Evaluation of a Virtual Environment Prototype for Studies on the Effectiveness of Technology-Based Safety Signs

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Abstract. This pilot study aimed to evaluate the viability of using a Virtual Environment (VE) prototype for conducting research regarding technology-based safety signs, i.e., Augmented Reality (AR) warnings. Using a complex work-related context (comprised of two hazardous situations with distinct salience levels) and a sample of 12 workers (27–60 years), the study's objectives were to assess: the AR safety signs' effectiveness in enhancing hazard-risk behaviors and promoting behavioral compliance; as well as the participants' overall user experience. To undergo such an evaluation, the following issues were addressed: simulator sickness; level of presence; hazard and safety sign perception; and overall usability. Results reveal that: the AR warnings were effective in identifying hazards and in prompting compliant behaviors; and despite slight simulator sickness, participants were highly engaged, as well as adequately perceived both hazards and warnings. Thus, the VE prototype proved to be adequate for safety sign research regarding AR warnings.

Keywords: Virtual environments · Workplace safety sign research · Ageing · Technology-based warnings · Augmented reality · Behavioral compliance · Hazard perception · Interaction · User experience · Usability

1 Introduction

One of the most important safety precautionary methods to prevent workplace accidents/injuries consists in adequately perceiving hazards and warnings, as well as in complying with the provided information. Regrettably, this third line of hazard control is not always successful [1]. This is, they often fail to: attract attention; provide knowledge; and incite behavioral compliance [2, 3]. The latter being, according to most cognitive models [4, 5], the ultimate outcome measure when determining the success (effectiveness) of such signs. Over the years, research on behavioral compliance has identified a number of significant criteria that defines the effectiveness of safety signs. Such criteria encompasses variables pertaining to warning design (e.g., location, typography, size, format/layout color, contrast), situational characteristics (e.g., familiarity, modeling, costs of

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compliance), as well as target audience issues (e.g., gender, age, cultural background, familiarity) [6, 7]. Regarding the age parameter, various studies [8, 9] alert to the fact that with old age, the visual, auditory and cognitive capacities decline; which subsequently puts older workers at a disadvantage in hazardous situations. Research on the rapidly ageing workforce population [10] points to the critical need for innovation in workplace safety signs, i.e., more adequately designed warnings.

In recent years, research has highlighted that technology-based warnings may be more effective in communicating safety-related information [11, 12]. Due to their dynamic displays, such computer/sensor-based signs may provide older workers with the appropriate cognitive support needed to compensate for their age-related perceptual/attention deficits [13]. Among the many possibilities disclosed by the use of such technical applications, this paper presents a pilot study which proposes the use of Augmented Reality (AR) as a promising technology to enhance workplace safety. AR is an interactive medium which combines/merges computer-generated information with the physical/real world [14]. In other words, it is a technology that superimposes digital imagery/graphics over a view of the real environment, in real-time. Such information is displayed in registration with and dependent on the geographic location, as well as the person's perspective of the physical world [15].

Although the use of AR is on the rise in various scientific areas [16], in the field of Safety Sign Research, knowledge on workplace AR safety signs is scarce. The current body of research, in the transportation domain, has emphasized a number of advantages in using such a medium, namely its ability to detect the presence of a hazard and alert the person in a timely manner [17, 18]. In this context, this paper discusses the definition and preliminary results regarding a pilot study that was designed to assess the effectiveness of workplace AR safety signs. This study is part of an ongoing investigation that is focused on enhancing workplace safety by designing more effective warnings for older workers (55–65 years old). Such a project is driven by the premise that, due to their dynamic and interactive conspicuity, AR safety signs can be designed to enhance the older workers' sensory perception of complex workplace environments and tailored to potentially dangerous situations. When compared to the conventional/static ISO-type counterparts, it is hypothesized that AR safety signs will be more effective in overcoming possible age-related limitations and augmenting hazard-risk perception, thereby prompting more compliant behaviors. However, since research regarding the effectiveness of safety signs is limited by several methodological, economical and ethical constraints, such a pilot study used an immersive Virtual Reality-based (VR) experimental set-up for such a purpose. Such a tool provided the ability to create an interactive and quasi-real Virtual Environment (VE) prototype in which behavioral compliance in simulated hazardous situations could be safely assessed, with an absolute control over the experimental conditions and variables.

