

Investigating the Effects of an Augmented Reality-Based Warning System on Safety and Trust in Human-Robot Collaboration

Mohsen Omidi^{1,2*}, Joris De Winter^{1,3}, Kevin De Pauw^{1,4}, Ilias El Makrini^{1,3},
Bram Vanderborght^{1,2}, Hoang-Long Cao^{1,3}

¹Brubotics, Vrije Universiteit Brussel, Pleinlaan 2, Elsene, 1050, Brussels, Belgium.

²imec-IMS, imec, Pleinlaan 2, Elsene, 1050, Brussels, Belgium.

³Flanders Make, Oude Diestersebaan 133, 3920, Lommel, Belgium.

⁴Human Physiology and Sports Physiotherapy research group, Vrije Universiteit Brussel, Pleinlaan 2, Elsene, 1050, Brussels, Belgium.

*Corresponding author(s). E-mail(s): mohsen.omidi@vub.be;

Contributing authors: joris.de.winter@vub.be; kevin.de.pauw@vub.be;

ilias.el.makrini@vub.be; bram.vanderborght@vub.be; hoang.long.cao@vub.be;

Abstract

Implementing efficient warning systems (e.g. visual, audio, or vibration alerts) is critical in human-robot collaboration (HRC) to enhance safety. Augmented reality (AR) is a promising technology for delivering such warnings. However, several studies have yet to fully investigate the effects of AR-based warning systems on safety and trust in HRC. In this work, we investigate the effects of an AR-based warning system on both safety and trust using objective and subjective measures as well as physiological response as stress indicators. Twenty-six people participated in our within-participant experiment. Our results suggest that while the AR-based warning system improves the subjective measure of safety, participants did not explicitly feel that their environment was safer with the system. Nevertheless, they demonstrated a higher level of trust in the AR system. However, this positive effect on trust was not reflected in any measure of physiological response, such as heart rate variability or electrodermal activity. Further studies should explore the long-term effects of AR-based warning systems on both safety and stress reduction.

Note: This is a preprint. The final version of this article is published in *The International Journal of Advanced Manufacturing Technology*, vol. 138, no. 7, pp. 3593–3602, 2025, and is available online at <https://doi.org/10.1007/s00170-025-15784-5>.

Keywords: augmented reality, human-robot collaboration, warning systems, safety, trust, stress

1 Introduction and Background

Warning systems play a crucial role in industrial safety by significantly reducing accidents, financial losses, injuries, and fatalities [1]. Contact with a robot arm, for instance, can cause bodily injury, cuts, lacerations, and occasionally death. According to the Syndic European Trade Union, over 80,000 workers were injured, with some being fatally injured, while operating machinery in 2019 [2]. A recent analysis of robot-related injury fatalities in the US up to 2017 revealed that stationary robots, particularly arm robots, accounted for 83% of these incidents [3]. Thus, implementing **efficient warning systems** is critical in industrial environments where robots ensure worker safety and the smooth operation of equipment [4]. These systems alert operators to potential risks, issues, or other urgent situations [5]. Various warning systems are employed, each with its advantages and disadvantages.

1.1 Widely used warning systems

Visual warning systems are among the most commonly used devices in industrial settings. These systems use tower lights, display panels, and other visual cues to alert workers, see Figure 1A [6]. Typically, warning lights use red, yellow, and green to indicate danger, caution, and normal operation, respectively [7–9]. Display panels provide detailed information about equipment status, including faults and maintenance needs [10, 11]. The main advantages of visual systems are their ease of understanding and ability to convey complex information. However, they may be less effective in bright environments where visual signals are hard to distinguish or if the worker is not looking in the correct direction.

