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OpenVerse

D3.3: Report on Demonstration Case on Virtual Worlds Enabled Robotics

Developing Industry-Focused Use Cases for Enhanced Collaboration

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Abstract	This deliverable reports on Task 3.3 of the OPENVERSE project, which develops and validates a demonstration case on Virtual Worlds–enabled robotics in an industrial context. The selected use case focuses on warehouse and in-house logistics operations related to e-commerce order fulfilment. A tailored Augmented Reality (AR) interface was designed to improve robot-to-human communication and reduce fulfilment errors. To evaluate its potential, a cross-European SME survey was

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	conducted alongside a user acceptance study comparing AR-based and paper-based workflows. Results highlight both the opportunities of AR to enhance engagement, accuracy, and collaboration, and the challenges posed by hardware usability, ergonomics, and adoption risks. The findings provide practical insights for SMEs considering AR adoption, and point to policy needs such as fostering ergonomic hardware innovation, ensuring technical reliability, and developing trust and accountability frameworks for immersive human-robot interaction. In this way, the work contributes to future research directions and to the broader OPENVERSE objective of enabling human-centric, sustainable Virtual Worlds in Europe.
Keywords	Virtual Worlds, human-robot collaboration, e-commerce, technology acceptance

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* R: Document, report (excluding the periodic and final reports)

DEM: Demonstrator, pilot, prototype, plan designs

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DATA: Data sets, microdata, etc.

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EXECUTIVE SUMMARY

This report presents the outcomes of Task 3.3, which demonstrates the potential of Virtual Worlds technologies to enhance safe human-robot collaboration in industry. The use case was situated in warehouse and in-house logistics for e-commerce order fulfilment, a sector facing both growing automation and robotisation. However to handle the massive amount of objects, the human dexterity is still far more superior than robot hands. To cognitively support the order pickers when collaborating with a cobot which had a unique Safebot technology to move fast when humans are on a safe distance and move slow or stop when humans are approaching (the speed and separation monitoring-SSM). As such strengths of human and robot are combined. This use case has spillovers to other sectors.

The study followed a two-step approach. First, a survey of 53 SME employees – from warehouse workers to business owners – from 17 European countries was conducted to assess attitudes toward AR adoption. Respondents expressed strong interest in AR, citing expected gains in productivity and workload reduction, while also voicing concerns about comfort, health, and device reliability. Second, a within-participant experiment was carried out with 27 participants to compare an AR-based fulfilment interface against traditional paper-based methods

Results showed that AR improved perceived enjoyment and social influence but lagged in completion time and intention to use, largely due to unfamiliarity with the technology and current hardware limitations. These findings underline that AR technologies can support more intuitive and engaging collaboration between workers and robots but also highlight the need for ergonomic improvements and robust trust frameworks to ensure broader adoption.

For SMEs, the results offer practical guidance on expected benefits, user acceptance factors, and barriers to implementation. For policymakers and technology providers, they point to the importance of supporting ergonomic hardware innovation, ensuring the technical reliability of immersive systems, and advancing trust and accountability frameworks to govern their use in industrial contexts. At a strategic level, the study suggests that Virtual Worlds can serve not only as technical tools but also as cultural and social enablers of

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industrial collaboration. For Europe, this creates an opportunity to position Virtual Worlds as drivers of both digital transformation and industrial sustainability.

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ABBREVIATIONS

AI	**Artificial Intelligence**
AR	**Augmented Reality**
EU	**European Union**
GDPR	**General Data Protection Regulation**
HMD	**Head-Mounted Display**
SDK	**Software Development Kit**
SME	**Small to Medium Sized Enterprise**
VR	**Virtual Reality**
XR	**Extended Reality**

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1 INTRODUCTION

1.1 THE OPENVERSE PROJECT

The OPENVERSE project is an initiative under the Horizon Europe framework, designed to pioneer a comprehensive, open, and human-centric virtual worlds. This endeavour is pivotal in shaping a future where digital transformation within the European Union is underpinned by principles of openness, inclusivity, ethical and environmental responsibility. At its core, OPENVERSE seeks to promote the technological sovereignty for the EU, ensuring that it stands at the forefront of the global digital arena. OPENVERSE emerges in response to the need for European virtual worlds that mirrors the region's values and aspirations. Unlike proprietary virtual worlds, OPENVERSE envisions a digital space that is democratic, where users maintain control over their data and digital identities, and where the barriers to entry are significantly lowered. This vision aligns with the European Union's broader strategies for digital transformation, which emphasise ethical standards, digital rights, and fostering an environment conducive to innovation and creativity.

