 %)	20 (55.6 %)
Experience Operating Robots		
Not experienced at all	7 (19.4 %)	10 (27.8 %)
Slightly experienced	10 (27.8 %)	14 (38.9 %)
Moderately experienced	16 (44.4 %)	9 (25.0 %)
Very experienced	1 (2.8 %)	3 (8.3 %)
Extremely experienced	2 (5.6 %)	0 (0.0 %)
Familiarity with Robots		
Not familiar at all	3 (8.3 %)	5 (13.9 %)
Slightly familiar	9 (25.0 %)	12 (33.3 %)
Moderately familiar	15 (41.7 %)	10 (27.8 %)
Very familiar	6 (16.7 %)	9 (25.0 %)
Extremely familiar	3 (8.3 %)	0 (0.0 %)
Familiarity with VR		
Not familiar at all	4 (11.1 %)	4 (11.1 %)
Slightly familiar	8 (22.2 %)	14 (38.9 %)
Moderately familiar	10 (27.8 %)	13 (36.1 %)
Very familiar	10 (27.8 %)	4 (11.1 %)
Extremely familiar	4 (11.1 %)	1 (2.8 %)
Emotional State		
Angry	0 (0.0 %)	0 (0.0 %)
Sad	0 (0.0 %)	0 (0.0 %)
Neutral	3 (8.3 %)	5 (13.9 %)
Satisfied	21 (58.3 %)	18 (50.0 %)
Happy	12 (33.3 %)	13 (36.1 %)

Table 5
Participants' physiological measures.

	Proximal (1.5 – 4 ft) Mean ± SD	Distal (12 – 25 ft) Mean ± SD	p-value
Mean HR (bpm)	86.05 ± 11.28	83.29 ± 13.71	0.354
Mean HRV (ms)	28.13 ± 14.29	32.69 ± 18.55	0.247
Mean ST (°C)	35.44 ± 1.00	35.32 ± 1.09	0.623
Mean EDR	0.52 ± 0.26	0.54 ± 0.26	0.755

not being statistically significant, was associated with lower EDR and HRV. In industrial settings, Gervasi et al. (2022) found that the distance of the robot workspace from the operator did not significantly influence average skin conductance response or HRV, indicating no significant differences based on proximity (Gervasi et al., 2022). Similarly, Eimontaite et al. (2020) found that robot distance did not significantly impact individuals' physiological states, as indicated by the non-significant differences in EDA and HR responses, aligning with the findings of this study (Eimontaite et al., 2020). It is important to note, however, that contextual factors such as the specific work environment (industrial vs. construction), types of robots (stationary vs. mobile), and other variables may influence human proxemic preferences and physiological responses across industries. Therefore, while comparisons across studies provide valuable insights, they also underscore the need for context-specific investigations into HRI to better understand the complex interplay between robot proximity and human physiological responses.

Nevertheless, it is noteworthy to mention that simply finding no statistically significant differences between the group means for HR, HRV, ST, and EDR does not necessarily indicate that participants' physiological state is not affected by the presence of four-legged robots on jobsites. The feedback provided by the participants suggests that the presence of robots on construction sites may need to be approached with caution. In fact, around half of the participants from the proximal (1.5 – 4 ft) group reported feeling uncomfortable or anxious in the presence of the four-legged robot, indicating that it was *"a bit overwhelming"*, that they were caught *"a little off-guard"*, that they felt *"a little nervous"*, and *"uneasy"*, and that they were *"concerned and worried"* because of the four-legged robot presence on the jobsite. A few other participants in the distal (12 – 25 ft) group also indicated feeling *"very uncomfortable"*, *"surprised"*, and *"cautious"* by the presence of the four-legged robot. These findings suggest that the presence of the four-legged robot on the jobsite could be associated with a negative impact on construction individuals, especially since anxiety, nervousness, and discomfort could all lead to decreased focus, impaired decision-making, and increased risk of injuries and accidents (Hwang et al., 2018; Xing et al., 2019; Fang et al., 2018; Haslam et al., 2005; Leung et al., 2017; Wong et al., 2009). Indeed, these factors and their consequences warrant additional investigations.

5.3. Impact of four-legged robot interaction space on attentional state

As previously indicated, participants' on-target fixation count (the number of times each subject looked at the four-legged robot) and total fixation durations (the cumulative or total time each subject spent looking at the four-legged robot) were measured. For each group (proximal and distal interaction distance), the fixation counts and total fixation durations were averaged by calculating the mean of these values across all participants within each group. Table 6 shows the statistical analysis of the differences between these group averages. Results revealed that participants of both interaction distance groups (proximal and distal) shifted some of their attention from the task at hand onto the four-legged robot. In addition, participants of the distal (12 – 25 ft) group allocated more of their attention at the four-legged robot (6.92 ± 3.97) when compared to those in the proximal (1.5 – 4 ft) group (2.94 ± 2.24), as evidenced by a higher average on-target fixation count. This difference was statistically significant ($p < 0.001$). These findings suggest that the distance from the four-legged robot significantly affects construction individuals' attentional state, specifically in terms of fixation count. Furthermore, participants of the distal (12 – 25 ft) group looked at the four-legged robot for longer period durations compared to the participants of the proximal (1.5 – 4 ft) group. However, no statistically significant difference in the fixation duration was found between the two groups ($p = 0.663$). Based on these results, it can be concluded

Table 6
Participants' attentional measures.

	Proximal (1.5 – 4 ft) Mean ± SD	Distal (12 – 25 ft) Mean ± SD	p-value
Fixation Count	2.94 ± 2.24	6.92 ± 3.97	<0.001*
Total Fixation Duration (ms)	454.02 ± 292.23	483.85 ± 286.63	0.663

that individuals may feel less comfortable interacting with the four-legged robot at farther rather than closer distances, as reflected by their increased attention towards the robot at greater distances. In fact, this finding is consistent with the results of previous studies on human-robot proxemics, which suggest that people generally prefer to interact with robots in the personal (between 1.5 ft and 4 ft) rather than the social (between 4 ft and 12 ft) space (Huettenrauch et al., 2006; Wojciechowska et al., 2019). One possible explanation for this preference is that individuals may perceive the robot as a closer team member when it operates at closer distances (1.5 to 4 ft), potentially leading to increased trust and comfort. In fact, a recent study analyzing trust dynamics in human-robot collaboration in construction found that closer proximity to the robot was positively correlated with higher levels of perceived trust, suggesting that as individuals interact more closely with robots, their trust in these robots increases (Chauhan et al., 2024). Closer distances allow individuals to observe the robot's actions more clearly, understand its role and intentions, and predict its movements, facilitating a smoother and more intuitive interaction. Conversely, when the robot is at a greater distance, it might be perceived as having a surveillance or monitoring role, which can provoke curiosity and distraction. Participants may feel the need to allocate more attention to the robot to discern its activities and intentions, driven by a sense of unfamiliarity and the need to ensure it poses no threat to their task performance. This effect has been observed in several HRI proxemics studies, indicating that familiarity and robot experience result in closer distances to robots (Takayama and Pantofaru, 2009). For example, Haring (2014) found that participants tended to come closer to the robot over time, suggesting increased familiarity that went beyond the initial surprise of the first encounter (Haring et al., 2014). Similarly, Walters noted that a significant percentage of subjects allowed the robot to approach very closely, indicating they did not feel threatened or uncomfortable, unlike how they might feel with an unfamiliar human (Walters et al., 2005).