Auditory warning systems use noises or sirens. These can include voice alarms that provide specific instructions or details about the alert, or buzzer alarms that emit basic buzzing sounds, see Figure 1B [12, 13]. The main advantage of auditory warning systems is their effectiveness in noisy environments, as they can alert workers even when they are not looking directly at the equipment [14]. However, workers may become less sensitive to

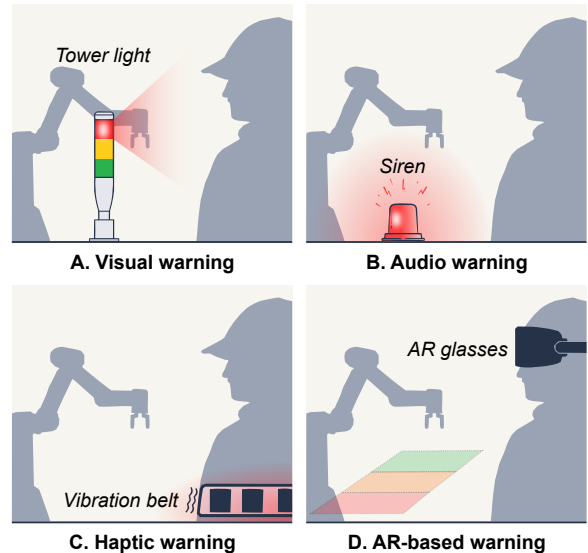


Fig. 1 Examples of warning systems have been implemented to improve safety using visual, audio, and haptic signals. Augmented reality (AR) is a potential alternative.

frequent sirens over time, reducing their effectiveness. Additionally, auditory alarms can contribute to noise pollution.

Haptic warning systems employ vibrations or other touch-based signals [15]. Examples include vibrating controllers on machines [16] and a vibrotactile band for workers, see Figure 1C [17]. These devices are particularly effective in noisy and bright environments where visual and auditory warnings might be missed [18]. However, haptic systems have a limited range of information they can convey, and if the sensations are too strong, they may become uncomfortable or ignored.

1.2 Augmented Reality as an alternative

The common disadvantages of visual, auditory, and haptic warning systems include their susceptibility to being overlooked in specific conditions such as bright lighting, noisy environments, or due to desensitization. In this context, using Augmented Reality (AR) that can project digital data into the real world as a warning interface is a potential alternative, see Figure 1D [19]. In human-robot collaboration, AR systems have already shown promise by providing real-time visual cues and feedback, enhancing situational

awareness, reducing uncertainty, and lightening the cognitive load on human operators [20–25].

The use of AR as a warning system has been studied, but there is still limited research on this topic. Several case studies have used AR to visualize the robot’s trajectory and safety zones [25–32]. This is expected to help human operators understand the robot’s next movement and consequently adjust their behavior to avoid dangerous situation. These studies have reported that AR-based warning systems offer certain advantages in improving safety, perceived safety, and trust. **However, the studies involved a limited number of participants, used non-validated questionnaires, and the results were not statistically validated.**

1.3 This study

In this work, **we investigate the effects of AR-based warning systems on safety, perceived safety, trust, and physiological response as stress indicators in an HRC context using a more rigorous experimental protocol than previous studies.** We first designed a color-based AR warning interface to display the robot’s trajectory and safety zones. Green indicates safety, yellow indicates caution, and red indicates danger, as illustrated in Figure 1D. This system was implemented in an industrial task in which an operator collaboratively assembled a product with a robot. We conducted a within-participant experiment where each participant completed a product assembly task with the robot in two conditions: with AR and without AR, in a counter-balanced order. After each condition, *safety* was evaluated based on whether there was a collision between the operator and the robot. *Perceived safety* and *trust* were assessed using validated questionnaires. *Physiological response* was further measured by an Empatica wristband.

