Impact of Drone Presence on Construction Individuals Working at Heights

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Abstract: Drones have had a significant impact on the construction industry. However, their safety implications on construction jobsites are yet to be explored. This user-centered study empirically investigates whether drone presence is associated with any physiological, attentional, and emotional impact on humans, particularly those working at heights who are susceptible to higher risks of injuries and fatalities. Through a between-subject study design, recruited participants were asked to perform construction tasks in a virtual reality environment, with or without the presence of drones, to measure these impacts. Results obtained from the objective and subjective measures showed that drone presence was not associated with changes in participants' physiological and emotional states. However, participants diverted some of their attention from the assigned task toward the drone. This study advances the knowledge of human–drone interaction in construction by informing the construction industry about the safety challenges of drone presence on individuals working at heights. **DOI: 10.1061/JCEMD4.COENG-13861.** *© 2023 American Society of Civil Engineers.*

Author keywords: Drones; Unmanned aerial vehicle (UAV); Safety; Attentional allocation; Emotional state; Physiological state.

Introduction

The complex, dynamic, and diverse nature of jobsites make the construction industry one of the most hazardous and fatal work environments (Borys 2012; Carter and Smith 2006; Li et al. 2012; US BLS 2019). The construction industry was the second-highest industry for occupational fatalities in the United States in 2021, accounting for one out of six occupational deaths or around 18% (951) out of 5,190 reported deaths (US BLS 2022). More than 28,000 worker fatalities occurred in the construction industry during the past 20 years, and around 200,000 nonfatal injuries are being reported every year (US BLS 2019). Among other causes, falls from heights have been identified as the leading source of serious worker injuries and deaths in the construction industry, accounting for about 30% of fatalities and 48% of serious injuries (Hu et al. 2011). In fact, one-third of all construction accidents are related to falls (Zhang and Fang 2013). As jobsite environments are often characterized by temporary and elevated work zones (e.g., ladders, scaffolds, roofs), construction workers operating in such locations are susceptible to much higher injury and fatality risks.

In addition to the hazardous working environment in the construction industry, the recent lag and decline in productivity growth have encouraged construction professionals to increase the use of automation and robotics in their processes to improve project performance and respond to the increasing skilled labor shortage (Delgado et al. 2019). One type of robot that has recently witnessed tremendous growth in the construction industry is drones, also known as "unmanned aerial vehicles" or "unmanned aerial systems." Advantages of drones include their ability to access hard-to-reach locations, be equipped with a variety of sensors, and accomplish tasks in less time and at a lower cost compared with conventional methods (Rakha and Gorodetsky 2018). As a result, drones are adopted throughout the entire project's life-cycle, ranging from preconstruction (e.g., site surveying and mapping, site planning) and construction (e.g., earthwork volumetrics, progress monitoring, safety monitoring and inspection, structure and infrastructure inspection) to postconstruction (e.g., facility maintenance, postdisaster assessment) (Albeaino et al. 2019). The integration of such aerial systems in construction and the expected exposure of onsite personnel to drones are anticipated to grow even more in the future (Albeaino et al. 2022).

While the potential applications and benefits of drones have been widely discussed, their integration into the construction industry raises additional occupational safety and health risks that have not been empirically evaluated yet (Jeelani and Gheisari 2021). More specifically, there is a lack of research examining the impact of working near drones on the health and safety of onsite individuals. Specifically, individuals who are working at heights are already exposed to a higher risk of death or serious injury arising from a fall, and the introduction of drones flying at a close distance from them might lead to adverse emotional, physiological, and attentional allocation impacts (Jeelani and Gheisari 2021). Therefore, understanding the potential safety impact of drones on construction individuals in such hazardous at-height scenarios is particularly important, especially considering the absence of specific regulatory

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Note. This manuscript was submitted on April 7, 2023; approved on August 2, 2023; published online on September 14, 2023. Discussion period open until February 14, 2024; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

guidelines or standards that would take into account the particular needs and safety implications associated with drone usage in the challenging and hazardous environments of construction jobsites (Xu and Turkan 2022a). Therefore, this study aims to empirically investigate whether drone presence is associated with any physiological, attentional, or emotional impact on individuals working at heights. To obtain empirical evidence yet ensure the safety of participants, a user-centered experiment was conducted in a virtual environment. The contribution of this study to the body of knowledge is to provide a better understanding of the safety challenges of drone integration on construction jobsites. This knowledge can ultimately improve the design of future aerial platforms and systems to satisfy the needs of the construction industry and enable the development of specific safety regulations for safe drone operation on construction sites.

Background

Construction Safety and Drone Integration

Compared with other industries, construction has the highest rate of workplace injuries and fatalities (Pinto et al. 2011), with the construction industry being responsible for nearly one in five (20%) workplace deaths (US BLS 2021). The construction industry poses an increased risk of falls, stemming from the nature of working outdoors, at heights, and in complex and dynamic environments (Hu et al. 2011). Of those injuries and fatalities, falls from heights remain the most prevalent source of accidents compared with other types of industries and other jobsite injuries (Nadhim et al. 2016). In fact, a review of accident statistics shows that, each year in the United States, falls from heights cause over 310 fatalities among construction workers and result in more than 10,350 serious injuries (NIOSH 2019). In 2020, 353 out of a total of 1,034 fatal injuries occurring in the construction industry were due to falls, with falls being responsible for approximately one-third (34%) of all construction-related fatalities (US BLS 2021). In that same year, the construction industry was responsible for roughly 50% of all fatal falls, slips, and trips that occurred in the workplace when compared with other industries (US BLS 2021). Some of the main commonalities among falls from heights injuries and fatalities include risky activities, individual characteristics, site conditions, organizational characteristics, and weather conditions as well as working on ladders, scaffolds, and roofs (Nadhim et al. 2016). In particular, working on ladders, scaffolds, and roofs are the three main locations where the majority of nonfatal and fatal fall incidents take place in the construction industry (Brown et al. 2020; Nadhim et al. 2016). Collectively, all three locations are responsible for approximately 75% of fall-related fatalities in construction (Dong et al. 2019). In addition, the construction industry alone accounts for 57% of all ladder-related deaths, 86% of all scaffold-related deaths, and 81% of all roof-related deaths occurring in the workplace (NIOSH 2019). These commonalities are often interrelated, making it difficult to conclude the primary causal factor. Despite the industry's increased interest in improving worker safety, these efforts have failed to eliminate jobsite injuries and fatalities.