Therefore, in light of the larger research project mentioned above, the present pilot study aimed to assess the feasibility of using the proposed VE prototype that was specifically designed (with a similar design, experimental setup and overall interaction framework to that of a previous study [19]) for conducting such studies. Using a complex work-related context (which comprised of two hazardous situations with distinct salience levels), the study's main objectives were two-folded: (1) to assess the proposed

AR warnings' effectiveness in enhancing hazard-risk behaviors and behavioral compliance; and (2) to evaluate overall user experience with such signs and respective VE prototype. In sum, topics under the VE interaction domain (pertaining to simulator sickness, level of presence, overall VE design, as well as hazard-risk and safety sign perception), are addressed in the current paper.

2 Method

2.1 Participants

A total of 12 adult workers (with different professions), 6 men and 6 women, aged 27 to 60 years old (Mean Age = 42.8, SD = 15.3), volunteered to participate in the study. Prior to beginning the experimental sessions, participants were required to sign a consent form and complete a demographic questionnaire; as well as were screened for color deficiencies (using the Ishihara Color Vision Test [20]) and cognitive impairment (by applying the Mini-Mental State Examination [21, 22]). In sum, all of the participants had a corrected and/or 20/20 vision, absent of any color limitations, and reported to have no physical and/or mental conditions that could prevent them from partaking in the study. Moreover, they reported to have no previous experience with a VR-based system set-up and/or simulation.

2.2 System Set-Up

In order to conduct such a study, an immersive VR system set-up (based on [19]) was used: the Oculus Rift Development Kit2 Head-Mounted Display, mounted with its type B lenses and set with its default pupillary distance (to sustain the sample's homogeneity), to visualize the VE; the Xbox 360 wireless gamepad to interact with the VE; wireless Sony headphones, model MDR-RF800RK, to hear the VE's sounds; and a Dell Alienware M18x laptop (with an Intel Core i7-3610QM processor, 16 GB of memory, and a Dual 2 GB GDDR5 Nvidia GTX 675 M SLI graphics card), to run the simulation. In order to collect quantitative data, the event log system (based on scripts and triggers that were specifically developed for this study) was adapted and used to automatically record the participants' interaction in real-time.

The VE prototype's scenery was designed using the Sketchup Pro software, and then exported to the Unity3D game engine (version 4.6.3f1) to define the simulation's mechanics. Smaller 3D resources, provided by both of the softwares' assets stores, were bought/adapted and used to create the study's settings. For methodological reasons (mainly to prevent possible simulator sickness), the 3D model was optimized in order to maintain an average image frame rate above 75 Hz per second throughout the simulation. The participants' viewpoint was set at eye-height (1.53 m above the ground), and its Field-of-View was set using the software's standard default settings. For the same reasons mentioned above (simulator sickness), the velocity at which the participants rotated/oriented their viewpoints was reduced to match real-life head movements, and their travel/navigational speed (which gradually increased to a maximum of 1.35 m/s) was maintained.

2.3 VE Prototype Design

Scenery. Based on an earlier prototype [19], for this pilot study the 3D model was adapted/redesigned to portray a complex work-related environment that comprised of two different types of hazardous situations (with distinct levels of salience), in which the presence of safety signs continued to be mandatory and behavioral compliance could be assessed. Subsequently, a 3rd large module was added to the original 3D model. All three modules (linked together via open spaces) represented different sections of a factory and/or with a particular dangerous situation: Module 0 remained absent of any hazards; Module 1 continued to depict an Overhead Hazard; and the recent Module 2 featured a Conveyor Hazard. Since the latter two consisted of an exposed hazard, their layout was designed to include two passages in which to circulate through, namely a dangerous path that comprised of the hazard and in which participants were to avoid crossing, plus a safety pathway void of any danger. Both lanes were clearly delineated by safety floor markings (Fig. 1). To enhance the VE's realism, a number of objects (shelves, boxes, forklifts, trash cans, garbage, tires, truck, containers) as well as conventional/static ISO-type safety signs [23] were placed throughout the various sections and architectural elements. All visual and auditory features were individually tweaked depending on the various situations.

Fig. 1. Screenshots of the entrances to Modules 1 and 2.

