Perceived Safety of Workers in Encounters with Large Industrial AGVs

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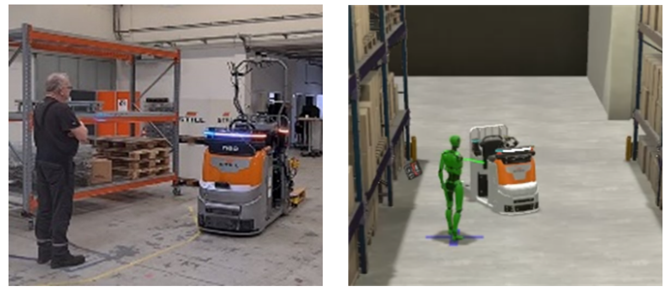
***Abstract*— Automated Guided Vehicles (AGV) in factory automation are increasingly capable of moving autonomously in close proximity to human workers. While their physical safety is regulated by standards and directives, perceived safety and workers' comfort in close-proximity interactions are being actively investigated in studies. There are three limitations in the prior art research to that end. Firstly, AGVs with larger payloads are understudied. Secondly, the test participants are usually students and not working professionals. Thirdly, while conducting in-person experiments with heavy machinery can be dangerous, the transfer of safety perception results from simulated experiments remains open. In this paper, we investigate industrial workers' perceived safety in shared spaces with large AGVs in a real-world encounter and in virtual reality. We vary the passing distance and the shape of the collision avoidance maneuver, and evaluate perceived threat level using a handheld pressure-sensitive trigger interface and a post-experiment questionnaire. Additionally, we ask participants to set their own collision avoidance parameters based on their experience with the demonstrated trajectory profiles. In a within-subject study, we found that, while the threat levels are perceived overall slightly higher in VR, the passing distance of 1.5 to 2 meters is preferred among the demonstrated profiles, as well as in the self-defined trajectories.**



(a) Real-world encounter (b) VR replication

Fig. 1: Participants interacting with an AGV: (a) real-world encounter and (b) corresponding replication in the VR environment.

I. Introduction

The use of Automated Guided Vehicles (AGVs) in industrial settings and warehouses has increased significantly in recent years [1]. The majority of industrial AGVs have a load capacity of 1-8 tons, maximum operating speed of 2-3 m/s, and their *physical* safety is regulated by the European Machine Directive [2] and ISO 3691-4 [3]. AGVs usually operate in mixed traffic, including pedestrians and manually driven industrial trucks, and can be categorized into autonomous and non-autonomous trucks [1], [4]. AGVs without autonomous functions strictly follow predefined trajectories, making their paths predictable to people in regular contact with them [5]. With the increase in autonomous route planning and collision avoidance, their trajectories become less predictable. This makes it important to evaluate their effect on the humans encountering them and draw design implications from these encounters, thus improving their legibility and achieving higher levels of *perceived* safety. User Experience (UX) tests [5] have shown that both explicit visual and auditory signals, as well as implicit information conveyed through the vehicle's driving behavior, can make its movement more predictable. Prior work has dealt with explicit external signals and lead to the VDMA recommendation "Design of visible and audible signals of driverless industrial trucks" [6]. At the same time, there are indications that people actually rely mainly on the robot's current movement to anticipate its future path and do not consider visual or auditory signals at all [5]. This motivates the movement of the robot as a potential factor in legibility and perceived safety.

In practice, evaluating the user experience of a moving robot is challenging, as it must be set up in the target environment and all potential risks posed by a large, heavy robot must be eliminated. Testing in a simulation using virtual reality (VR) or augmented Reality (AR) would significantly reduce effort and eliminate the risk of collisions with test subjects [8]. The question of whether findings from the VR/AR testing can be transferred to the real-world settings is currently being investigated in numerous research projects [9], e.g. in the automotive industry and for delivery robots. Schneider and Bengler [10] state that a quantitative transfer of outcomes from VR to reality should be approached cautiously due to moderate correlations across many studies and the limited number of studies explicitly aimed at evaluating comparability.