At the same time, drones have recently started to influence how construction processes are designed, constructed, operated, and maintained. Such integration in construction processes stems from recent developments, which enabled drones to become highly efficient in accomplishing traditional tasks safely, and in less time and at lower cost (Rakha and Gorodetsky 2018). In addition, drones' flexible and location-independent characteristics make them ideal for accessing unreachable jobsite locations (Albeaino and Gheisari 2021). As a result, these aerial vehicles have been applied for a wide variety of applications in construction. In the preconstruction phase, they have been used for site feasibility evaluation and site planning tasks (Zhou et al. 2018). During the construction phase, these aerial robots are relied upon for site mapping, earthwork volume calculations, progress monitoring, and safety inspection (Martinez et al. 2021; Park et al. 2018; Siebert and Teizer 2014). In the postconstruction phase, drones are used for structure and infrastructure inspections, postdisaster reconnaissance, and marketing purposes (Albeaino et al. 2022; Mutis and Romero 2019; Zhang et al. 2020). The types of drones utilized, along with their on-board payload systems, vary based on different range and characteristics and depend on the specific construction application. In the construction industry, common platforms include rotary-wing vehicles, with quadcopters being particularly prevalent, followed by fixed-wing vehicles (Albeaino et al. 2019; Albeaino and Gheisari 2021). Rotary-wing vehicles offer advantages such as propeller redundancy, hovering midair, vertical takeoff and landing capabilities, and suitability for vertical construction projects (Albeaino et al. 2019). On the other hand, fixed-wing vehicles provide longer flight endurance, the ability to carry heavier payloads, and the capability to cover wider photogrammetric areas (Albeaino et al. 2019). In addition, common sensors employed in construction include red-green-blue (RGB) and thermal cameras, as well as light detection and ranging (LiDAR) and laser scanning devices (Albeaino et al. 2019; Albeaino and Gheisari 2021). By incorporating these drones and sensor technologies, construction professionals can efficiently carry out various tasks, effectively enhancing the overall construction process. It is envisioned that the onsite interaction and collaboration between humans and drones will increase in the future, especially with the current interest in expanding automation in daily construction tasks to address skilled labor shortage and productivity rate decreases (Delgado et al. 2019). This, together with the advancements in robotics and sensors will enable drones to become ubiquitous and essential tools on construction jobsites.

Safety Risks of Drones in the Construction Domain

Despite their advantages and various construction applications, the presence of drones in an already hazardous and dynamic construction jobsite environment can adversely affect the health and safety of construction professionals. Particularly for construction professionals working at heights who are already exposed to a higher falling risk, drones can exacerbate the causal factors of falls compared with others working on site. Drone presence might be associated with negative physiological, emotional, or attentional state changes, potentially increasing the likelihood of worker-related jobsite accidents (Jeelani and Gheisari 2021).

Introducing drones to the jobsites can affect individuals' physiological and emotional states in the long term. More specifically, the presence of novel, potentially threatening stimuli such as drones in a worker's environment can elicit negative physiological and emotional responses (Palomba et al. 1997). This exacerbates the current psychological conditions of construction workers, a large portion of whom continuously report feeling depressed, anxious, and nervous (Brown et al. 2022). Experiencing a negative change in humans' physiological or emotional state while at heights has been shown to reduce balance (Zaback et al. 2019) which could, in turn, increase the risk of injuries or fatalities resulting from subsequent falls. In terms of physiological state, an excessive increase in the physiological demand levels negatively affects attentiveness, motivation, and efficiency while accomplishing physical tasks

(Abdelhamid and Everett 1999, 2002; Bouchard and Trudeau 2008; Gatti et al. 2014). As for the emotional state, humans' hazard identification, decision-making, and risk perception abilities, as well as their awareness and attitude, could all be affected by negative emotional and mental states, factors that, in turn, most likely cause jobsite injuries (Bhandari et al. 2016; Fang et al. 2018; Leung et al. 2017; Wong et al. 2009; Xing et al. 2019).

While the primary purpose behind deploying drones on site is not to monitor construction workers, the onboard drone sensors (e.g., RGB and thermal cameras, motion detectors) inevitably capture their movements. Such drone-mediated monitoring capability creates among workers a feeling of "being watched," especially since they are having both their task-related and non-essential activities continuously recorded in real-time and inappropriate activities identified. This factor can adversely affect their mental health by provoking anxiety and stress responses (Amick and Smith 1992). In addition, the perception of being watched increases the time pressure and construction work progress rate. This adds to the task's cognitive demand (Haslam et al. 2005; Hwang et al. 2018), potentially resulting in secondary effects (e.g., fatigue) that, once more, increase the likelihood of falls (Dawson and Fletcher 2001). Another factor that could provoke a stress response is the fear of being struck by a fast-moving aerial robot while already working in a high-risk environment. Long-time exposure to such psychosocial stressors might cause construction workers to suffer from mental and psychophysiological illnesses caused by chronic emotional and biological arousal (Amick and Smith 1992), potentially causing posture instability and jobsite injuries (Langdon and Sawang 2018; Leung et al. 2016a, b; Wu et al. 2018).