However, it is important to consider the practical significance of the obtained findings in terms of the safety performance of construction individuals, especially since the average fixation durations for the proximal (1.5 – 4 ft) and the distal (12 – 25 ft) groups were 0.45 and 0.48 s, respectively. While allocating more attention to the four-legged robot could possibly distract individuals from the task at hand, it could also be indicative of people's awareness and attentiveness about the four-legged robot presence in the environment. The former could have negative effects on construction individuals and impair their ability to complete a task safely (Cohen et al., 2017; Ke et al., 2021), whereas the latter could result in improved awareness and performance on jobsites. Specifically, humans possess constrained cognitive resources for processing information, requiring them to selectively attend to specific stimuli while disregarding others (Wahn and König, 2017). When a distracting stimulus, such as four-legged robots, diverts individuals' focus from their primary tasks, it can deplete their attentional resources, potentially compromising their performance and ability to accurately assess risks associated with their tasks (Wahn and König, 2017; Weisberg and Reeves, 2013). This becomes particularly critical in hazardous construction settings, where distractions can lead to unsafe behavior and severe accidents (Namian et al., 2018; Ghodrati et al., 2018). The presence of a four-legged robot on site may exacerbate these risks by negatively affecting the behavior of construction individuals, thereby increasing the likelihood of injuries or fatalities. Therefore, future research should focus on evaluating the practical significance of the obtained findings by understanding the balance between heightened awareness and potential distraction, as this is crucial for improving safety protocols and mitigating hazards that could be potentially caused by four-legged robots on construction sites. This observation was also reflected in the responses to the open-ended feedback question, which showed that both group participants had mixed opinions about the presence of the four-legged robot on jobsites. On one hand, it is clear that the presence of the four-legged robot on the jobsite was seen as a distraction by some participants. For example, some reported being *"drawn"* to the robot and watching them *"cautiously"*, factors that forced them to divert some of their attention away from the construction task they had been assigned to complete. One participant also indicated that: *"the presence of a four-legged robot working near me remained on my mind for the entire duration of the experiment, potentially taking away some of my alertness and cognition"*. Two other students commented that they found themselves *"looking at the robot more than the actual construction work"*, and that they were *"focusing on the robot for what felt like the majority of the experiment, instead of paying attention to the periphery and what else was going on the jobsite"*. Some others also indicated that their attention was divided between the robot and the workers, and that they were initially *"more distracted"* and *"mildly startled"* by the presence of the robot, but as time passed, they became more *"accustomed"* to it. Such distractions from the task at hand could be dangerous in the workplace, potentially resulting in accidents or injuries. On the other hand, several other participants reported *"not [being] bothered"* by the presence of the robot, that they *"barely noticed"* the robot, and that it did not hinder their ability to focus and complete their tasks. Examples of participants' comments include that they *"did not notice the presence of the four-legged robot"* as much as they *"were focusing on the workers"*, that the robot was of *"no more concern than the other workers"*, and that the robot *"required very little to no supervision"* compared to the different workers on site. Therefore, future research should focus on evaluating the practical significance of the obtained findings by understanding the balance between heightened awareness and potential distraction, as this is crucial for improving safety protocols and mitigating hazards that could be potentially caused by four-legged robots on construction sites. Future research should investigate how changes in participants' attentional allocation caused by the four-legged robot impact different outcomes, such as task performance and safety, to gain a more comprehensive understanding of the implications of these findings.

5.4. Impact of four-legged robot interaction space on emotional state

Participants' emotional states were measured using the PANAS-SF before starting and after completing the experiment (see Fig. 5), and the changes (Δ) in the positive and negative affect scores were calculated for both groups (Table 7). Results showed that both groups experienced an increase in positive Affect and a decrease in negative Affect after the experiment. Additionally, participants in the distal (12 – 25 ft) group experienced slightly more positive emotional changes (2.58 ± 3.53) compared to those in the proximal (1.5 – 4 ft) group (1.89 ± 2.19), as well as slightly more negative emotional changes (−1.58 ± 2.97 vs. −0.53 ± 2.62, respectively). However, the differences in the positive and negative Affects between both groups were not statistically significant ($p \geq 0.115$). Therefore, the four-legged robot operation distance was not found to play a role in significantly impacting construction individuals' emotional states. These results align with user-centered experiments in construction and industrial settings. For instance, in a study assessing trust dynamics in human-robot collaborative tasks within the construction industry, robot proximity in open workspaces with low-level of HRI was not found to be significantly associated with changes in valence or arousal, showing only weak correlations (Chauhan et al., 2024). Similarly, another study in industrial settings found no statistical evidence that distance from robots influenced participants' valence or arousal (Gervasi et al., 2022). These findings further support the notion that robot distance may not play a significant role in influencing emotional states in construction and industrial contexts.

Table 7
Participants' PANAS-SF Scores.

	Proximal (1.5 – 4 ft) Mean ± SD	Distal (12 – 25 ft) Mean ± SD	p-value
ΔPositive Affect	1.89 ± 2.19	2.58 ± 3.53	0.319
ΔNegative Affect	−0.53 ± 2.62	−1.58 ± 2.97	0.115

The increase in positive Affect and decrease in negative Affect after completing the experiment could be attributed to other factors. For example, the observed change in participants' positive and negative Affects could be attributed to their exposure to VR, or alternatively, to a change in their perception of the presence of the four-legged robot on jobsites at the end of the experiment. In fact, many participants indicated such a change in their open-ended feedback responses, reporting their robot perception to be *"odd at first"*, but then becoming *"normal"* with time. This evolution of their perceptions from initial discomfort to eventual normalization over the course of the experiment is a phenomenon well-documented in psychology as the familiarity or mere exposure effect (Kim et al., 2013). In addition, one participant reported becoming *"warier"* if the robot had a *"human-like face or was forming emotions"*. This attribution of human-like characteristics or emotions to the robot demonstrates the effect of anthropomorphism (Złotowski et al., 2015). Further research is needed to study these effects, both quantitatively and qualitatively, as they relate to the safety impacts associated with four-legged robots on jobsites.