2 Materials and Methods

2.1 Study design

We designed a within-participant experiment to investigate the effects of an AR-based warning system on safety, perceived safety, trust, and physiological response. Each participant experienced a

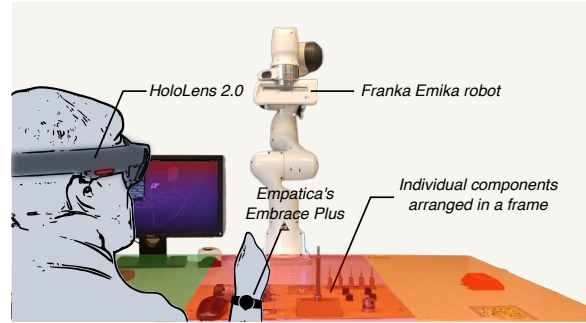


Fig. 2 The experimental setup consists of a Franka Emika robot and components for the assembly operation. A person wears a HoloLens with AR visualization of workspace zones based on safety conditions.

product assembly task with the robot in two conditions: *AR* and *No AR*, in a counter-balanced order. After each condition, we assessed safety, perceived safety, trust, and physiological response. The experiment was conducted at Brubotics, Vrije Universiteit Brussel, Belgium, and obtained ethical approval from the institutional ethics committee (ECHW_457).

2.2 Participants

We recruited 26 participants including 18 males and 8 females, aged between 20 and 37 and the mean age of the participants was 26.11 years ($SD = 3.88$). All participants were volunteers who fully understood the purpose of the study and confirmed that they did not suffer from any mental or physical disorders, cardiovascular conditions, or color blindness.

2.3 Design of a color-based AR warning system

2.3.1 The collaborative task

We selected an industrial assembly operation in which a human and a robot collaboratively assemble a product as illustrated in Figure 2. The product is an ice crusher unit for an Alberts smoothie machine¹, see Figure 3 [34]. The individual components are arranged in a frame and positioned on a table in front of the robot. The task description of the assembly process is presented in Table 1. In principle, the pick and place

¹Alberts Smoothie Station: <https://www.alberts.be>

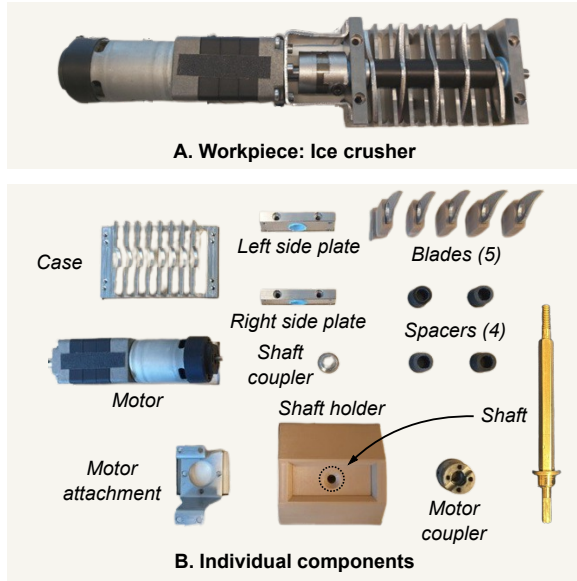


Fig. 3 The workpiece. (A) Assembled ice crusher of a smoothie machine. (B) Individual components of the ice crusher [33].

tasks are carried out by the robot, and the screwing and connecting tasks are done by the human, which requires more dexterity skills.

2.3.2 Hardware

For this work, we selected Franka Emika [35] as the robot platform to carry out a human-robot collaborative task. The robot has seven degrees of freedom which is suitable for various tasks. Microsoft HoloLens 2.0 was implemented as the AR head-mounted device [36] for visualizing workspace zones. An Empatica's EmbracePlus wristband was used to collect physiological response.

2.3.3 Color-based safety zone visualization

An AR interface was developed using Unity3D, a widely used game engine and development platform [37]. The main feature of this AR interface is its dynamic color-based visualization that responds in real-time to robot's movement. We selected three basic colors (red, yellow, green) to overlay on the workspace zone to represent the safety conditions based on the accessibility and the next robot's location [38, 39], see Figure 4.

Table 1 Task description of the ice crusher assembly. Each task is assigned either to the robot (R) or the human operator (H).