Regarding the attentional allocation, the nearby presence of drones can distract humans from their original tasks. Being distracted at work while accomplishing tasks at heights was identified as one of the leading causes of falls on construction sites (Hanapi et al. 2013; Ke et al. 2021). Humans' ability to process information is hindered by attentional resources, forcing them to selectively concentrate on some information while neglecting others (Wahn and König 2017). When a distracting stimulus such as a drone forces humans to divert their focus from their original tasks, their attentional resources might be exhausted, compromising their performance and ability to rationally quantify risks associated with their underlying tasks (Weisberg and Reeves 2013). This potentially exacerbates the work conditions on the jobsite and generates additional hazards to an already challenging and risky jobsite environment.

Only a few studies have investigated the safety challenges of drones in construction (Gheisari and Esmaeili 2019; Khalid et al. 2021; Kim et al. 2016; Namian et al. 2021; Xu et al. 2020; Xu and Turkan 2022b; Zhu et al. 2022). Of those, Jeelani and Gheisari (2021) theoretically explored the safety risks that could potentially be caused by drone deployment on jobsites and inferred that drone presence could have a physical, attentional, and psychological impact on construction professionals. Through a survey study, Namian et al. (2021) identified several hazards caused by drones on jobsites, including potential collisions with property, collisions with humans, and distractions. To improve current regulatory guidelines, Xu and Turkan (2022a) developed a model that identifies potential drone safety risks and proposes mitigation strategies accordingly. However, no previous study had quantitatively and experimentally evaluated the health and safety risks posed by drones, mainly for those working on heights. This study therefore expands and extends the understanding of drone-associated safety challenges in the construction domain by focusing on evaluating whether drone presence is associated with any physiological, attentional, or emotional impact on those working on heights on the construction jobsites. Findings from this study will contribute to and help inform the industry regarding the safe integration and best practices for drone usage in construction. Furthermore, advancing knowledge about safe drone integration in construction will contribute to developing training interventions for workers and operators alike, improve the design of drone platforms and systems for construction applications, and develop specific safety regulations regarding the safe operation of drones in the construction industry.

Research Goal

This study aimed to empirically evaluate how drone presence on construction jobsites affects those who work at heights. Drones are more likely to operate at height due to their flying nature and influence individuals working on elevated platforms. Those individuals working at heights are already at an increased risk of fatality or injury on jobsites, and drones can potentially exacerbate the causal factors leading to such injuries or fatalities. While drones have been shown to potentially affect health and safety in many ways, this study focuses only on the physiological, attentional, and emotional impacts of drone presence on those working at heights. Through a between-subject design, this user-centered study employs virtual reality (VR) technology and a set of subjective and objective measures to assess how drone presence affects those who work at heights. VR simulations allow data collection via experimentation that otherwise might not be possible due to the hazards posed by drones on construction sites. Previously explored research into simulating height conditions has shown that users exhibit physiological responses and a sense of presence, similar to real-world conditions (Chander et al. 2021; Kisker et al. 2021).

Methodology

Three phases were required to accomplish the aim of the study: (1) scenario content design, (2) virtual scenario development, and (3) user-centered experiment (Fig. 1). In Phase (1), content analysis and literature search were performed to identify construction activities and locations that have commonly preceded injuries and fatalities generated from falls from heights. Phase (2) consisted of replicating the identified falls from heights activities and locations in VR while incorporating dynamic drones, workers, equipment, and activities to simulate a real-world construction environment. In Phase (3), and through a between-subject study design, recruited participants were asked to perform the developed VR-based construction tasks with or without the presence of drones, to measure their physiological, attentional, and emotional impacts when working at heights.

Scenario Content Design

The literature was reviewed to identify various construction activities and locations that contribute to falls from heights (Nadhim et al. 2016). The findings consistently showed that working on ladders, scaffolds, and roofs are the primary causes of injuries and fatalities in falls from heights incidents in construction (Brown et al. 2020; Nadhim et al. 2016). These locations alone account for approximately 75% of fall-related fatalities in the industry (Dong et al. 2019). The literature also showed that the construction industry is responsible for the majority of workplace deaths involving ladders (57%), scaffolds (86%), and roofs (81%) (NIOSH 2019). Moreover, to gather additional data on fatal and non-fatal construction worker injuries caused by falls from heights, the