5.5. Impact of four-legged robot interaction space on situational awareness

Regardless of the interaction distance [proximal (1.5 – 4 ft) or distal (12 – 25 ft)] between construction individuals and the four-legged robot, the SART questionnaire scores indicate that participants of both groups were almost equally aware of their surroundings and the four-legged robot after completing the task in VR (Table 8). This was evidenced by the non-significant p-value of 0.897. Therefore, the results do not provide enough evidence supporting the fact that the four-legged robot operation distance has a significant impact on individuals' situational awareness. However, it should be noted that both group scores were slightly above the midpoint score of the SART scale, a factor that could indicate that the general presence of the four-legged robot in the environment could have a negative impact on participants' situational awareness. This was also reflected in participants' open-ended feedback responses, suggesting that working with robots on the jobsite requires *"adequate training to enhance individuals' situational awareness and refrain from any hazard or injury"*. In addition, another participant indicated that construction individuals need to be *"alert of the situation"* when working with robots on jobsites. Reduced situational awareness could affect individuals' ability to understand, anticipate, and proactively respond to potential issues or accidents that may arise on jobsites, potentially leading to a higher risk for errors or accidents (Ibrahim et al., 2023). These concerns are particularly important considering that studies within industrial settings have found that variations in the level of robot assistance can directly impact situational awareness. Specifically, increased automation and higher levels of robot assistance are often associated with decreased situational awareness (Gombolay et al., 2017; Kaber and Endsley, 2004; Hopko et al., 2021). These findings align with the feedback provided by the participants in this study, suggesting that the introduction of robots, regardless of their specific operational distance, could negatively influence situational awareness. Therefore, future research should focus on objectively and subjectively evaluating whether individuals' situational awareness is negatively impacted by the presence of four-legged robots on jobsites. If so, appropriate training interventions should be provided for construction individuals and more intuitive human-four-legged robot systems need to be developed to optimize and ensure safe human-robot interaction in construction.

Table 8
Participants' SART Scores.

	Proximal (1.5 – 4 ft) Mean ± SD	Distal (12 – 25 ft) Mean ± SD	p-value
SART (range: −14 – 46)	18.92 ± 4.48	18.75 ± 6.30	0.897

5.6. Impact of four-legged robot interaction space on risk perception

Participants' risk perception scores (range: 0 – 14,055.75) on the scenario and task that they were asked to complete in VR are shown in Table 9. When asked about the list of injury types along with their associated frequencies that may potentially occur in the VR construction scenario, both the proximal (1.5 – 4 ft) group and the distal (12 – 25 ft) group reported somewhat similar percentages. Specifically, the proximal (1.5 – 4 ft) group indicated a 58.33 % risk of discomfort or pain injury, a 48.61 % risk of requiring first aid, a 33.33 % risk of requiring medical attention, a 34.72 % risk of losing work time, and a 22.92 % risk of experiencing permanent disability or fatality. The distal (12 – 25 ft) group reported a 56.25 % risk of discomfort or pain injury, a 50.69 % risk of requiring first aid, a 31.94 % risk of requiring medical attention, a 34.72 % risk of losing work time, and a 19.44 % risk of experiencing permanent disability or fatality. The results therefore did not support the fact that construction individuals' risk perception levels were affected by the distance between them and the four-legged robot ($p = 0.389$). While the current study's results align with findings from industrial settings where proximity to robots did not significantly affect risk perception (Gervasi et al., 2022), they diverge from the intuitive notion that distance from robots universally affects perceived risk. This concept, rooted in Hall's proxemics theory (Hall, 1969), has been relied upon in previous studies across various fields, including construction (You et al., 2018; Rubagotti et al., 2022). This divergence highlights the need for a nuanced understanding of risk perception in human-robot interactions on construction sites, suggesting that factors beyond proximity, such as the nature of the robot's tasks and the context of its operation, may also play crucial roles.

Nevertheless, regardless of the four-legged robot operation distance, participants expressed their concern about the potential risks associated with the presence of such mobile collaborative robots on jobsites. Some participants were concerned that the four-legged robot could *"hurt workers on site"* and reported that the robot could be a *"tripping hazard"*, that they may end up *"hitting some robots if there were many on the jobsite"*, and that the presence of the robot makes the task *"seem more dangerous"*. Thorough risk assessments are needed to objectively and subjectively evaluate how people perceive risks with robots on construction sites. Such assessments should be followed by proper safety protocols to address the concerns raised by the participants about the potential of the four-legged robot to cause onsite harm or accidents. This ultimately ensures safe human-robot integration in construction.

5.7. Impact of four-legged robot interaction space on attitude

Participants' scores on NARS and its three subscales measuring their attitudes towards robots were similar across both groups, as summarized in Table 10. Specifically, both groups had slightly positive attitudes toward situations of interaction with the four-legged robot, as evidenced by their average scores on Subscale 1 which fell below the subscale's midpoint. Also, participants did not exhibit particularly positive or negative attitudes toward the social influence of the four-legged robot (Subscale 2) or the emotions in interaction with it (Subscale 3). The average ratings for both subscales fell at the midpoints of Subscales 2 and 3. Therefore, the results did not indicate any significant impact of the four-legged robot operation distance on construction individuals' attitudes ($p \geq 0.547$). The obtained results are consistent with the

Table 9
Participants' risk perception scores.

	Proximal (1.5 – 4 ft) Mean ± SD	Distal (12 – 25 ft) Mean ± SD	p-value
Risk Score (range: 0 – 14,055.75)	3,278.95 ± 2,799.68	2,805.07 ± 1,709.78	0.389

Table 10
Participants' NARS Subscale Scores.

	Proximal (1.5 – 4 ft) Mean ± SD	Distal (12 – 25 ft) Mean ± SD	p-value
Subscale 1: Situations of Interaction (range: 6 – 30)	13.25 ± 4.03	12.86 ± 3.73	0.672
Subscale 2: Social Influence (range: 5 – 25)	16.03 ± 3.53	15.53 ± 3.47	0.547
Subscale 3: Emotions in Interaction (range: 3 – 15)	9.22 ± 2.51	8.97 ± 2.34	0.663

findings of a systematic review that summarized the responses of more than 13,000 participants across 97 studies, indicating that people generally have positive attitudes towards robots (Naneva et al., 2020). The findings also align with those from an industrial setting, where slightly positive attitudes towards situations of interactions were reported, and neutral attitudes towards social influence and emotions in interactions were observed (Gervasi et al., 2022). This consistency across settings supports the idea that attitudes towards robots are generally positive and stable. However, some evidence in HRI suggests that individuals with negative attitudes towards robots often maintain greater distances and feel less comfortable interacting with them (Takayama and Pantofaru, 2009). Since neutral to positive attitudes were reported in this study regardless of operation distance, it indicates that participants did not have strongly negative attitudes towards the robot, and the four-legged robot's operational distance was not a key factor in shaping participants' attitudes. The relatively neutral attitude of participants towards robots in the three subscales is also reflected in their responses to the open-ended feedback, which were slightly split between positive and negative perceptions of the robot presence.