Furthermore, existing studies of perceived safety in encounters with AGVs focus either on small service robots that do not pose a threat to humans or on autonomous vehicles (AV). In contrast, the robots in intralogistics are much larger and more dangerous than service robots, and travel at

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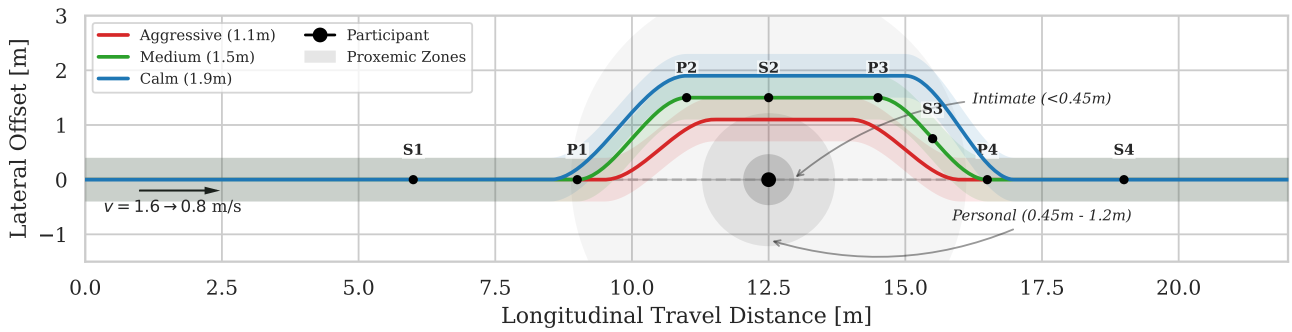

Fig. 2: Three AGV trajectory profiles (aggressive, medium and calm) around the static participant, positioned at 12.5 m. Circles around the participant show the three proxemics zones [7].

much lower speeds than AVs. Additionally, many academic studies recruit university students as test participants, who have a rather different background compared to the industry workers. Finally, most studies do not employ continuous threat assessment measures reported during the encounter, but instead rely on post-hoc questionnaires.

In this paper, we examine perceived safety during encounters with an industrial AGV among real factory workers. We compare three trajectory profiles, which differ in the distance to the person. In addition to the questionnaires, we use the pressure-sensitive controller trigger as a continuous measure of perceived threat, and compare the real-world experience to the VR replication. Finally, we ask participants to set their preferred collision avoidance parameters in VR. Our study aims to address the following research questions:

- How does the perceived safety in encounters with industrial AGVs relate to the passing distance?
- To which extent the perceived safety in encounters with industrial AGVs in VR compares to a real-world experience?
- What are the preferred collision avoidance parameters (the lateral and longitudinal distances) from the perspective of a standing person?

II. Related work

A worker's safety in shared spaces with industrial-level AGVs is a critical issue that ISO standards [3] aim to address. However, these norms do not address perceived safety and threat levels people experience in proximity to these platforms, which are often expressed as hesitation or reduced walking speeds [11]. Perceived safety is shown to depend on the approach direction of the robot, its speed, and appearance [1]. However, the majority of the experiments still take place in laboratory settings and do not leverage commercially deployable AGVs [1]. Furthermore, most studies do not employ continuous measures reported during the encounter but instead rely on post-hoc questionnaires [1], which often miss the moment when perceived danger spikes, which could inform the collision avoidance behavior and intent communication design for AGVs.

Exposing participants to large heavy vehicles in real-world encounters can lead to injuries and is also logistically challenging, especially in real production environments. Therefore, in domains such as autonomous driving [12] and industrial AGV interaction [4], Virtual Reality (VR) is a well-established method. VR has been used to evaluate the effect of explicit communication from AGVs (with and without an LED eHMI) on trust and perceived safety [4]. A central question for this line of research, though, is the transferability of VR to the real world. For HRI applications, researchers found that people accept closer distances to physical robots than to virtual ones [13], that trust and engagement transfer well for service robots [14] and for industrial manipulators [15]. However, some researchers point to task dependency as a factor in transferability [16], while others question it altogether [17]. To the best of our knowledge, there are no systematic studies of perceived safety transferability between VR and the real factory floor for large AGVs. In this work, we adopt measures such as continuous trigger press [18], [19], which is tightly coupled to proximity to the AGV, and apply them to large-payload AGVs across matched VR and real-world conditions.