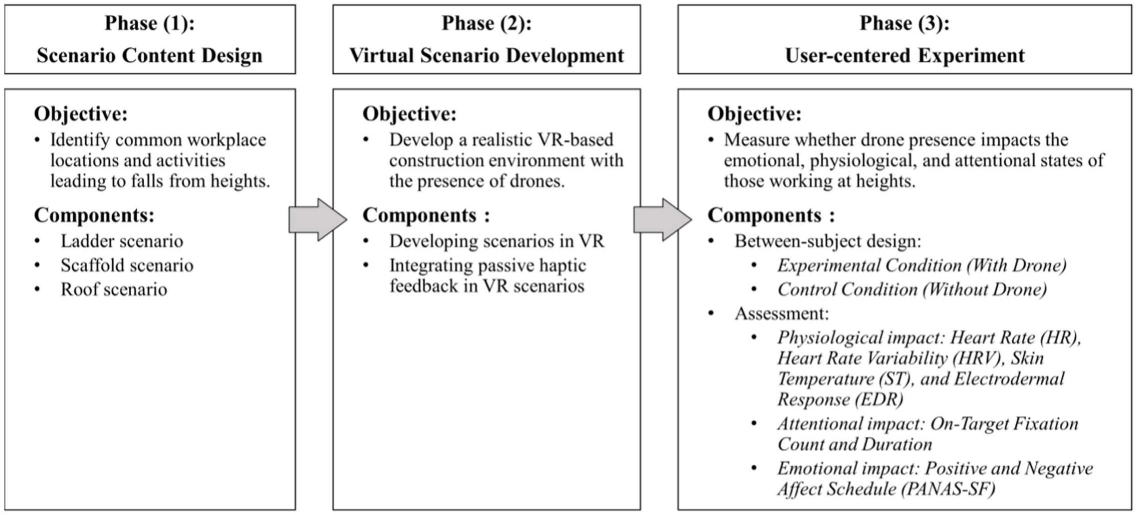

Fig. 1. Research methodology.

Occupational Safety and Health Administration (OSHA)'s Integrated Management Information System (IMIS) database (OSHA 2023) and The Center for Construction Research and Training (CPWR)'s fatality maps (CPWR 2023) were searched over the past five years. Using keywords such as "ladder," "scaffold," and "roof," a total of 650 incidents related to roofs (337), ladders (179), and scaffolds (134) were identified. The corresponding narrative descriptions of these incidents were analyzed to inform the design of the scenario content.

Based on the literature search as well as the analyses performed on OSHA's IMIS and CPWR fatality maps, three specific construction activities or locations were chosen for this study: (1) ladder; (2) scaffold; and (3) roof. These locations were selected due to their association with high safety risks, as they have consistently accounted for more than half of all fall-related worker accidents in the construction industry over the past decade (US DOL 2019). This could further expose construction workers to additional hazards that potentially aggravate their work safety performance, rendering such environments even more hazardous.

Then, three scenarios were designed based on the ladder, scaffold, and roof locations. In the ladder scenario, subjects had to help the onsite painting crew by standing on a ladder placed against a building and painting the building facade. For the scaffold scenario, subjects had to supervise a scaffolding erection crew while monitoring slab concrete placement activities. Subjects were also required to count the number of scaffolding components transported by a construction worker across the formwork to the scaffolding erection crew. For the roof scenario, subjects had to assist the jobsite supervisor by monitoring the productivity of a roofing crew, which was progressively installing shingles and sweeping the workplace area. During each scenario, users were asked a few scenario-specific questions to encourage their full attention and engagement with their surroundings.

VR Scenario Development

This phase focused on the development of the three construction scenarios in VR. To develop the VR-based construction site environment, 3D computer-aided design (CAD) models were imported into an environment in unity (Fig. 2). These CAD models included heavy earthmoving equipment, buildings, temporary structures, cranes, drones, and cast-in-place concrete structures. The 3D models were imported as film box format (.FBX) into unity and organized in a manner congruent with a typical active construction site. The virtual environment was developed on a high-performance computer with an Intel Core i7-9700 CPU at 3.60 GHz processor, 64 GB of RAM, and an Nvidia GeForce RTX 2070 GPU. For enhanced realism, all models were rendered using the high-definition rendered pipeline. Sound effects were produced using FL Studio (FL Studio 2022) and Audacity (Audacity Team 2021) to emulate those typically present on a real-world construction jobsite. The drone sounds from a DJI Phantom 4 Pro were used, as this aerial platform has been among the most popular drones used in construction over the past decade (Albeaino et al. 2019; Albeaino and Gheisari 2021). A spatial blend was used to enable spatial audio effects and enhance the realism of sounds within the environment. The three scenarios (i.e., ladder, scaffold, and roof) were created; then, the virtual drones with proper movements and flying patterns were integrated into each scenario. Additional animated 3D models of construction workers simulating different real-world construction activities were also incorporated into each scenario. Finally, to enhance the realism and increase the likelihood of users developing a sense of presence while experiencing the VR scenarios, some physical elements (e.g., ladder, scaffold railing, ramp) were built in the real world to provide passive haptic feedback (Fig. 2).

User-Centered Experiment

A between-subject design with two experimental conditions was used in this study to assess how drone presence on construction jobsites affects those who work at heights:

1. Experimental condition (with drone condition): Subjects would experience the ladder, scaffold, and roof VR scenarios while drones are present in their work environment.
2. Control condition (without drone condition): Subjects would experience the ladder, scaffold, and roof VR scenarios without the presence of drones.

There were two primary reasons for adopting a between-subject experiment design. The first reason was to eliminate the carryover effect of learning and fatigue typically associated with a within-subject experiment design where participants experience multiple conditions in succession, a factor that potentially causes their performance or perception in later conditions to be influenced by their previous experiences (Leroy 2011). In this between-subject design,

Fig. 2. VR development workflow. (Images by Gilles Albeaino.)

each participant experienced only one condition (with or without drones), reducing the likelihood of carryover effect of learning and fatigue while ensuring the independence of data across conditions. The second reason for choosing a between-subject design was to address the potential risks associated with prolonged exposure to VR. Each scenario (i.e., ladder, scaffold, roof) in the experiment lasted 2.5 min, resulting in a total VR experience of 7.5 min. This duration was kept within the recommended VR exposure time (<10 min) to minimize the occurrence of adverse sickness symptoms such as dizziness, which have been linked to extended VR exposure (Chang et al. 2020; Munafo et al. 2017). The study was approved by the University of Florida Institutional Review Board (UFIRB#202001920).