6. Conclusion and recommendations

This study aimed to empirically evaluate the impact of four-legged robot proxemics on construction individuals' physiological, attentional, and emotional states, as well as their situational awareness, risk perception, and attitudes towards four-legged robots. Employing a VR setup simulating a material handling and bricklaying task, recruited construction individuals assumed the role of jobsite supervisors and interacted with a four-legged robot at two different interaction distances: proximal (1.5 – 4 ft) and distal (12 – 25 ft). The results indicated that the four-legged robot interaction space did not significantly influence construction individuals' physiological states, emotional states, situational awareness, risk perception, and attitudes towards four-legged robots. However, analysis of attentional impact revealed that participants across both interaction space groups diverted some attention from the task to the four-legged robot. Notably, those in the distal group allocated significantly more attention to the robot, particularly in terms of fixation count, indicating a significant proxemics impact on attentional states. Additional research is warranted to study the practical significance of these attentional dynamics on construction workers' task performance and safety outcomes, balancing potential distractions with increased awareness of the four-legged robot's presence for improved workplace safety measures.

While this study originally aimed to explore the impact of four-legged robot proxemics on construction workers, participants' responses to the open-ended feedback question brought attention to potential risks associated with the mere presence of robots on jobsites. If not properly addressed, these risks could have profound implications on the well-being and performance of construction individuals. Regardless of the four-legged robot space of interaction, participants reported feelings of discomfort, anxiety, distraction, and heightened alertness in the presence of the robot. This underscores the need for further investigations into how the presence of robots in the workplace affects onsite individuals. Additionally, participants' responses highlighted the influence of mere exposure and anthropomorphism on human-robot interaction. This calls for deeper exploration into how familiarity with robots and the human-like appearance of robots shape construction individuals' perceptions and safety behaviors. Understanding these factors is crucial for enhancing the effectiveness and safety of human-robot collaboration in construction settings. These findings emphasize the importance of considering human factors in the design and implementation of robotics in construction environments, highlighting the necessity for additional research and the development of appropriate safety protocols to ensure the safe deployment of robots, especially in dynamic and safety–critical settings like construction sites.

The study's findings highlight several practical implications for enhancing safety and collaboration between humans and four-legged robots on construction sites. Currently, there are limited regulatory standards or guidelines concerning the operation of mobile collaborative robots (e.g., four-legged robots) on jobsites. This hinders the deployment of these robots in human-occupied areas and significantly constrains human-robot collaboration in these settings. To address this, training programs should expose construction individuals to the applications, benefits, and risks associated with four-legged robots on construction sites. This would help familiarize construction individuals with robotic systems, thereby mitigating feelings of unease – which were noticeable particularly in the proximal space—and enhancing their ability to work alongside robots. Such training programs should also include simulated interaction scenarios to help workers build confidence and understand the operational capabilities and limitations of the robots. In terms of robot design, enhancing visibility and predictability of robot movements can significantly improve safety and reduce discomfort. Equipping robots with clear visual or auditory signals to indicate robot movements and intentions would help minimize surprise and anxiety among construction individuals, especially at greater distances (>12 ft). Additionally, integrating sensors that enable robots to detect human presence and adjust their behavior accordingly can further enhance safety and collaboration. Collaboration with regulatory bodies is essential to update and expand safety standards to reflect the unique challenges posed by four-legged robots. Establishing robust emergency response protocols and continuous monitoring and data analysis will be crucial for ongoing refinement of these standards and protocols. Addressing implementation challenges, such as costs and logistics, will also be necessary to ensure effective adoption of these recommendations.

Despite its significant contributions, this study has limitations. First, although VR provided a controlled environment for experimentation, its fidelity in replicating the complex, dynamic nature of actual construction sites and capturing real-world interactions and safety risks may be limited. Testing the VR environment to ensure it accurately simulates real-world conditions is crucial for maintaining ecological validity and generalizability. The decision to use VR in this study was primarily driven by safety concerns, as construction sites are dynamic and hazardous, posing significant safety risks to participants when experimenting with four-legged robots in the real world. Nevertheless, future research should address this gap by replicating the study in real-world or simulated physical construction environments to validate its outcomes and explore the safety impacts of four-legged robots in such settings. In addition, the objective and subjective tools used to assess physiological states, emotional states, situational awareness, risk perception, and attitudes towards robots were selected based on their validity and suitability for the study objectives. These tools were also widely adopted and used in HRI research to study human behavior near or around robots. However, it is important to note that the accuracy of these tools may be compromised in a VR setting. In addition, the sensitivity of these tools to detect subtle changes in response to proximal versus distal four-legged robot interactions may also vary. Future studies should explore alternative measurement methods or refine existing tools to enhance sensitivity to small but potentially meaningful differences. Furthermore, while the 2-minute duration in VR dedicated to physiological and attentional data collection provided sufficient data for initial analysis, it may be considered brief for capturing extensive physiological changes. Shorter durations might limit the depth of interaction and adaptation to the VR environment, which could affect the perception of long-term collaborative dynamics between humans and robots. To address this limitation, extending the duration of future studies is recommended to better capture long-term physiological responses and perceptual changes. This approach will help evaluate whether prolonged exposure affects participants' interactions with the robot and how these interactions might differ from short-term engagements. Considering longer data collection periods will also ensure more robust data capture and analysis, thereby enhancing the validity of the conclusions regarding human-robot interactions in varied time settings. Another limitation stems from the controlled environment of the study, wherein participants interacted with the four-legged robot at rest, while controlling for potential effects caused by external stressors. Individuals on real-world construction sites are subject to various stressors (e.g., fatigue, heat stress) which could interact with even subtle psychophysiological changes and potentially lead to significant safety implications. Additional investigations should delve into these real-world stressors to comprehensively understand their relationship with the presence of four-legged robots and their impact on safety outcomes. Furthermore, the study sample consisted only of construction management students, which neglects the diverse backgrounds and experiences prevalent among construction individuals on jobsites. Future research should encompass a broader spectrum of participants, covering a more diverse and experienced pool that better represents the construction workforce. This approach ensures that the findings are applicable and generalizable across various demographics and professional backgrounds within the construction industry. In addition, the simplicity of the task conducted in the study may limit the applicability of the obtained findings to more complex construction activities that four-legged robots are expected to assist with. Examining task complexity is crucial, as it can significantly affect human workload and, consequently, the dynamics, effectiveness, and safety of human-robot interactions on construction sites. Future studies should aim to include a diverse range of tasks, encompassing various levels of complexity and configurations. Moreover, exploring different levels of human-robot collaboration is essential, as tasks requiring higher levels of interaction might present unique challenges and opportunities compared to those involving lower levels of collaboration. By incorporating a variety of tasks with differing complexities and configurations and investigating various levels of human-robot collaboration, future studies can ensure broader generalizability of findings to different real-world construction scenarios and provide deeper insights into their impact on overall performance and safety. Finally, this study only focused on physiological and attentional risks, and did not consider other potential risk categories that four-legged robots are expected to be associated with on construction sites, such as physical or contact risks. Further investigations are warranted to comprehensively assess all potential risk factors associated with the integration of four-legged robots into construction environments. Ultimately, this would ensure the development of robust training programs, safety protocols, and mitigation strategies.