III. Methods

A. Study Design

In this paper, we investigate the perceived safety of people in interactions with AGVs, experienced in virtual reality and in the real world. For this purpose, we design a collision avoidance scenario in an intralogistic environment in which the robot follows a pre-programmed maneuver around the standing participant (see Fig. 1). The robot platform is an iGo neo OPX order picker (Still GmbH), modified into an autonomous research vehicle as part of the IMOCO4.E project[1]. Navigation is managed via the ROS2 stack, utilizing a custom cubic-spline planner coupled with the Regulated Pure Pursuit (RPP) plugin for precise, vehicle-specific path tracking. To facilitate human-robot interaction, the platform is augmented with a prototypical external HMI (eHMI) system comprising four RGB-LED strips and a broadband speaker, supporting the optical and acoustical signals aligned with the VDMA recommendation [6].

Trajectory of the robot is parametrized by a sequence of control points that define its evasive behavior relative to a

[1] https://www.imoco4e.eu

stationary participant (see Fig. 2). The robot approaches the participant along a linear path at a max. velocity of $1.6\,\text{m/s}$, then decelerates to $0.8\,\text{m/s}$ until S_1, where an amber flashing signal is initiated via the eHMI to communicate intent. The evasive maneuver begins at the turn-in point P_1, which is adjustable along the longitudinal axis to vary the onset of the swerve. The lateral displacement and the duration of the parallel bypass are governed by points P_2 and P_3, while P_4 determines the longitudinal coordinate for the return to the original path. Acceleration back to the initial velocity commences at point S_4. Utilizing this geometric framework, we define three discrete trajectory profiles: an *aggressive* version with minimal permissible safety distances, a *calm* version with generous clearance, and a *medium* version serving as an intermediate baseline. The distances in Fig. 2 are specified relative to the person's position and the center point of the robot's footprint.

The virtual reality part of the experiment is created in Unity. The robot behavior and signaling are comparable across the real-world and VR versions of the study. To ensure a realistic experience with sufficient immersion, we use a shaded CAD model and implement realistic driving sounds. The simulation runs on a stationary PC using SteamVR and streams wirelessly to a VR headset (HTC XR Elite).

In addition to experiencing the predefined profiles, we asked the participants to parameterize their custom trajectories using a VR interface. The interface utilizes virtual representations of the AGV at each control point, which participants can manipulate via a VR controller to adjust the path's geometry. The resulting trajectory is visualized as a projection on the virtual floor. Participants can conduct virtual test-runs and are permitted unlimited iterations to refine their design. The self-defined trajectories are executed exclusively in the virtual environment to prevent artificial restrictions on the participants' preferred safety boundaries.

B. Data Collection and Metrics

The study was conducted at the STILL GmbH in Hamburg, Germany, a major manufacturer of forklift trucks and other material-handling equipment. The location has approximately 3000 employees. All test subjects were recruited from the local workforce. The study cohort ($N = 10$) comprised professional staff from industrial assembly and internal logistics divisions, balanced for age (50% aged 20–49, 50% aged ≥ 50) and technical experience, with 40% of participants reporting significant prior AGV interaction. The gender distribution included 9 males and 1 female participant, all of whom were active employees in truck assembly or forklift operation at Still GmbH.

We employ a multi-modal approach to quantify user perception, combining continuous real-time input with discrete psychometric scales. During each trial, participants provided a continuous measure of perceived threat level $T(s) \in [0, 1]$ via a pressure-sensitive trigger on the VR controller, recorded with respect to the total travel distance of the robot s. Controller input ranges from a null value (fully relaxed) to a maximum value (maximum perceived risk). From $T(s)$ we derive three per-trial metrics: the *trigger use rate*, the percentage of trials in which the trigger was engaged at any point; the *total duration* (t_{total}), the cumulative time the trigger was held active; and the *area under the curve* (AUC),

$$\text{AUC} = \int_{s_{\text{start}}}^{s_{\text{end}}} T(s)\,\mathrm{d}s, \qquad (1)$$

with s_{start} and s_{end} bounding the analysis window along the AGV path.