An a priori power analysis was performed using G*Power v. 3.1.9.7 (Faul et al. 2007). The analysis, utilizing an effect size d of 0.80 (Cohen 1969), a significance level α of 0.05, and a desired power of 0.80 (Beck 2013), showed that a total sample size of 52 participants (26 participants per group) would be required. Considering potential participant dropouts in addition to other technical and external factors, the sample size was increased by 35% to 71 participants in total.

Several qualitative and quantitative measures were collected throughout the study to assess the physiological, attentional, and emotional impacts of drone presence on subjects participating in VR scenarios at heights. For the physiological impact, a wearable Shimmer GSR+ and Shimmer Bridge Amp were used (Fig. 3) to gather the following four measures:

- Heart Rate (HR): Determined from the photoplethysmography (PPG) signal obtained from the Shimmer GSR+ by counting the number of systolic peaks obtained per minute (Askarian et al. 2019). Increased stress is associated with increased HR (Dobkin and Pihl 1992; Turner 1994).
- Heart Rate Variability (HRV): Calculated using the root mean square of successive differences time-domain method as the variation in time between successive heartbeats (Shaffer and Ginsberg 2017). Increased stress is associated with decreased HRV (Lischke et al. 2018).
- Skin Temperature (ST): Measured using Shimmer Bridge Amp's skin-surface temperature probe. An acute stressor or

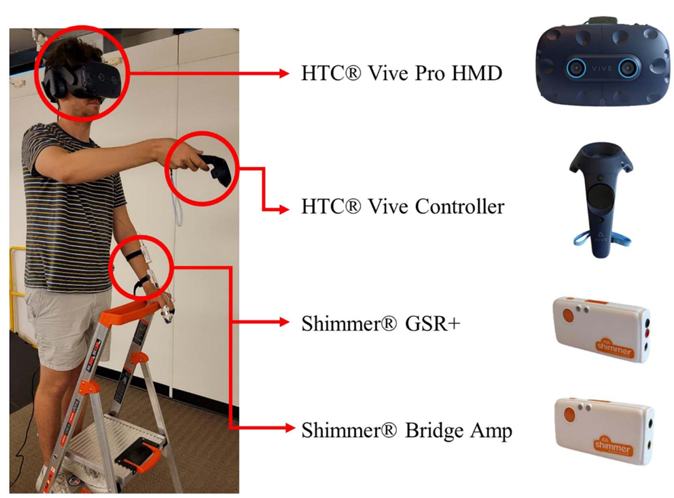

Fig. 3. Data collection hardware. (Images by Gilles Albeaino.)

stimulus results in a swift and momentary drop in ST (Herborn et al. 2015).

- Electrodermal Response (EDR): Phasic component of the electrodermal activity (EDA) obtained from Shimmer GSR+. EDR measures acute stress responses characterized by rapid, short-term changes in EDA potentially resulting from a stimulus or stressor (Boucsein 2012; Greco et al. 2021). These sympathetic nervous system changes often occur because of increased stress, which increases the rate of sweat gland activity and the skin's electrical conductivity (Boucsein 2012; Braithwaite et al. 2013).

For the attentional impact, an HTC Pro head-mounted display (HMD) with a Tobii Pro eye tracker (Fig. 3) was used to measure the fixations, which were counted if users had maintained consecutive gaze of at least 100 ms on the area of interest (Negi and Mitra 2020):

- On-Target (Drone) Fixation Count: Determined by counting the number of times users had looked at the drone during the experiment, which is reflective of the amount of distraction caused by the drone (Harbluk et al. 2002; Savage et al. 2013).
- On-Target (Drone) Fixation Duration: Determined by counting the duration each subject spent fixating on the drone, which also reflects the distraction and amount of attention attracted by drones during the tasks. Distraction (i.e., attentional diversion) could cause unsafe jobsite behavior, resulting in poor safety performance and workplace injuries and fatalities (Cohen et al. 2017; Ke et al. 2021).

To gain insight into subjects' emotional state, they were asked to complete a validated survey:

- Positive and Negative Affect Schedule (PANAS-SF): Consists of 10 questions for evaluating the positive affect subscale (odd-numbered questions) and 10 questions for the negative affect subscale (even-numbered questions) (Watson et al. 1988). The questionnaire was used in the pre- and postexperiment phases of this study to assess whether participants' emotional states (i.e., positive and negative affect) changed after completing the experiment (Appendix S1). The changes (Δ) in participants' responses for the positive affect and negative affect subscale scores before and after the experiment were analyzed. Positive change in the positive affect subscale score is indicative of increased positive affect levels, and a negative change in the negative affect subscale score indicates lower negative affect levels upon experiment completion.

To gather participants' feedback regarding their overall experience, an open-ended question was included at the end of the experiment. More specifically, all participants were required to answer the following question: "In a few sentences, please provide your feedback regarding the experiment." This question allowed participants to freely express their impressions without any bias toward the presence or absence of the drone, especially since the experiment consisted of two groups, namely, the *with drone* and *without drone* groups. The reason for using a general question was to accommodate the experimental design (between-subjects experiment, where half of the participants were assigned to the *with drone* group and the other half to the *without drone* group). This allowed participants from both groups to share their individual thoughts after completing the experiment. Participants' responses to the open-ended feedback question were collected, analyzed, and incorporated into various sections of the manuscript to report their impressions after completing the experiment.

It should be noted that a brief familiarization period was provided for participants prior to the start of each task (i.e., ladder, scaffold, roof) simulated in the VR environment. Specifically, participants were given around 30 s to explore the VR environment and familiarize themselves with their surroundings before starting each task. This allowed them to become accustomed to the effects of VR, the HMD, and the experience of working at heights. In addition, the psychophysiological and attentional data collected during this familiarization period were not included in the subsequent analyses to control for any potential influence of participants' initial psychophysiological and attentional responses to the VR environment, the HMD, and simulated height. The focus was on the data collected during the 7.5 min duration of the VR experiment, where participants completed the ladder, scaffold, and roof tasks while working at heights, with or without the presence of drones.