CRediT authorship contribution statement

Gilles Albeaino: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Idris Jeelani:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Masoud Gheisari:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Raja R.A. Issa:** Writing – review & editing, Supervision.

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.

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References

Abdelhamid, T.S., Everett, J.G., 1999. Physiological demands of concrete slab placing and finishing work. J. Constr. Eng. Manag. 125, 47–52.
Abdelhamid, T.S., Everett, J.G., 2002. Physiological demands during construction work. J. Constr. Eng. Manag. 128, 427–437.
K. Afsari, S. Halder, M. Ensafi, S. DeVito, J. Serdakowski, Fundamentals and Prospects of Four-Legged Robot Application in Construction Progress Monitoring, in: 57th Annual Associated Schools of Construction International Conference, 2021: pp. 274–283. DOI: 10.29007/cdpd.
K. Afsari, S. Halder, R. King, W. Thabet, J. Serdakowski, S. DeVito, M. Ensafi, J. Lopez, Identification of Indicators for Effectiveness Evaluation of Four-Legged Robots in Automated Construction Progress Monitoring, in: 2022: pp. 610–620. DOI: 10.1061/9780784483961.064.
Albeaino, G., Brophy, P., Jeelani, I., Gheisari, M., Issa, R.R., 2023. Psychophysiological Impacts of Working at Different Distances from Drones on Construction Sites. J. Comput. Civ. Eng. 37, 04023026.
Albeaino, G., Brophy, P., Jeelani, I., Gheisari, M., Issa, R.R.A., 2023. Impact of Drone Presence on Construction Individuals Working at Heights. J. Constr. Eng. Manag. 149, 04023119. https://doi.org/10.1061/JCEMD4.COENG-13861.
G. Albeaino, I. Jeelani, M. Gheisari, R.R.A. Issa, Attentional Impact of Drones on Construction Sites, in: EPiC Series in Built Environment, EasyChair, 2023: pp. 121–129. DOI: 10.29007/t7jn.
Askarian, B., Jung, K., Chong, J.W., 2019. Monitoring of Heart Rate from Photoplethysmographic Signals Using a Samsung Galaxy Note8 in Underwater Environments. Sensors (basel) 19, 2846. https://doi.org/10.3390/s19132846.
R. Bednarik, M. Tukiainen, An eye-tracking methodology for characterizing program comprehension processes, Proceedings of the 2006 Symposium on Eye Tracking Research & Applications (2006) 125–132. DOI: 10.1145/1117309.1117356.
Bellicoso, C.D., Bjelonic, M., Wellhausen, L., Holtmann, K., Günther, F., Tranzatto, M., Fankhauser, P., Hutter, M., 2018. Advances in real-world applications for legged robots. J. Field Rob. 35, 1311–1326. https://doi.org/10.1002/rob.21839.
Bellicoso, C.D., Krämer, K., Stäuble, M., Sako, D., Jenelten, F., Bjelonic, M., Hutter, M., 2019. Alma-articulated locomotion and manipulation for a torque-controllable robot. IEEE, in, pp. 8477–8483.
Bhandari, S., Hallowell, M.R., Van Boven, L., Gruber, J., Welker, K.M., 2016. Emotional states and their impact on hazard identification skills. In 2831–2840.
US BLS, National Census of Fatal Occupational Injuries in 2022, 2023. https://www.bls.gov/news.release/pdf/cfoi.pdf.
W. Boucsein, Electrodermal activity, Springer Science & Business Media, 2012.
Bowen, P., Edwards, P., Lingard, H., Cattell, K., 2014. Occupational stress and job demand, control and support factors among construction project consultants. Int. J. Proj. Manag. 32, 1273–1284. https://doi.org/10.1016/j.ijproman.2014.01.008.
Braithwaite, J.J., Watson, D.G., Jones, R., Rowe, M., 2013. A guide for analysing electrodermal activity (EDA) & skin conductance responses (SCRs) for psychological experiments. Psychophysiology 49, 1017–1034.
R. Bretin, E.S. Cross, M. Khamis, Co-existing With a Drone: Using Virtual Reality to Investigate the Effect of the Drone's Height and Cover Story on Proxemic Behaviours, CHI Conference on Human Factors in Computing Systems Extended Abstracts (2022) Article 377. DOI: 10.1145/3491101.3519750.
S. Brown, A.B. Trueblood, W. Harris, X.S. Dong, Construction worker mental health during the COVID-19 pandemic, CPWR, 2022. https://stacks.cdc.gov/view/cdc/115986.
Chang, E., Kim, H.T., Yoo, B., 2020. Virtual Reality Sickness: A Review of Causes and Measurements. Null 36, 1658–1682. https://doi.org/10.1080/10447318.2020.1778351.
Chauhan, H., Pakbaz, A., Jang, Y., Jeong, I., 2024. Analyzing Trust Dynamics in Human-Robot Collaboration through Psychophysiological Responses in an Immersive Virtual Construction Environment. J. Comput. Civ. Eng. 38, 04024017. https://doi.org/10.1061/JCCEE5.CPENG-5692.
Cohen, J., LaRue, C., Cohen, H.H., 2017. Attention interrupted: Cognitive distraction & workplace safety. Prof. Saf. 62, 28–34.
Dakhli, Z., Lafhaj, Z., 2017. Robotic mechanical design for brick-laying automation. Cogent Engineering 4, 1361600.
Daza, M., Barrios-Aranibar, D., Diaz-Amado, J., Cardinale, Y., Vilasboas, J., 2021. An Approach of Social Navigation Based on Proxemics for Crowded Environments of Humans and Robots. Micromachines (basel) 12, 193. https://doi.org/10.3390/mi12020193.
Dobkin, P.L., Pihl, R.O., 1992. Measurement of Psychological and Heart Rate Reactivity to Stress in the Real World. Psychother. Psychosom. 58, 208–214. https://doi.org/10.1159/000288629.

Boston Dynamics, Public Safety Solutions, Boston Dynamics (2021). https://www.bostondynamics.com/solutions/public-safety (accessed April 27, 2022).

I. Eimontaite, C. Jaksic, S. Fletcher, T. Johnson, A.-M. Oostveen, Will operators work in close proximity to industrial robots? A study of acceptance using psychological and physiological responses, in: A Study of Acceptance Using Psychological and Physiological Responses (October 23, 2020). TESConf, 2020. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3718020.