Scenario and Simulation. For this pilot study, the scenario was modified and the simulation divided into three phases. Firstly, in order to enhance the participants' user experience, a contextual narrative (in voice-over, whilst visualizing a backdrop of the factory's entrance) was provided, in which they were asked to imagine the following situation: it is the end of the afternoon; they are back home after a day at work, and decide to take their dog for a walk; as they pass by an industrial part of town, their dog is startled by a cat and then enthusiastically runs after it into a factory; naturally, they run after their dog too; upon arrival to the factory's gate, they realize that the security guard is not present; however, since they are worried about their dog, they enter the factory, at their own risk, to retrieve it. In light of the given cover story, in the 2nd part of the simulation, the participants were required to perform the study's task, i.e., to catch their dog. Throughout the simulation, the background ambient noise was that of a stereotypical, yet realistic factory, accompanied by the sound of the dog barking every 15 s. When participants caught the dog, the simulation would end by thanking them for partaking in the study.

Game Strategy. To perform the experiment's task, participants had to search for and detect the dog, as well as retrieve it. In addition to carrying out this visual search and target detection task, participants had to keep track of the dog's trail, as it ran after the cat throughout the factory's divisions. In addition to running away from the participants as soon as they reached it, the dog would constantly sprint across the dangerous paths (i.e., in which the hazards were present). Such a task was designed to attract and maintain the participants' attention throughout the course of the simulation. As participants entered Modules 1 and 2, they were confronted with a 1st set of AR safety signs that popped up to alert to the presence of a hazard, as well as to advise them to circulate on the safety path (which appeared either to their left or right). In that precise moment, participants were forced to decide between 2 pathways: to follow the dog across the dangerous path; or to take the safety route. In other words, they had to evaluate the costs of complying with the AR warnings' information. This is: to circulate via the safety path, which was a slightly longer and less direct route to the dog; and/or follow the more direct, yet unsafe path to the dog, i.e., model the dog's behavior. If participants chose not to comply with the AR safety signs and to follow the dog's path, they would be confronted with another, yet similar set of AR warnings, before approaching the hazard, thus yielding them with a 2nd opportunity to adopt the safest behavior.

AR Safety Signs. In light of the study's primary objective, a set of AR warnings (visual displays) was designed for this investigation. These included two types of simple and light-weighted 2D cues, namely billboards (floating panels) and pins (target annotations). In consistency with the ISO standards [23], the billboards afforded participants with the necessary safety information, i.e., the identification of the hazard's presence, type and level of severity, as well as the behaviors to be adopted/avoided. Whereas, the pins merely served to identify points of interest (the precise location of the safety path and hazard) and augment the hazards' level of severity. Both types of signs were context and location-based: billboards would only appear when participants were inside the modules' preceding demarcated entrance areas and the hazards were within their view/sight; and pins would show up in the same context and location, plus when the participants were travelling through the dangerous path (Fig. 2).

Fig. 2. Screenshots of AR billboards and pins, in Modules 1 and 2.

To enhance legibility and readability, the billboards appeared: aligned, centered and fixed at eye-height [24] and at a distance of 1.3 m [25]; with saturated texts and symbols, on a semitransparent (55%) black rectangular background [26]; and accompanied by a semitransparent (70%) white arrow that indicated the safety paths' locations. Similarly, safety path pins were fixed 1.5 m above the ground [27], hovering over the factory's floor markings and consisted of a saturated symbol on a semitransparent (70%) white background. To increase the dangerous object's conspicuity, a hazard pin was fixed directly above it. Furthermore, to convey its level of severity, this pin's semitransparent (70%) background would vary in color (from white, yellow, orange to red) if participants approached it.

Environmental Cues. In order to replicate a complex work-related environment, comprising of attentional and perceptually demanding situational characteristics, for this pilot study, two distinct levels of hazard salience were designed for each module. In Module 1, the Overhead Hazard represented a conspicuous/explicit situation: as participants followed the dog's path, at a certain point in the VE, an alarm would go off (auditory cue) and the crane/container would begin to move (visual cue) to the right hand side of the module (Fig. 2). Whereas the Conveyor Hazard, in Module 2, featured a non-conspicuous/implicit danger: the conveyor belt remained stationary, void of any visual and auditory cues. This environmental situation was designed to assess the AR safety signs' effectiveness in both static (non-conspicuous) and dynamic (conspicuous) situations, as well as with the intention of providing participants with an engaging and life-like experience.