Tasks	Description	R/H
Phase 1	<i>Assembling the motor part</i>	
T1	Pick and place shaft	Robot
Phase 2	<i>Assembling the shaft, spacers, and blades</i>	
T2	Pick and place blade 1	Robot
T3	Pick and place spacer 1	Robot
T4	Pick and place blade 2	Robot
T5	Pick and place spacer 2	Robot
T6	Pick and place blade 3	Robot
T7	Pick and place spacer 3	Robot
T8	Pick and place blade 4	Robot
T9	Pick and place spacer 4	Robot
T10	Pick and place blade 5	Robot
T11	Pick and place left side plate	Robot
Phase 3	<i>Attaching the motor to the coupler and connector using screw</i>	
T12	Pick and screw nut	Human
T13	Pick and place case	Robot
T14	Pick and place assembled shaft	Robot
T15	Pick and place left side plate	Robot
T16	Screw left side plate	Human
T17	Pick and place right side plate	Robot
T18	Screw right side plate	Human
Phase 4	<i>Connecting and securing the motor and shaft parts together</i>	
T19	Pick and place motor	Robot
T20	Pick and place motor attachment	Robot
T21	Screw motor attachment	Human
T22	Pick and place motor coupler	Robot
T23	Screw motor coupler	Human
T24	Pick and place shaft coupler	Robot
T25	Screw shaft coupler	Human
T26	Pick and place assembled motor	Robot
T27	Connect motor to shaft	Human
T28	Screw motor to shaft	Human

- Yellow zone: An early warning signal to inform the human that the robot will be in that zone in the next three seconds.
- Red zone: A warning signal to inform the human that the cobot is carrying out a task. It is dangerous and the human should not enter.
- Green zone: A safe signal for the human to present in the zone for working.

The zone's color changes to yellow three seconds before the robot approaches a zone to pick up or place an object as a warning to the operator. When the robot arrives at a specific zone, the zone's color changes to red, indicating the robot's presence. These warning signals give the operator enough time to stop their movement, step back,

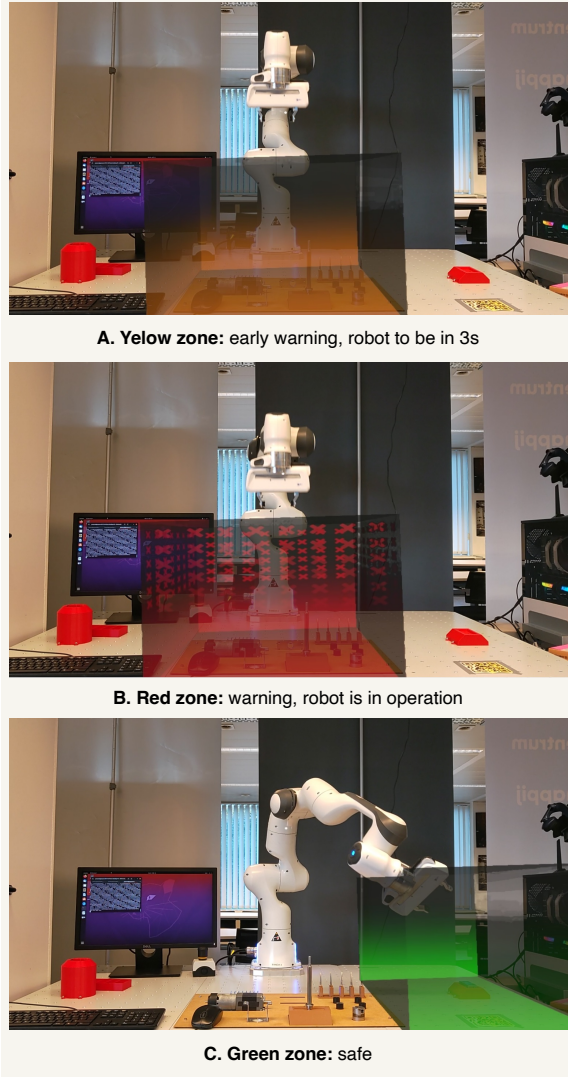


Fig. 4 The AR workspace zone visualization with three basic colors: yellow as early warning, red as dangerous, and green for safe.

and avoid potential collisions or disruptions in the collaborative workflow. Once the robot leaves a zone, the zone’s color changes to green, informing the operator that it is safe to start or continue working.