Fang, W., Ding, L., Luo, H., Love, P.E.D., 2018. Falls from heights: A computer vision-based approach for safety harness detection. Autom. Constr. 91, 53–61. https://doi.org/10.1016/j.autcon.2018.02.018.

Gervasi, R., Aliev, K., Mastrogiacomo, L., Franceschini, F., 2022. User Experience and Physiological Response in Human-Robot Collaboration: A Preliminary Investigation. J Intell Robot Syst 106, 36. https://doi.org/10.1007/s10846-022-01744-8.

Ghodrati, N., Yiu, T.W., Wilkinson, S., 2018. Unintended consequences of management strategies for improving labor productivity in construction industry. J. Saf. Res. 67, 107–116. https://doi.org/10.1016/j.jsr.2018.09.001.

Gombolay, M., Bair, A., Huang, C., Shah, J., 2017. Computational design of mixed-initiative human–robot teaming that considers human factors: situational awareness, workload, and workflow preferences. The International Journal of Robotics Research 36, 597–617.

Greco, A., Valenza, G., Lanata, A., Scilingo, E.P., Citi, L., 2016. cvxEDA: A Convex Optimization Approach to Electrodermal Activity Processing. IEEE Trans. Biomed. Eng. 63, 797–804. https://doi.org/10.1109/TBME.2015.2474131.

Greco, A., Valenza, G., Lazaro, J., Garzon-Rey, J.M., Aguilo, J., De-la-Camara, C., Bailon, R., Scilingo, E.P., 2021. Acute stress state classification based on electrodermal activity modeling. IEEE Trans. Affect. Comput. 1. https://doi.org/10.1109/TAFFC.2021.3055294.

Halder, S., Afsari, K., 2022. Real-time Construction Inspection in an Immersive Environment with an Inspector Assistant Robot, EPiC Series in Built. Environ. 3, 389–397.

Halder, S., Afsari, K., Serdakowski, J., DeVito, S., Ensafi, M., Thabet, W., 2022. Real-Time and Remote Construction Progress Monitoring with a Quadruped Robot Using Augmented Reality. Buildings 12. https://doi.org/10.3390/buildings12112027.

Halder, S., Afsari, K., Chiou, E., Patrick, R., Hamed, K.A., 2023. Construction inspection & monitoring with quadruped robots in future human-robot teaming: A preliminary study. Journal of Building Engineering 65, 105814. https://doi.org/10.1016/j.jobe.2022.105814.

S. Halder, K. Afsari, J. Serdakowski, S. DeVito, R. King, Accuracy Estimation for Autonomous Navigation of a Quadruped Robot in Construction Progress Monitoring, in: Computing in Civil Engineering 2021, 2021: pp. 1092–1100. DOI: 10.1061/9780784483893.134.

E.T. Hall, Distances In Man, in: The Hidden Dimension, Anchor Books, New York, NY, USA, 1969.

Haring, K.S., Matsumoto, Y., Watanabe, K., 2014. Perception and trust towards a lifelike android robot in Japan. In: Transactions on Engineering Technologies: Special Issue of the World Congress on Engineering and Computer Science 2013. Springer, pp. 485–497.

Hasan, A., Baroudi, B., Elmualim, A., Rameezdeen, R., 2018. Factors affecting construction productivity: a 30 year systematic review. Eng. Constr. Archit. Manag. 25, 916–937. https://doi.org/10.1108/ECAM-02-2017-0035.

Haslam, R.A., Hide, S.A., Gibb, A.G.F., Gyi, D.E., Pavitt, T., Atkinson, S., Duff, A.R., 2005. Contributing factors in construction accidents. Appl Ergon 36, 401–415. https://doi.org/10.1016/j.apergo.2004.12.002.

Henkel, Z., Bethel, C.L., Murphy, R.R., Srinivasan, V., 2014. Evaluation of proxemic scaling functions for social robotics. IEEE Trans. Hum.-Mach. Syst. 44, 374–385.

Herborn, K.A., Graves, J.L., Jerem, P., Evans, N.P., Nager, R., McCafferty, D.J., McKeegan, D.E.F., 2015. Skin temperature reveals the intensity of acute stress. Physiol. Behav. 152, 225–230. https://doi.org/10.1016/j.physbeh.2015.09.032.

Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., Van de Weijer, J., 2011. Eye tracking: A comprehensive guide to methods and measures. Oxford University Press.

Hopko, S.K., Khurana, R., Mehta, R.K., Pagilla, P.R., 2021. Effect of cognitive fatigue, operator sex, and robot assistance on task performance metrics, workload, and situation awareness in human-robot collaboration. IEEE Rob. Autom. Lett. 6, 3049–3056.

Huettenrauch, H., Eklundh, K.S., Green, A., Topp, E.A., 2006. Investigating Spatial Relationships in Human-Robot Interaction, in. IEEE/RSJ International Conference on Intelligent Robots and Systems 2006, 5052–5059. https://doi.org/10.1109/IROS.2006.282535.

Hwang, S., Jebelli, H., Choi, B., Choi, M., Lee, S., 2018. Measuring workers' emotional state during construction tasks using wearable EEG. J. Constr. Eng. Manag. 144, 04018050.

Ibrahim, A., Nnaji, C., Namian, M., Koh, A., Techera, U., 2023. Investigating the impact of physical fatigue on construction workers' situational awareness. Saf. Sci. 163, 106103. https://doi.org/10.1016/j.ssci.2023.106103.

Jang, Y., Seol, W., Lee, K., Kim, K., Kim, S., 2022. Development of quadruped robot for inspection of underground pipelines in nuclear power plants. Electron. Lett 58, 234–236.

H. Jebelli, B. Choi, S. Lee, Application of Wearable Biosensors to Construction Sites. II: Assessing Workers' Physical Demand, Journal of Construction Engineering and Management 145 (2019) 04019080. DOI: 10.1061/(ASCE)CO.1943-7862.0001710.

H. Jebelli, B. Choi, S. Lee, Application of Wearable Biosensors to Construction Sites. I: Assessing Workers' Stress, Journal of Construction Engineering and Management 145 (2019) 04019079. DOI: 10.1061/(ASCE)CO.1943-7862.0001729.

Jeelani, I., Gheisari, M., 2021. Safety challenges of UAV integration in construction: Conceptual analysis and future research roadmap. Saf. Sci. 144, 105473. https://doi.org/10.1016/j.ssci.2021.105473.

Jose, A.D., Collison, D., 1970. The normal range and determinants of the intrinsic heart rate in man. Cardiovasc. Res. 4, 160–167. https://doi.org/10.1093/cvr/4.2.160.

Kaber, D.B., Endsley, M.R., 2004. The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task. Theor. Issues Ergon. Sci. 5, 113–153.

Ke, J., Zhang, M., Luo, X., Chen, J., 2021. Monitoring distraction of construction workers caused by noise using a wearable Electroencephalography (EEG) device. Autom. Constr. 125, 103598. https://doi.org/10.1016/j.autcon.2021.103598.