Measures. In order to evaluate the feasibility of using the proposed VE prototype for conducting studies on the effectiveness of workplace AR safety signs, two usability test beds (one for each of the study's objectives) were carried out, in which behavioral and subjective measures were collected consecutively. The 1st test bed was designed to assess the AR safety sign's effectiveness in enhancing hazard-risk behaviors and invoking behavioral compliance, by observing the participants' actions and path trajectories, namely if they followed the dog across the dangerous path, or they took the safety route. In each module, this evaluation was divided into three decision-making moments, namely if and when the participants were confronted with both sets of AR warnings, and then the hazard. The study's hypothesis, regarding this particular assessment, was that the AR safety signs would be effective in prompting the compliant behavior of circulating on the safety path. However, if participants chose not to comply with such signs, it was hypothesized that: the Overhead Hazard's conspicuity would influence the participants' behavior and incite them to take the safety path; whereas, in the 2nd module participants would fail to adopt safe behaviors due the Conveyor Hazard's lack of salience.

The 2nd test bed sought to evaluate the participants' overall user experience, by collecting their subjective perceptions on their interaction with the VE prototype and respective AR safety signs. Subsequently, the following post-hoc questionnaires (adapted from [19]) were applied:

Simulator Sickness Questionnaire (SSQ). In order to evaluate to what extent the VE could be satisfactorily used, this questionnaire (applied twice, before and after the experimental session) evaluated the occurrence of possible simulator symptoms and their effects on the participants' performance. On a 4-point scale, participants scored 23 (overall body and eye-related) symptoms, by indicating the associated level of severity (which ranged from "None" to "Severe").

Presence Questionnaire (PQ). In order to understand the extent at which participants acted/interacted realistically/naturally, this survey assessed the participants' sense of presence levels and the quality of their experience with the VE. On a 9-point scale, participants ranked 37 questions which fell under categories pertaining to the VE's features: level of immersion; control factors; sensorial quality; distraction factors; and level of realism.

VE Design Questionnaire (VDQ). With this questionnaire, participants evaluated, on a 9-point scale, the VE's overall design characteristics according to the following heuristics (divided into 12 questions): contextual narrative coherency; task compatibility; natural engagement; natural expression of action; and level of entertainment.

Hazard-risk Perception Questionnaire (HPQ). In order to understand whether the participants adequately perceived the hazards' severity, this survey (comprised of 11 questions) aimed to evaluate (using a 9-point scale) a number of factors related to hazard awareness, risk judgment and salience. It was applied twice, at the end of the experimental session, for each module/hazard respectively.

AR Perception Questionnaire (APQ). This questionnaire sought to assess whether the AR safety signs had had an influence on the participants' overall hazard-risk perception. Using a 9-point scale, participants ranked 10 questions regarding the AR safety signs' salience, hazard identification and influence. This survey was also applied twice, accordingly to each module/hazard, at the end of the experimental session.

Procedure. The study was divided into five main stages, and the average duration of the whole procedure was approximately 1 h 20 min. Throughout the experimental sessions, participants sat a desk for comfort and security reasons, as well as were accompanied by the researcher's presence for technical and methodological reasons (i.e., in order to: observe the participants' interaction inside the VE; monitor their dexterity in using the study's devices; as well as program the experimental simulations).

Introduction to the Study. As previously mentioned, prior to the experimental sessions, participants signed a consent form and filled in a demographic questionnaire, as well as were subsequently screened for color deficiencies and cognitive impairment. They were then debriefed about the study and its different phases, as well as introduced to its devices and system set-up. To avoid influencing the participants' behavior, they were oblivious of the study's real objectives.

Training Session: Phase 1. Before beginning the actual experimental session, participants underwent a pre-experimental training session, using a completely different VE which was specifically designed for the participants to: familiarize themselves with the study's interaction and visualization devices; learn how to interact within the VE and acquire the ability to control their movements in a more realistic/natural manner; and become accustomed with the study's virtual/immersive paradigms. This training session was divided into two key moments. Firstly, participants practiced (for approximately 15 min) using the gamepad (by performing a number of navigation tasks), while visualizing the VE on the laptop's screen. Secondly, only after the participants stated to be at ease with the control device, did they place the Head-Mounted Display.