2.4 Procedure

Participants were asked to stand in front of the workcell with the experimental setup. All parts of the smoothie machine ice crusher unit as the assembly task were placed on the table. The

experimenter explained the assembly instructions verbally. Participants could review and ask questions related to the experiment and the task before starting.

Before performing the task, an initial calibration was conducted to capture the baseline physiological parameters of the Empatica wristband, which was used to assess the physiological response. Participants were asked to sit for 5 minutes and then their parameters were set as a reference.

Each participant experienced two conditions (*AR* and *No AR*) in a counter-balanced order. In the *AR* condition, the participant wore the HoloLens, while in the *No AR* condition, they interacted with the robot in a normal way. On average, it takes approximately ten minutes to assemble one ice crusher unit in each condition. After each condition, participants were asked to fill in questionnaires to assess perceived safety and trust.

2.5 Measurements

Safety was evaluated based on whether there was a collision between the operator and the robot. *Perceived safety* was assessed using the Godspeed questionnaire [40]. *Trust* was assessed using the Trust in HRC questionnaire [41]. The questionnaire items were filled out using a 5-point Likert scale. *Physiological response* was further assessed using Empatica’s EmbracePlus wristband. We focused on heart rate variability (HRV) and skin conductance level (SCL), a tonic component of electrodermal activity (EDA). These measurements are physiological indicators of stress [42, 43].

2.6 Data analysis

Data analysis was conducted using Python using `scipy` and `pingouin` packages. Normality and homogeneity were assessed using Shapiro-Wilk and Bartlett tests, respectively. The results of these tests determined whether to apply parametric or non-parametric tests. The significance level was set at 0.05.

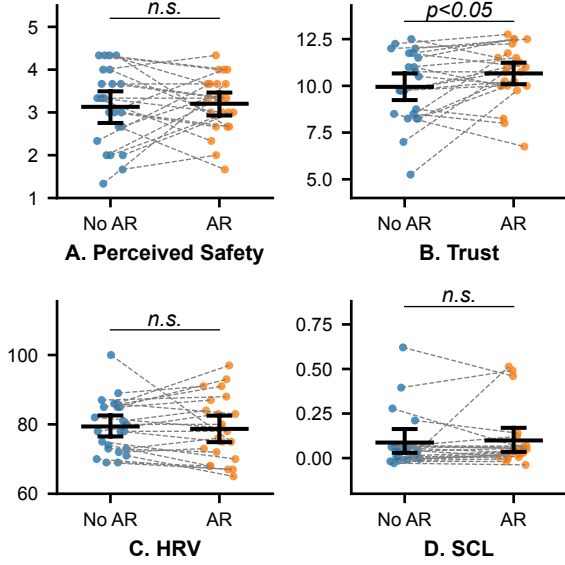


Fig. 5 Experimental results. Participants demonstrated a higher level of trust but did not subjectively perceive the AR-based system as safer. There were no significant changes in physiological response i.e. heart rate variability (HRV) and skin conductance level (SCL).

3 Results and Discussion

3.1 Safety

During the experiment, three collisions (11.5% of the cases) occurred between participants and the robot, all of which took place during the No AR condition, while no collisions were observed during the AR condition. This objective measurement suggests that the AR-based warning system provides a safer working environment by offering real-time indications of safe and hazardous zones, allowing participants to adjust their behavior and avoid collisions with the robot while performing the collaborative task. Since collisions occurred with three participants, we excluded their data from the remaining analysis to maintain consistent conditions across participants and avoid potential bias in the results.

