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Enhancing perceived safety in human–robot collaborative construction using immersive virtual environments

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ABSTRACT

Advances in robotics now permit humans to work collaboratively with robots. However, humans often feel unsafe working alongside robots. Our knowledge of how to help humans overcome this issue is limited by two challenges. One, it is difficult, expensive and time-consuming to prototype robots and set up various work situations needed to conduct studies in this area. Two, we lack strong theoretical models to predict and explain perceived safety and its influence on human–robot work collaboration (HRWC). To address these issues, we introduce the Robot Acceptance Safety Model (RASM) and employ immersive virtual environments (IVEs) to examine perceived safety of working on tasks alongside a robot. Results from a between-subjects experiment done in an IVE show that separation of work areas between robots and humans increases perceived safety by promoting team identification and trust in the robot. In addition, the more participants felt it was safe to work with the robot, the more willing they were to work alongside the robot in the future.

1. Introduction

Human–robot work collaboration (HRWC) can be used to describe work situations where humans and robots work side by side to complete a task. Advances in robotics now permit humans to work collaboratively with robots [1,2]. This collaboration allows humans to off-load repetitive and tedious tasks to their robots [3,4]. This is particularly beneficial because such tasks are often responsible for a class of physical injuries labeled as repetitive motion injuries [5]. The use of robots also frees up humans to focus on other tasks that cannot be easily performed by robots [6]. HRWC may be particularly important for construction work because many construction tasks require repetitive physical movements and the need for collaborative work.

One major challenge to leveraging HRWC is that humans often feel unsafe working around robots [7,8]. Humans are less willing to work with or alongside robots when they believe it is unsafe to do so, regardless of the actual level of safety [9]. Perceived safety is the degree to which someone believes it is safe to engage in a behavior. Despite this, the existing literature on safety and robots has focused only on technical design issues [10,11] and has ignored the issues associated with perceived safety. Yet, our human behavior is often driven by how we perceive the world.

Despite the importance of perceived safety in facilitating HRWC, two challenges have limited our ability to advance our understanding of this area in the context of construction work. One, it is difficult, expensive and time-consuming to prototype robots and set up various work situations needed to conduct studies in this area. For example, one could easily imagine the need to vary the design of the robot, the task and the characteristics of the construction sites. We believe that the use of immersive virtual environments (IVEs) can help to overcome these issues. Immersive virtual environments (IVEs) are computer-generated simulated environments that represent a physical environment and allow user interactions with virtually rendered objects [12,13]. By adapting IVEs, various types of robots, interactions, and tasks can be easily tested and evaluated to determine the best HRWC practices, without the need to build and evaluate physical prototypes [14–16].

Two, we lack strong theoretical models that can predict and explain perceived safety and its influence on HRWC. We believe such theoretical models should be more specific with regard to perceived safety rather than more general with regard for any outcome related to work or collaboration. To address this challenge, we introduce the Robot Acceptance Safety Model (RASM). The RASM asserts that individuals' willingness to work with a robot is relative to their perceived safety associated with the task involving the robot.

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In this paper, we specifically examine the impact of workspace sharing between the human and robot. RASM asserts that: (1) separation of the work area between a human and a robot increases one's willingness to work with that robot by facilitating perceived safety; (2) the separation of the work area increases perceived safety by promoting team identification and trust in the robot; and (3) the more individuals believe it is safe to work alongside a robot the more likely they will be to work alongside the robot in the future.

To empirically test our model, we conducted an experimental study involving 30 participants. In this study, we employed IVEs in a simulation and experiment environment. We used IVEs to create two conditions of a construction task involving a robot. In one condition, participants and their robot worked side by side but each had their own work area separated by a safety fence. In the other condition, participants and their robot worked in the same work area. We found that humans felt safer working with their robot when they each had their own work area separated by the fence. Separate work areas led to higher perceptions of safety by promoting team identification with and trust in the robot. Perceived safety promoted participants' willingness to work with their robot in the future. Results of this study contribute to our understanding of how to effectively employ robots at construction sites.

The following sections of this paper describe the objectives, motivation, and current status of the use of IVEs in HWRC in the area of construction. Then we present the methodology of the research, followed by the study results. Finally, we discuss a summary of the contributions and future research implications.

2. HRWC and immersive virtual environments

Research that falls under the heading of HRWC has been conducted for more than a decade [17–21]. Most of this research has focused on building safer robots. Scholars have developed technologies such as advanced controls [19,22–24], sensor equipment [25–27], and path-planning techniques [28].