Kim, J., Chung, D., Kim, Y., Kim, H., 2022. Deep learning-based 3D reconstruction of scaffolds using a robot dog. Autom. Constr. 134, 104092. https://doi.org/10.1016/j.autcon.2021.104092.

Kim, A., Han, J., Jung, Y., Lee, K., 2013. The effects of familiarity and robot gesture on user acceptance of information. IEEE, in, pp. 159–160.

Kim, Y., Kim, S., Chen, Y., Yang, H., Kim, S., Ha, S., Gombolay, M., Ahn, Y., Cho, Y.K., 2024. Understanding human-robot proxemic norms in construction: How do humans navigate around robots? Autom. Constr. 164, 105455. https://doi.org/10.1016/j.autcon.2024.105455.

Kolvenbach, H., Wisth, D., Buchanan, R., Valsecchi, G., Grandia, R., Fallon, M., Hutter, M., 2020. Towards autonomous inspection of concrete deterioration in sewers with legged robots. J. Field Rob. 37, 1314–1327.

Lanatà, A., Valenza, G., Greco, A., Gentili, C., Bartolozzi, R., Bucchi, F., Frendo, F., Scilingo, E.P., 2015. How the Autonomic Nervous System and Driving Style Change With Incremental Stressing Conditions During Simulated Driving. IEEE Trans. Intell. Transp. Syst. 16, 1505–1517. https://doi.org/10.1109/TITS.2014.2365681.

Langdon, R.R., Sawang, S., 2018. Construction Workers' Well-Being: What Leads to Depression, Anxiety, and Stress? J. Constr. Eng. Manag. 144. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001406'].

Larsson, P., Dekker, S.W.A., Tingvall, C., 2010. The need for a systems theory approach to road safety. Saf. Sci. 48, 1167–1174. https://doi.org/10.1016/j.ssci.2009.10.006.

Lenhardt, R., Sessler, D.I., 2006. Estimation of Mean Body Temperature from Mean Skin and Core Temperature. Anesthesiology 105, 1117–1121. https://doi.org/10.1097/00000542-200612000-00011.

Leung, M.-Y., Liang, Q., Olomolaiye, P., 2016. Impact of job stressors and stress on the safety behavior and accidents of construction workers. J. Manag. Eng. 32, 04015019.

Leung, M., Liang, Q., Chan, I.Y., 2017. Development of a stressors–stress–performance–outcome model for expatriate construction professionals. J. Constr. Eng. Manag. 143, 04016121.

N.G. Leveson, A New Approach To System Safety Engineering, 2002. https://dspace.mit.edu/bitstream/handle/1721.1/71860/16-358j-spring-2005/contents/readings/book2.pdf.

Lipscomb, H.J., Glazner, J.E., Bondy, J., Guarini, K., Lezotte, D., 2006. Injuries from slips and trips in construction. Appl. Ergon. 37, 267–274.

Lischke, A., Jacksteit, R., Mau-Moeller, A., Pahnke, R., Hamm, A.O., Weippert, M., 2018. Heart rate variability is associated with psychosocial stress in distinct social domains. J. Psychosom. Res. 106, 56–61. https://doi.org/10.1016/j.jpsychores.2018.01.005.

M.E. Dawson, A.M. Schell, D.L. Filion, The Electrodermal System, in: G.G. Berntson, J.T. Cacioppo, L.G. Tassinary (Eds.), Handbook of Psychophysiology, 4th ed., Cambridge University Press, Cambridge, 2016: pp. 217–243. DOI: 10.1017/9781107415782.010.

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. DOI: 10.1145/1957656.1957786.

Munafo, J., Diedrick, M., Stoffregen, T.A., 2017. The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects. Exp. Brain Res. 235, 889–901. https://doi.org/10.1007/s00221-016-4846-7.

Namian, M., Albert, A., Zuluaga, C.M., Behm, M., 2016. Role of safety training: Impact on hazard recognition and safety risk perception. J. Constr. Eng. Manag. 142, 04016073. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001198.

Namian, M., Albert, A., Feng, J., 2018. Effect of distraction on hazard recognition and safety risk perception. J. Constr. Eng. Manag. 144, 04018008.

Naneva, S., Sarda Gou, M., Webb, T.L., Prescott, T.J., 2020. A Systematic Review of Attitudes, Anxiety, Acceptance, and Trust Towards Social Robots. Int. J. Soc. Robot. 12, 1179–1201. https://doi.org/10.1007/s12369-020-00659-4.

Y. Nassar, G. Albeaino, I. Jeelani, M. Gheisari, R.R.A. Issa, Human-Robot Collaboration Levels in Construction: Focusing on Individuals' Cognitive Workload, in: American Society of Civil Engineers, 2024: pp. 639–648. DOI: 10.1061/9780784485262.065.

Navon, R., Kelly, P.W., Johnston, D.W., 1993. Human Factors in Introducing On-Site Construction Automation. J. Constr. Eng. Manag. 119, 801–812. https://doi.org/10.1061/(ASCE)0733-9364(1993)119:4(801).

S. Negi, R. Mitra, Fixation duration and the learning process: an eye tracking study with subtitled videos, J Eye Mov Res 13 (2020) 10.16910/jemr.13.6.1. DOI: 10.16910/jemr.13.6.1.

Nomura, T., Kanda, T., Suzuki, T., 2006. Experimental investigation into influence of negative attitudes toward robots on human–robot interaction. AI & Soc. 20, 138–150. https://doi.org/10.1007/s00146-005-0012-7.

Nunan, D., Sandercock, G.R.H., Brodie, D.A., 2010. A Quantitative Systematic Review of Normal Values for Short-Term Heart Rate Variability in Healthy Adults. Pacing Clin. Electrophysiol. 33, 1407–1417. https://doi.org/10.1111/j.1540-8159.2010.02841.x.

Pinch, T.J., Bijker, W.E., 1984. The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other. Soc Stud Sci 14, 399–441. https://doi.org/10.1177/030631284014003004.

Rozenfeld, O., Sacks, R., Rosenfeld, Y., Baum, H., 2010. Construction Job Safety Analysis. Saf. Sci. 48, 491–498. https://doi.org/10.1016/j.ssci.2009.12.017.

Rubagotti, M., Tusseyeva, I., Baltabayeva, S., Summers, D., Sandygulova, A., 2022. Perceived safety in physical human–robot interaction—A survey. Rob. Auton. Syst. 151, 104047. https://doi.org/10.1016/j.robot.2022.104047.