Following each run, a discrete assessment is recorded using a 5-point Likert scale ranging from *"much too unsafe"* to *"much safer than necessary"*. To evaluate the effect of modality (VR and real-world), we asked the participants to rate the similarity in (a) relative safety ($1 =$ much safer in real, $5 =$ much safer in VR), (b) velocity perception ($1 =$ much faster in VR, $5 =$ much faster in real), (c) spatial proximity ($1 =$ much closer in VR, $5 =$ much closer in real), and (d) overall encounter perception ($1 =$ very strong, $5 =$ not at all). These quantitative metrics are augmented by semi-structured qualitative interviews conducted at the midpoint and the end of the study to record insights into participants' perception of the "reality gap."

IV. Results

Perceived threat levels based on the trigger press are summarized in Fig. 3. Both in VR and real-life, participants pressed the trigger most actively in the *aggressive* profile; the *medium* and *calm* trajectories elicited only low-amplitude signals. The trigger presses in the real encounter were more pronounced at the beginning of the collision avoidance maneuver, whereas in the VR the trigger reactions were registered through the trial.

Table I aggregates the three objective metrics across profiles and modalities. All three decreased from *aggressive* to *calm* in both modalities, consistent with reduced perceived threat as the lateral clearance grew. The cross-modality offset was most pronounced in the *aggressive* profile, where VR produced a 75 % higher mean AUC (3.5 ± 3.3 vs. 2.0 ± 2.0), a 67 % longer mean t_{total} (6.4±4.8 s vs. 3.8±3.7 s), and a 15-percentage-point higher trigger use rate (90 % vs. 75 %). t_{total} remained higher in VR for both the *medium* (1.8 vs. 1.1 s) and *calm* (2.4 vs. 0.9 s) profiles, with the largest *relative* VR/RW gap appearing in the *calm* profile. The two non-aggressive profiles otherwise showed small and inconsistent differences: AUC differed by 0.1 in *medium* and 0.3 in *calm*, and the trigger use rate favoured VR for *aggressive* and *calm* but the real world for *medium* (50 % vs. 40 %). Inter-participant variance was large due to a small sample size.

Subjective safety ratings increased across profiles from *aggressive* to *calm* (Fig. 4 left). In the *aggressive* profile, both modalities clustered at the unsafe end: VR ratings spanned 1–2, while most real-world encounters were rated 2. For the *medium* profile, medians were comparable but the spread differed in direction — VR extended downward to 1, real-world upward to 5. The largest median offset appeared in the *calm* profile, where the VR median (3, spread 2–4) lay one point below the real-world median (4, spread 4–5). Averaged

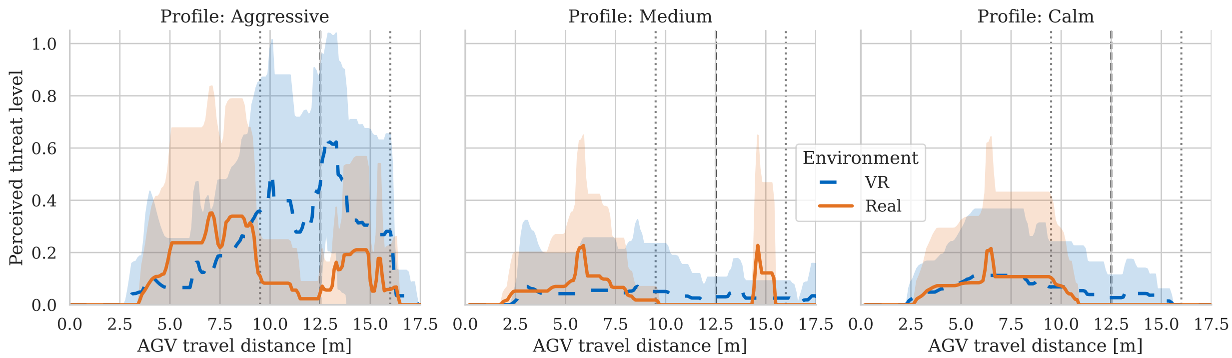

Fig. 3: Evolution of the perceived threat levels with proximity to the AGV along the three trajectory profiles, recorded using continuous trigger press. Vertical lines denote the key maneuvers (P1, S2 and P4 from Fig. 2).