Advances in robotics now allow robots to work collaboratively alongside human workers in an interactive, intuitive, and safe manner [2,29]. In the past, safety fencing has been used to separate humans from robots to help to prevent injuries caused by physical contact [30]. However, in cellular manufacturing environments, heavy-duty industrial robots are beginning to work in closer range with humans [31]. An example of this is in BMW factories, in which robots work alongside human workers for automobile door assembly tasks [32]. Although manufacturing is beginning to engage in more HRWC without safety fencing, this has not necessarily spilled over into construction work [8].

Construction sites present their own challenges that limit the ability to adopt the systems and practices developed for manufacturing environments. Construction environments are often more dynamic, unstructured, and physically demanding than others [33]. The location of workspaces on a construction site is fluid and temporary rather than fixed and permanent like in many manufacturing plants. Workspaces on a construction site are also shared and more open than those at a manufacturing plant, making it more difficult to close off from other workers [34]. For this reason, a safety fence is often installed between a robot and a worker to avoid potential injuries. However, this can be cumbersome and problematic in construction work, where more interactive coordination between humans and robots may be beneficial [35]. In addition, there is no empirical evidence on whether such separation is necessary or beneficial for HRWC in construction work [36].

Despite the potential importance and relevance of perceived safety, it has received very little attention in the context of construction environments. We found no prior research that empirically examined perceived safety in the context of construction work with robots. Researchers from other fields examining the impact of perceived safety have not focused on the work arrangement itself. Instead, this work is focused on the relationship between perceived safety and the characteristics of the robot, including motion and speed [29,37], behaviors such as presence of pre-warning of physical contact [38], and design [39]. Considering the increases in the adoption of robots in construction work and the distinct characteristics of these sites, there is an urgent need to examine perceived safety in HRWC in the context of construction work.

To address this, we employed an IVE to avoid time-consuming and costly prototype building while still effectively evaluating perceived safety of the task [40]. IVEs are proven to increase both experimental control and mundane realism, which enhances participants' engagement, thereby increasing experimental validity [41]. For example, Heydarian et al. [12] employed an IVE to measure the sense of presence felt by participants performing office-related activities. Weistroffer et al. [40] used a virtual environment to evaluate the end-user's perception of a robot and its movement. Inoue et al. [42] used virtual robots to test the effect of their movement. However, very little attention has been directed at the use of IVEs in HRWC or use of IVEs to study unstructured work environments such as construction sites. Therefore, our goal is to extend the current literature by implementing an IVE to understand how perceived safety influences HRWC in two unstructured work environments: (1) working with a robot in two work areas separated by a fence and (2) working with a robot within the same work area.

3. Research model and hypotheses

Safety is an important issue in construction work because accidents can lead to serious injuries and even fatalities [34,43]. Heavy-duty machinery is one of the primary causes of accidents on construction sites [44], and the fear of being hit by such equipment is a major reason many construction workers feel unsafe [45]. In addition, safety concerns in the form of fear and worry have been found to increase cognitive load for workers, often contributing significantly to worker burnout [46].

To examine HRWC for construction tasks, we propose the Robot Acceptance Safety Model (RASM). RASM consists of several important factors influencing perceived safety in HWRC. In general, the RASM proposes that collaborative attitudes and beliefs regarding the robot can impact the perceived safety associated with the collaborative task. In this study, the RASM specifically asserts that the separation of work areas between workers and their robot increases the individuals' perceived safety, and that the impact of work separation on perceived safety is mediated by team identification and trust in robots. RASM also posits that increases in perceived safety increase an individual's willingness to work with the robot in the future. The RASM model is depicted in Fig. 1.

3.1. Hypotheses

The greater the separation is between humans and robots, the higher the degree of perceived safety. This assertion is supported by early research on personal space, a concept originally introduced by Hall [47]. A common definition of personal space is "an area with an invisible boundary surrounding a person's body, into which intruders may not come" ([48], p. 26). Personal space is important to humans because it allows us to regulate the degree of access others have to us [49]. The ability to control the degree of access to ourselves is directly related to our emotional well-being [50,51]. When someone violates our personal space by moving too close to us we can feel uncomfortable and at times threatened by their presence [50–52].

Scholars studying personal space quickly identified the importance of emotional closeness between two actors in understanding the degree of personal space needed [47,50]. We need less personal space when interacting with those we are emotionally close to on a personal level [53]. For example, people would need much less personal space when interacting with their spouse than with a stranger [47]. Individuals tend