Training Session: 2nd Phase. After calibrating this device, participants 1st completed a perceptual quality test regarding a series of visual stimuli placed inside the VE, and then trained the same navigation tasks, mentioned above, with both devices. As soon as the participants declared that they felt at ease to continue with the study's subsequent phases, the training session ended. In order to check for any preliminary indications of simulator symptoms and effects, participants completed the 1st SSQ. In sum, this pre-experimental training session lasted approximately 25 min in total, and served to homogenize the study's sample in terms of its performance plus perceptual ability.

Experimental Session. After a 5 min break, participants placed once again the HMD, and the experimental session began, devoid of any dialogue. As soon as the simulation's contextual narrative was provided, participants performed the study's visual search and target detection task. Such interactions were video/audio recorded for later analysis.

Follow-Up Questionnaires. Immediately after completing the simulation, participants filled out the 2nd/last SSQ (to assess the existence and/or increase in simulator sickness, due to having been exposed to two VE's over a time period of approximately 15 min in total). After another 5 min break, participants completed the PQ, followed by the VDQ. Once they had completed these two questionnaires, participants were confronted with a video of their interaction within the VE. While analyzing the video of their performance, they consecutively and simultaneously filled in the HPQs and APQs for each of the VE's modules/hazards.

3 Results

3.1 Behavioral Data

The data obtained in Module 1 (Overhead Hazard), reveals that 66.7% of the participants complied with the 1st set of AR safety signs, and followed the safety path (see Table 1). Among the participants who decided not to comply with this 1st set, data discloses that half of them complied with the 2nd group of AR warnings. Amongst those who disregarded this 2nd set of signs and decided to follow the dangerous path, one participant took the safety path after the crane/container began to move. Whereas, the remaining participant waited for the crane/container to be immobilized in order to continue on the dangerous path.

Table 1. Descriptive statistics (Percentage values) for behavioral compliance measures.

	Module 1: Overhead		Module 2: Conveyor	
Decision-making moments	Safety path	Dangerous path	Safety path	Dangerous path
#A: 1st set of AR warnings	66.7%	33.3%	75.0%	25.0%
#B: 2nd set of AR warnings	16.7%	16.7%	25.0%	0.0%
#C: Hazard	8.0%	8.0%	0.0%	0.0%

In Module 2 (Conveyor Hazard), when the participants were confronted with the 1st set of AR warnings, data discloses that there was a slight 8.3p.p. increase in compliance, when compared to the same moment in Module 1. Moreover, the remaining 25% of the participants complied with the 2nd set of safety signs.

3.2 Subjective Data

Data obtained from the *SSQs* exposes the incident of slight simulator sickness. When analyzing both overall body and eye-related symptoms, only the following effects were accounted for: fatigue (25%); sweating (25%); and nausea (33%). After having been exposed to two VEs, approximately 15 min in total, one can infer that although the participants overall well-being was slightly affected, it did not impact their interaction and experience.

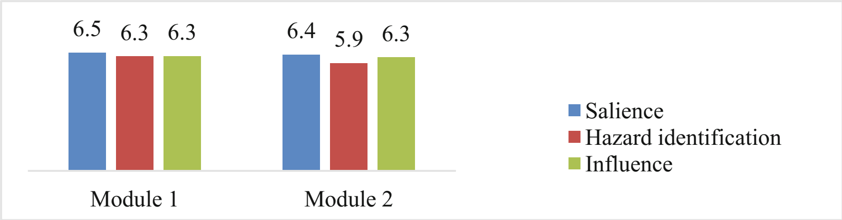
Regarding the *PQ*, the gathered results reveals that: participants' immersion levels were more than very high (Mean = 6.8, SD = 1.3); the VE's interaction and control factors, as well as its sensorial quality were very high (Mean = 6.1, SD = 1.1); participants were rarely distracted by the VE's system set-up devices (Mean = 6.2, SD = 1.5); and the VE's level of realism was also very high (Mean = 6.2, SD = 1.0).

In what concerns the *VDQ*, the attained data reveals that the participants found the simulation's: contextual narrative more than very coherent (Mean = 6.9, SD = 1.2); task compatibility was very high (Mean = 6.3, SD = 1.4); natural engagement was also very high (Mean = 6.4, SD = 1.4); natural expression of action likewise (Mean = 5.9, SD = 1.4); and entertainment factor fairly high (Mean = 5.5, SD = 1.4).