Data Collection and Processing

- Physiological Data: Physiological data (i.e., HR, HRV, ST, and EDR) from the Shimmer devices were synchronously collected at a sampling frequency of 128 Hz, logged in, and wirelessly streamed via Bluetooth to the Shimmer Consensys Pro software. Data were analyzed between the experimental (i.e., with drone) and control (i.e., without drone) groups. The PPG to HR algorithm provided in the Shimmer Consensys Pro software was used to derive participants' HR values and interbeat intervals (IBI), values of which were used to determine the HRV. The software applies a low-pass filter to the HR and IBI during data collection with a corner frequency of 5 Hz and 200 taps. In addition, a high-pass filter with a cut-off frequency of 0.05 Hz and a Hampel filter were used to process the ST data. The EDA was further broken down into the EDR (phasic) and EDL (tonic) components using the convex optimization approach (Greco et al. 2016). Participants' EDA data were processed using a low-pass filter with a low cutoff frequency of 1.5 Hz to collect the EDL (tonic component) between 0 and 0.05 Hz and the EDR (phasic component) between 0.05 and 1.5 Hz (Braithwaite et al. 2013).
- Eye Tracking Data: As previously indicated, participants' gaze metrics of interest for the *with drone* group were: (1) on-target (drone) fixation count and (2) on-target (drone) fixation duration. The Tobii Pro eye tracker, which is incorporated within the HMD, allowed for the measurement of users' gaze positions throughout the experiment. A fixation was considered only if users had maintained the gaze for at least 100 ms on the area of interest (Negi and Mitra 2020). A C# script was developed to calculate the fixation durations from gaze positions and corresponding timestamps.
- Self-Assessment Data: The change (Δ) in subjects' responses to the PANAS-SF questionnaire that was administered pre- and postexperiment were analyzed to determine the score (between 10 and 50) for the positive (summing odd-numbered items) and negative (summing even-numbered items) affect as recommended in Watson et al. (1988).

Results and Discussion

Demographics

Seventy-one participants were included in the study, randomly assigned to either the experimental (with drone, $N = 35$) or control (without drone, $N = 36$) group. Overall, the study population consisted mostly of men (79%, $N = 56$) and the average age was 27 ± 5.5 years. More than half of the participants were graduate students (63.4%, $N = 45$), and the majority had less than five years of construction experience (87%, $N = 62$). Most participants were familiar with robots (78%, $N = 55$) and had slight to moderate experience of operating robots (63%, $N = 45$). Most participants considered themselves slightly to moderately familiar (73%, $N = 52$) with VR. With regard to the participants' emotional state, almost all

Table 1. Demographic information

Parameter	With drone $N = 35$	Without drone $N = 36$
Gender		
Male	25 (71%)	31 (86%)
Female	10 (29%)	5 (14%)
Age		
18 to 24 years	15 (43%)	13 (36%)
25 to 31 years	12 (34%)	19 (53%)
32 to 38 years	5 (14%)	4 (11%)
More than 39 years	3 (9%)	0 (0%)
Education level		
Undergraduate	9 (26%)	9 (25%)
Graduate	20 (57%)	25 (69%)
High school	6 (17%)	2 (6%)
Construction experience		
0 to 1 year	16 (46%)	22 (61%)
1 to 5 years	14 (40%)	10 (28%)
More than 5 years	5 (14%)	4 (11%)
Experience operating robots		
Not experienced at all	10 (29%)	11 (31%)
Slightly experienced	14 (40%)	12 (33%)
Moderately experienced	9 (26%)	10 (28%)
Very experienced	2 (5%)	3 (8%)
Extremely experienced	0 (0%)	0 (0%)
Familiarity with robots		
Not familiar at all	2 (6%)	4 (11%)
Slightly familiar	13 (37%)	12 (33%)
Moderately familiar	16 (46%)	14 (39%)
Very familiar	4 (11%)	6 (17%)
Extremely familiar	0 (0%)	0 (0%)
Familiarity with virtual reality		
Not familiar at all	1 (3%)	3 (8%)
Slightly familiar	16 (46%)	12 (33%)
Moderately familiar	11 (31%)	13 (36%)
Very familiar	5 (14%)	6 (17%)
Extremely familiar	2 (6%)	2 (6%)
Emotional state		
Angry	0 (0%)	0 (0%)
Sad	2 (6%)	0 (0%)
Neutral	3 (9%)	4 (11%)
Satisfied	13 (37%)	25 (70%)
Happy	17 (48%)	7 (19%)

participants identified themselves as being satisfied or happy (87%, $N = 62$). Group-specific demographics, which show a relatively homogeneous mix of participants in the *with drone* and *without drone* groups, are summarized in Table 1.

Physiological Impacts of Drone Presence on Those Who Work at Heights

The aim was to determine whether the drone presence has a significant physiological impact on individuals working at heights. A significance level α of 0.05 was set in this study, adhering to standard hypothesis testing practices. The null and alternative hypotheses were as follows:

- H_0: The presence of drones does not have a significant physiological impact on individuals who work at heights.
- H_1: The presence of drones has a significant physiological impact on individuals who work at heights.