3.2 Perceived Safety

We found no significant improvement in perceived safety, see Figure 5A. The results from a paired t-test showed that the mean perceived safety in the AR condition ($M=3.20$, $SD=0.65$) was not

significantly higher than in the No AR condition ($M=3.1$, $SD=0.90$, n.s.).

Although safety was objectively improved by the implementation of the AR-based warning system, participants did not perceive their environment as significantly safer. This might come from the selected lab-based HRC task, which was designed with a high level of safety and has no potential for highly dangerous situations. The robot also operates at a low speed, reducing the likelihood of physical injury from collisions. Additionally, it is equipped with an internal torque sensor that can detect collisions and automatically stop the robot, further enhancing safety by default.

3.3 Trust

There was a significant improvement in Trust, see Figure 5B. The results from a paired t-test showed that the mean trust score in the AR condition ($M=10.66$, $SD=1.49$) was significantly higher than in the No AR condition ($M=9.95$, $SD=1.83$; $t(22)=2.13$; $p<0.05$; Cohen's $d=0.42$).

Although participants did not explicitly perceive the AR-based warning system as safer, they expressed a higher level of trust in the AR-based warning system. This trust likely arises from their recognition of the system's ability to provide real-time alerts and clear indications of safe and dangerous zones. This helped them better understand the working environment, leading to fewer near-collision situations, which improved confidence in the technology.

3.4 Physiological response as stress indicators

We found no statistically significant difference between the two conditions in physiological responses, see Figure 5C-D. Specifically, the results from a paired t-test showed that the mean HRV values were not significantly different between the AR ($M=78.70$, $SD=9.19$) and the No AR conditions ($M=79.39$, $SD=7.61$; $t(22)=0.49$, n.s.). Regarding the SCL, we identified data from one participant as an outlier since their values were significantly higher than the rest, probably due to a measurement error. The results from a Wilcoxon test showed that the mean SCL values were not significantly different between the AR

($M=0.099$, $SD=0.160$) and the No AR conditions ($M=0.087$, $SD=0.155$; $W=113.0$, n.s.).

These results indicated that there was no significant difference in stress levels when using the AR-based warning system. This suggests that while AR may enhance situational awareness and improve safety by providing real-time information, it does not immediately reduce the stress associated with the collaborative task. This could be attributed to the low-stress nature of the controlled lab environment. Furthermore, AR is a novel technology for participants, and it may take time for the positive effect on trust to be reflected in reduced stress levels.

4 Conclusion

In this study, we conducted an experiment to examine the effects of an AR-based warning system on safety, trust, and physiological responses in a human-robot collaboration context. Our findings suggest that while the system has the potential to enhance safety by visually highlighting dangerous zones, participants did not explicitly perceive the environment as safer. However, they demonstrated a higher level of trust in the AR system. Due to the highly safe nature of the controlled lab environment, combined with the relatively short duration of the experiment, we did not observe significant changes in physiological responses.

Future research should explore the long-term effects of AR-based warning systems in more dynamic and realistic settings, reassessing their impact on perceived safety, trust, and physiological indicators of stress. Additionally, it will be important to investigate whether AR can actively contribute to reducing stress levels in long-term HRC scenarios.

Declarations

Funding This work was funded by the EU OPENVERSE with project number 101135701–OPENVERSE, and the Interuniversity Microelectronics Centre (imec), a research and development organization of Flanders, as part of the AAA Valence project.

Conflict of interest/Competing interests The authors declare that they have no conflict of interest.

Consent to participate The study obtained ethical approval from the institutional ethics committee (ECHW.457). The authors declare that this research was conducted in full accordance with the Declaration of Helsinki. Informed consent was obtained from all individual participants involved in the study.

Availability of data and materials Data are available from the corresponding author upon reasonable request.

Code availability Not applicable

Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by M.O., J.D.W, and H.L.C. The first draft of the manuscript was written by M.O and H.L.C. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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