As for the *HPQs*, the collected results indicate that in Module 1 the participants were more than aware of the Overhead Hazard (Mean = 5.6, SD = 2.4), whereas in Module 2 they were only fairly aware of the Conveyor Hazard (Mean = 4.6, SD = 2.6). Regarding their hazard-risk judgments, participants perceived the Overhead Hazard as fairly dangerous (Mean = 4.8, SD = 2.2), while the Conveyor Hazard as simply dangerous (Mean = 4.2, SD = 1.9). The most significant difference between results for this criterion pertained to the severity of injury: participants considered that the Overhead Hazard could cause a very severe injury (Mean = 5.8, SD = 2.6), whereas the Conveyor Hazard's degree of injury was only severe (Mean = 3.9, SD = 2.2). In what concerns the hazards' level of salience, the participants found the Overhead Hazard to be more than high (Mean = 5.6, SD = 1.9), whereas the Conveyor Hazard was only fairly high (Mean = 4.5, SD = 2.6).

Regarding the *APQs*, the obtained data in Table 2 reveals that the participants found that the AR safety signs were very salient, as well as had clearly identified the hazards' presence, type and level of severity, as well as the behaviors to be adopted/avoided. In conclusion, participants felt that the AR warnings had highly influenced their behavior in both modules.

Table 2. Descriptive statistics (Mean values) regarding the *AR Perception Questionnaires (APQs).*



4 Conclusion

The present paper presents and discusses the framework, as well as preliminary findings regarding a pilot study that aimed to assess the feasibility of a VE prototype that was specifically designed for studies regarding the effectiveness of workplace AR safety signs. In order to undergo such an evaluation, the study comprised of two key moments: (1) it assessed the AR safety signs' effectiveness in enhancing hazard-risk behaviors and invoking behavioral compliance, by gathering behavioral data on the participants interaction inside the VE; and (2) it analyzed the participants' subjective perceptions on their overall user experience with such signs and VE prototype, by collecting data regarding simulator sickness, level of presence, overall VE design, as well as hazard-risk and safety sign perception.

By analyzing the study's results regarding the 1st usability test bed, one can infer that the AR warnings were effective in prompting the compliant behavior of circulating on the safety path, and that more than 65% of the participants complied with the 1st set of AR warnings, in both modules. The appearance of a 2nd group of warnings also proved to be significant in invoking behavioral compliance. Thus, the study's hypothesis for this particular assessment was confirmed. As for the study's hypotheses regarding the participants' hazard-risk behaviors, when confronted with the hazards, one can infer that the Overhead Hazard's conspicuity had a slight influence on the participants' behavior. However, such findings are inconclusive due to the lack of significant data across the experimental conditions. Subsequently, further testing, with a larger sample, will have to be carried out in order to verify the effect of the hazards' salience on the participants' behavioral compliance.

Nevertheless, when comparing such data with results gathered in the 2nd usability test bed, regarding the participants' hazard-risk perceptions, one can infer that the participants had reasonably perceived the hazards' severity. However, since in Module 2 there was a significant decrease in the participants' hazard-risk judgments, one can conclude that the AR safety signs did not effectively enhance hazard perception. The reasons behind this finding are unclear. Nevertheless, one can infer that such low hazard awareness levels may have been associated to the following motives: that by following the AR safety signs' indications, participants may have trusted that such a system would keep them from harm's way; and that by circulating on the safety path, they were deviated from fully experiencing the hazards' possible dangers.

By analyzing the results gathered regarding simulator sickness and sense of presence, one can conclude that, overall, participants had: a sickness free experience, as well as very high levels of presence and engagement, thereby attesting that they had interacted with the VE prototype in a realistic/natural manner. Moreover, they found the 3D model and simulation to have been coherently and realistically designed.

Lastly, when comparing the behavioral data with the results obtained in the APQs, one can infer that the AR safety signs: had a significant influence on the participants' behaviors; and were effective in identifying the hazard, as well as in informing the participants on which behaviors to adopt/avoid.

In conclusion, such a study demonstrated that the VE prototype is adequate for conducting studies on the effectiveness of workplace AR warnings, as well as highlights AR technology as a promising tool to communicate, in a timely manner, safety-related information in complex workplace environments.

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