S. Halder, K. Afsari, J. Serdakowski, S. DeVito, A Methodology for BIM-enabled Automated Reality Capture in Construction Inspection with Quadruped Robots, in: C. Feng, T. Linner, I. Brilakis, D. Castro, P.-H. Chen, Y. Cho, J. Du, S. Ergan, B. Garcia de Soto, J. Gašparík, F. Habbal, A. Hammad, K. Iturralde, T. Bock, S. Kwon, Z. Lafhaj, N. Li, C.-J. Liang, B. Mantha, M.S. Ng, D. Hall, M. Pan, W. Pan, F. Rahimian, B. Raphael, A. Sattineni, C. Schlette, I. Shabtai, X. Shen, P. Tang, J. Teizer, Y. Turkan, E. Valero, Z. Zhu (Eds.), Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC), International Association for Automation and Robotics in Construction (IAARC), Dubai, UAE, 2021: pp. 17–24. DOI: 10.22260/ISARC2021/0005.

Samarakoon, S.M.B.P., Muthugala, M.A.V.J., Jayasekara, A.G.B.P., 2022. A Review on Human-Robot Proxemics. Electronics 11, 2490. https://doi.org/10.3390/electronics11162490.

Shaffer, F., Ginsberg, J.P., 2017. An Overview of Heart Rate Variability Metrics and Norms, Front. Public Health 5, 258. https://doi.org/10.3389/fpubh.2017.00258.

Simeonov, P.I., Hsiao, H., DotsonM, B.W., Ammons, D.E., 2005. Height Effects in Real and Virtual Environments. Hum Factors 47, 430–438. https://doi.org/10.1518/0018720054679506.

Sun, Y., Jeelani, I., Gheisari, M., 2023. Safe human-robot collaboration in construction: A conceptual perspective. J. Saf. Res. 86, 39–51. https://doi.org/10.1016/j.jsr.2023.06.006.

Sund-Levander, M., Forsberg, C., Wahren, L.K., 2002. Normal oral, rectal, tympanic and axillary body temperature in adult men and women: a systematic literature review. Scand. J. Caring Sci. 16, 122–128. https://doi.org/10.1046/j.1471-6712.2002.00069.x.

Sussell, A., Peterson, C., Li, J., Miniño, A., Scott, K.A., Stone, D.M., 2021. Suicide Rates by Industry and Occupation — National Vital Statistics System, United States. MMWR Morb Mortal Wkly Rep 72 (2023), 1346–1350. https://doi.org/10.15585/mmwr.mm7250a2.

Sustarevas, J., Butters, D., Hammid, M., Dwyer, G., Stuart-Smith, R., Pawar, V.M., 2018. MAP - A Mobile Agile Printer Robot for on-site Construction, in. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2018, 2441–2448. https://doi.org/10.1109/IROS.2018.8593815.

L. Takayama, C. Pantofaru, Influences on proxemic behaviors in human-robot interaction, in: IEEE, 2009: pp. 5495–5502.

R.M. Taylor, Situational awareness rating technique (SART): The development of a tool for aircrew systems design, in: Situational Awareness, Routledge, 2017: pp. 111–128.

Tixier, A.-J.-P., Hallowell, M.R., Albert, A., van Boven, L., Kleiner, B.M., 2014. Psychological antecedents of risk-taking behavior in construction. J. Constr. Eng. Manag. 140, 04014052. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000894.

J.R. Turner, Cardiovascular reactivity and stress: Patterns of physiological response, Springer Science & Business Media, 1994.

Wahn, B., König, P., 2017. Is Attentional Resource Allocation Across Sensory Modalities Task-Dependent? Adv Cogn Psychol 13, 83–96. https://doi.org/10.5709/acp-0209-2.

Walters, M.L., Dautenhahn, K., Te Boekhorst, R., Koay, K.L., Kaouri, C., Woods, S., Nehaniv, C., Lee, D., Werry, I., 2005. The influence of subjects' personality traits on personal spatial zones in a human-robot interaction experiment. IEEE, in, pp. 347–352.

D. Watson, L.A. Clark, A. Tellegen, Development and validation of brief measures of positive and negative affect: the PANAS scales., Journal of Personality and Social Psychology 54 (1988) 1063.

Weisberg, R.W., Reeves, L.M., 2013. Cognition: from memory to creativity. John Wiley & Sons.

Wetzel, E.M., Umer, M., Richardson, W., Patton, J., 2022. A Step towards automated tool tracking on construction sites: Boston dynamics SPOT and RFID, EPiC Series in Built. Environ. 3, 488–496.

A. Wojciechowska, J. Frey, S. Sass, R. Shafir, J.R. Cauchard, Collocated Human-Drone Interaction: Methodology and Approach Strategy, in: 2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI), 2019: pp. 172–181. DOI: 10.1109/HRI.2019.8673127.

Wong, F.K., Chan, A.P., Yam, M.C., Wong, E.Y., Kenny, T., Yip, K.K., Cheung, E., 2009. Findings from a research study of construction safety in Hong Kong: Accidents related to fall of person from height. Journal of Engineering, Design and Technology.

Wong, F.K., Chan, A.P., Yam, M.C., Wong, E.Y., Tse, K.T., Yip, K.K., Cheung, E., 2009. Findings from a research study of construction safety in Hong Kong: Accidents related to fall of person from height. Journal of Engineering, Design and Technology 7, 130–142.

Wu, X., Li, Y., Yao, Y., Luo, X., He, X., Yin, W., 2018. Development of construction workers job stress scale to study and the relationship between job stress and safety behavior: An empirical study in Beijing. Int. J. Environ. Res. Public Health 15, 2409.

Xing, X., Li, H., Li, J., Zhong, B., Luo, H., Skitmore, M., 2019. A multicomponent and neurophysiological intervention for the emotional and mental states of high-altitude construction workers. Autom. Constr. 105, 102836. https://doi.org/10.1016/j.autcon.2019.102836.

Y. Kim, Y. Chen, S. Kim, Y.K. Cho, How Much Distance Should Robots Keep from Other Workers at Construction Jobsites?, in: Construction Research Congress 2024, American Society of Civil Engineers, 2024: pp. 893–902. DOI: 10.1061/9780784485262.091.

You, S., Kim, J.-H., Lee, S., Kamat, V., Robert, L.P., 2018. Enhancing perceived safety in human–robot collaborative construction using immersive virtual environments. Autom. Constr. 96, 161–170. https://doi.org/10.1016/j.autcon.2018.09.008.

Yu, S.-N., Ryu, B.-G., Lim, S.-J., Kim, C.-J., Kang, M.-K., Han, C.-S., 2009. Feasibility verification of brick-laying robot using manipulation trajectory and the laying pattern optimization. Autom. Constr. 18, 644–655.

Zhu, Z., Jeelani, I., Gheisari, M., 2023. Physical risk assessment of drone integration in construction using 4D simulation. Autom. Constr. 156, 105099. https://doi.org/10.1016/j.autcon.2023.105099.

Złotowski, J., Proudfoot, D., Yogeeswaran, K., Bartneck, C., 2015. Anthropomorphism: opportunities and challenges in human–robot interaction. Int. J. Soc. Robot. 7, 347–360.