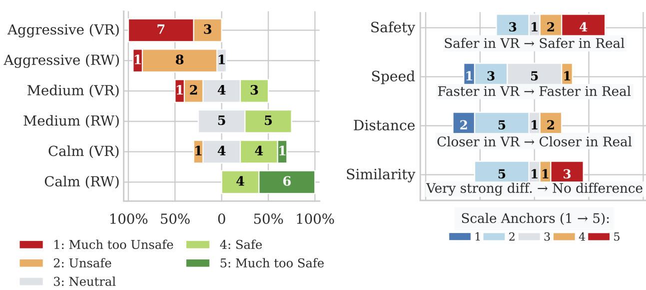

Fig. 4: Subjective Measures (5-pt Likert scale). **Left:** Safety ratings for three robot trajectory profiles across Virtual Reality (VR) and Real-World (RW) modalities (M.t. = Much too). **Right:** Cross-modality perception differences: (a) relative safety, (b) relative speed, (c) relative distance, and (d) overall encounter similarity.

TABLE I: Perceived threat metrics across the three trajectory profiles and two modalities (Mean $\pm$ SD)

Profile	**Modality**	**Trigger rate [%]**	**AUC**	t_{total} **[s]**
Aggressive	Real	75	2.0 ± 2.0	3.8 ± 3.7
	VR	90	3.5 ± 3.3	6.4 ± 4.8
Medium	Real	50	0.7 ± 1.3	1.1 ± 2.3
	VR	40	0.6 ± 1.7	1.8 ± 3.4
Calm	Real	20	0.7 ± 2.0	0.9 ± 2.5
	VR	30	0.9 ± 2.0	2.4 ± 4.7

across the three predefined profiles, VR ratings were 0.7 points below their real-world equivalents.

From the VR and real-world similarity questionnaire (Fig. 4 right), (a) relative safety ranged from 1 to 4 with no ratings at 5 (mean 2.3), consistent with the directional bias seen in Fig. 4; (b) relative speed and (c) relative distance had narrow spreads concentrated between 2 and 3 (means 2.6 and 2.3), with consistent reports that distances felt closer and speeds higher in VR; and (a) overall encounter similarity had a wide spread from 2 to 5 (mean 3.2).

V. Discussion

The perceived threat level measurements are consistent with the Likert-scale ratings after each test run. Both show that participants feel slightly less safe in VR. This result is consistent with the questionnaire results after the direct

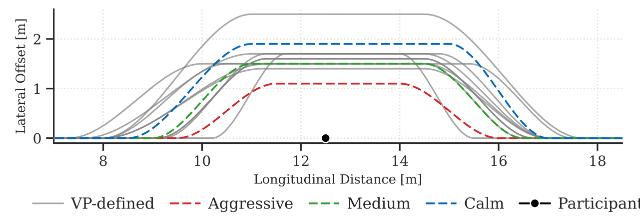

Fig. 5: Preferred collision avoidance profiles of participants in VR.

comparison, where participants, on average, felt slightly less safe in the VR environment, judged distances slightly closer, and reported a slightly higher speed. This interpretation is also consistent with the answers during the qualitative interview: seven participants stated that the results would be well transferable, one said there would be some differences, and two said comparison would be difficult. Interestingly, three participants stated that they felt less safe in VR, even though, in the back of their minds, they always knew that, being in a virtual space, they were in no real danger.

Regarding the desired parameters of the collision avoidance behavior, participants reported the lateral distance and the start of the collision avoidance maneuver as the main sources of discomfort. The self-defined trajectories, shown in Fig. 5, reflect that a combination of the medium profile (in terms of the lateral offset) and the calm profile (in terms of the longitudinal distance) is preferred.

Limitations: With $N{=}10$, our findings with respect to the perceived safety and preferred distance are indicative. Determining the safe parameters for collision avoidance would require a larger sample size to achieve statistical significance, and should consider the robot's speed as a factor in perceived safety. Furthermore, our findings are based on a single scenario with a stationary participant. Further encounter types need to be considered in future work [20]. Finally, while the gender distribution among participants mirrors the actual workforce at the production site, future studies should include more balanced distributions to avoid potential biases.

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