The measured physiological values for HR, HRV, ST, and EDR were all considered to be within typical or normal ranges of previously observed values found for a normal resting person and in the human–robot literature (Dawson et al. 2016; Duncan and Murphy 2013; Jose and Collison 1970; Kulic and Croft 2005; Lenhardt and Sessler 2006; Nunan et al. 2010; Sund-Levander et al. 2002). The results from this study showed that participants' average HR value in the *without drone* group (91.92 ± 11.61 bpm) was higher than the one obtained from the *with drone* group (85.21 ± 13.01 bpm), and that difference was determined to be significant between the two groups ($p = 0.03$). No other statistically significant differences were found for HRV, ST, or EDA between the experimental and control groups ($p \geq 0.33$) (Table 2). Therefore, the results, which were evaluated using a significance level α of 0.05, did not provide conclusive evidence to support the alternative hypothesis that drone presence causes a significant change in the physiological response of participants. Participants from both groups exhibited almost similar physiological responses when accomplishing their tasks. The obtained physiological values were comparable with those found in other studies assessing human responses to heights in VR (Kisker et al. 2021; Simeonov et al. 2005). The results therefore indicate that participants' physiological response may not have been affected by the drone presence but rather originated from their experience of virtual height simulation. The qualitative feedback from participants supported this idea, as they reported experiencing a realistic feeling of being at heights, with comments such as "I felt dizzy when I realized how high up I was," "It was scary!" and "some scenes even made me feel a little nervous."

Attentional Impacts of Drone Presence on Those Who Work at Heights

The aim was to determine whether the drone presence has a significant attentional impact on individuals working at heights. The gaze data results showed that the *with drone* group participants fixated their gaze on the drone 17.89 ± 8.00 times (Table 3). On average, users in the *with drone* group spent 10.26 ± 5.34 s looking at the drone while accomplishing their tasks in VR. The results indicate that the drone presence forced users to divert some of their attention from their assigned task toward the drone. Diverting attentional resources between the drone and the task at hand can deplete humans' attention, distract them from work, and subsequently affect their performance (Wahn and König 2017; Weisberg and Reeves 2013). This is particularly concerning for those working in high-risk environments (such as those working at heights or

Table 2. Participants' physiological data results

Parameter	Normal ranges	With drone Mean ± SD	Without drone Mean ± SD	p-value
HR (bpm)	60–100 (Jose and Collison 1970)	85.21 ± 13.01	91.92 ± 11.61	0.03*
HRV (ms)	19–75 (Nunan et al. 2010)	42.68 ± 25.07	39.20 ± 17.09	0.50
ST (°C)	29.2–36.2 (Lenhardt and Sessler 2006; Sund-Levander et al. 2002)	34.89 ± 1.41	35.17 ± 1.05	0.35
EDR	0.2–1 (Dawson et al. 2016)	0.25 ± 0.17	0.30 ± 0.24	0.33

Note: $^{*}p < 0.05$.

Table 3. Participants' gaze data results

Parameter	With drone Mean ± SD
Drone fixation count	17.89 ± 8.00
Drone fixation duration (s)	10.26 ± 5.34

operating heavy equipment), as being distracted from work can lead to unsafe behavior and severe accidents. While this increase in drone attentional allocation could be significant, further studies are warranted to determine whether the diverted attention from the task at hand onto the drone has practical safety implications. For example, and to better understand how humans allocate their attention and maintain situational awareness while accomplishing a construction task, future research exploring additional gaze metrics such as on- and off-target fixation counts and durations as well as saccade velocity and amplitude is recommended. Comparative analyses could be performed with and without drone presence, with the aim of gaining valuable insights on how drones may potentially cause distractions on construction sites. The qualitative feedback indicated that, while drones attracted some of participants' attention and distracted them, most found the distraction manageable. For example, one participant described drone presence as "obnoxious" but "manageable." Other participants indicated that "I was not bothered by the presence of drones on the worksite," "I do not feel the drones distract much since there are so many other noises on jobsites." It can be expected that as drones become more prevalent on construction sites over time, humans may become accustomed to their presence and be less prone to distraction caused by them.

Emotional Impacts of Drone Presence on Those Who Work at Heights

The aim was to determine whether the drone presence has a significant emotional impact on individuals working at heights.

- H_0: The presence of drones does not have a significant impact on the emotional state of individuals who work at heights.
- H_1: The presence of drones has a significant impact on the emotional state of individuals who work at heights.

The results from pre- and postexperiment PANAS-SF questionnaires indicated that the average baseline positive affect scores for the *with drone* group and *without drone* group were 34.06 ± 7.24 and 34.75 ± 5.93, respectively. The average baseline negative affect scores for the two groups were 19.89 ± 6.04 and 19.92 ± 5.42. The differences were not statistically significant, indicating homogeneity between both groups. The difference or change (Δ) between baseline and postexperiment affect scores indicates that participants' emotional state changed after the VR interaction (Table 4). However, no statistically significant differences in the average change (Δ) in positive affect and negative affect scores were found between the two groups. These findings, evaluated using a significance level α of 0.05, suggest that there was not enough evidence to support the alternative hypothesis that the presence of drones has a significant impact on the emotional state of individuals who work at heights.

Table 4. Participants' PANAS-SF results

PANAS-SF	With drone Mean ± SD	Without drone Mean ± SD	p-value
Δ Positive affect score	1.26 ± 2.95	1.22 ± 3.00	0.96
Δ Negative affect score	−0.51 ± 2.96	−1.14 ± 2.98	0.38

Summary and Conclusion

This study investigated whether the presence of drones has an impact on the physiological, attentional, or emotional states of individuals working at heights. To accomplish this aim, a virtual construction site was first developed to simulate a real-world jobsite environment in VR. The VR environment included under-construction buildings with typical construction equipment, sounds, and animated 3D character models simulating workers performing typical construction activities. A between-groups experiment was then conducted to evaluate, using wearable sensors and self-reported questionnaires, how drones affected participants' attentional, physiological, and emotional states. Recruited participants were randomly assigned to either a *with drone* or *without drone* group in which they were asked to perform different tasks in VR while having their physiological (i.e., HR, HRV, ST, EDR), attentional (i.e., on-target fixation counts and durations) allocation, and emotional states (i.e., PANAS-SF) measured. The results did not provide any evidence indicating that working at heights with drones causes significant psychological or emotional distress among individuals. However, participants of the *with drone* group diverted some of their attention from the task they were required to perform onto the drone, highlighting the need for additional studies to evaluate the practical significance and safety implications associated with the distraction potentially caused by drones in the workplace.

This study has several limitations. First, simply finding that drone presence was not associated with any statistically significant emotional state or physiological state changes among the participants while performing construction tasks in VR does not indicate that there is no potential for drones to pose a safety hazard on construction jobsites. While the metrics used in this study to assess participants' psychophysiological and attentional responses have been used with success in prior research applications examining stimuli effects on people in VR and human-robot interactions (Duncan and Murphy 2013; Kisker et al. 2021; Sakib et al. 2021; Simeonov et al. 2005; Tiberio et al. 2013), there is a small possibility that the applied metrics could be not sensitive enough to measure the slight differences in participants' emotional and physiological states. Therefore, and given the dynamic nature of the construction industry, it cannot necessarily be confirmed that the metrics used and results obtained in other studies would completely align with those adopted in the current analysis. Additional metrics such as self-reported stress or cognitive load questionnaires, electroencephalography for measuring participants' psychophysiological state, assessing similar and other characteristics of participants' experiences, emotional states, physiological states, and attentional allocation could be used to corroborate this study's findings. In addition, this study was limited to assessing humans' physiological, attentional, and emotional states and did not include an assessment of how drones might impact task performance (e.g., time, quality, and cognitive load), warranting additional investigations. It is also worth noting that this study was limited by the subjects, being mostly students with limited experience in construction. In addition, the study did not take into consideration various factors such as construction background (e.g., architecture, engineering, construction), construction trade (e.g., machinery, electricity, carpentry), construction experience, or levels of familiarity and comfort with high-altitude tasks, which could have influenced their perceptions of safety risks as well as their psychophysiological and attentional responses. As a result, a meaningful comparative analysis across different backgrounds, trades, experiences, and fields and the presentation of their relationship with physiological, attentional, and emotional impacts of drones on construction individuals working at heights were not possible. A more diverse and representative sample group that includes professionals with varying construction backgrounds and years of experience is needed to enhance the understanding of how such factors influence the psychophysiological and attentional variables being investigated in this study and generalize its findings.

Another limitation stems from the VR nature of the experiment, a factor that also makes it difficult to fully align the findings of this study to real-world experimentation. The developed VR environment provided a realistic sense of being and immersion on a construction site, as evidenced by participants' qualitative feedback on the VR realism, which showed that the developed environment gave a "near-real life experience" of working on a construction site, making users feel as if they "were on an actual construction site," that the environment was "real," "accurate," and "realistic," and that it is "a good example of what being on a jobsite is like." Realistic VR simulations have also been shown to elicit real-world psychophysiological responses in participants (Kisker et al. 2021; Simeonov et al. 2005). However, additional factors such as environmental conditions (e.g., increased exposure to heat or cold, inclement weather) and mental or physical fatigue, which individuals experience in the real world, could amplify changes in emotional state, physiological state, and attentional allocation. Further research is warranted to incorporate these real-world stressors while exposing users to drones and assess their corresponding psychophysiological and attentional responses. In addition, while VR is a powerful tool for simulating real-world conditions, the specific reflection of the developed construction site, particularly from the perspective of construction individuals with extensive experience in high-altitude tasks, was not assessed. This limiting factor highlights the need for additional investigations, such as conducting focus group tests or interviews with experts, with the aim of ascertaining and validating how well the developed VR environment reflects the reality of construction sites and the various operations performed at heights. Such efforts ultimately help to ensure the accuracy and fidelity of the simulated environment.

To enhance the generalizability of the findings, future studies should conduct task-specific comparative analyses by exploring the impacts of drones on construction individuals in different tasks and settings, including ones beyond those utilized in this study. This is particularly important since drone applications in construction have distinctive characteristics, levels of human–human and human–robot collaboration, complexity, and risk factors. These factors differentiate one task from another and may potentially result in different psychophysiological and attentional impacts on construction individuals. Additional research must also focus on different factors that are known to affect human–robot interaction, such as robot (i.e., aerial and ground) approach speed, interaction distance, approach angle, anthropomorphism, and form factor as well as trust (Albeaino et al. 2022; Jeelani and Gheisari 2021; Kanda et al. 2004; Nonaka et al. 2004). Finally, other risks that are expected to be associated with robot deployment on jobsites should also be investigated, including physical contact risks as well as auditory distraction.

Data Availability Statement

Some data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request (data processing codes).

Acknowledgments

This material was produced under Grant No. 21-6-PS from the Center for Construction Research and Training (CPWR). It does not necessarily reflect the views or policies of the NIOSH, nor does mention of trade names, commercial products, or organizations imply endorsement by the US Government. This material is also based upon work supported by the National Science Foundation under Grant No. 2024656. The research team would like to thank Shrishail Zalake and David Anderson Allen from the University of Florida for their help with the technical development of the VR environment.

Supplemental Materials

Appendix S1 is available online in the ASCE Library (www.ascelibrary.org).

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