1.2 PURPOSE AND SCOPE OF THE TASK AND DELIVERABLE

Task 3.3, “Demonstration case on Virtual Worlds Enabled Robotics: Developing Industry-Focused Use Cases for Enhanced Collaboration”, explores the potential of Virtual Worlds in enhancing human-robot collaboration within industrial settings, with a particular focus on collaborative robotics (i.e. allowing human-robot interaction). Building on the foresight scenarios developed in Task 2.4, the task investigates technological and behavioural aspects of Virtual Worlds as they relate to human-robot interaction in industry.

By leveraging Extended Reality (XR) interfaces, the task aims to develop a demonstrator that improves communication of collaborative robots’ current states and activities, enabling workers to more easily understand and interact with them. This approach is aimed at reducing the learning curve, supporting skills development, and enhancing efficiency in industrial operations. In doing so, it envisions a future where human-robot collaboration is both beneficial and essential to addressing Europe’s welfare and prosperity challenges in industrial contexts.

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To assess user perspectives, a small-scale experiment involving up to 50 participants will be conducted. This study will help identify the benefits and potential challenges of Virtual Worlds–supported robotics applications. Expert and stakeholder input from the public and European SMEs will also be incorporated to enrich the analysis and contextualise findings.

The task will be developed in close interaction with other project activities, including foresight sessions (T2.4), ethical and legal requirements (T3.4), and IPR and governance model development (T3.5). Its outcomes will contribute to identifying the skills needed to support Virtual Worlds adoption in Europe and will feed into the project roadmap (T2.5), as well as WP6 activities.

At the project level, Task 3.3 supports the overarching objective**:**

- *OO3: Analyse the ethical, legal, and socio-economic conditions and requirements of a European Open and Human-centric Virtual worlds concept, including:*
  a) a foundational overview of current Virtual worlds trends and their emerging potentials, b) the identification of suitable IPR models and challenges for SMEs related to the single market based on free and open source principles, and c) the delivery of both an original demonstration case on Virtual worlds enabled robotics as well as an exploratory study on the potential issues related to the user perspective within existing and upcoming Virtual worlds environments.

Task 3.3 specifically supports this objective by delivering:

- a demonstration case on Virtual Worlds–enabled robotics, and
- an exploratory study of potential issues related to user perspectives in industrial contexts.

This deliverable presents the outcomes of Task 3.3. The contributions of this study are as follows:

- We gathered key barriers and drivers of AR adoption from a cross-European SME survey, highlighting hardware limitations and user comfort as critical factors for future uptake.

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- We designed and validated an AR interface for robot-assisted order fulfilment aimed at reducing error rates through intuitive visual cues, real-time feedback, and robot-to-human communication.
- We conducted a within-participant experiment on user acceptance study of AR systems, comparing AR and paper-based methods, to support the ecological validity of introducing AR technologies in warehouses.

1.3 STRUCTURE OF THE DOCUMENT

The structure of this deliverable is as follows:

Section 2 introduces the rationale for the chosen use case and outlines the process of use case selection.

Section 3 presents the design of the Augmented Reality (AR) order fulfilment interface, describing the task, interface content, and technology stack.

Section 4 reports on the validation through a user acceptance study, including experimental design, participants, procedures, data analysis, and results.

Section 5 discusses the key findings, their implications for human-robot collaboration, and their relevance for the adoption of Virtual Worlds in industrial contexts.

Section 6 concludes the document with a summary of insights, limitations, and recommendations for future developments.

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2 RATIONALE AND USE CASE SELECTION

To effectively demonstrate how Virtual Worlds can enhance human-robot collaboration, it was important to select an application area where both improvement is needed to improve productivity and support human workers. We identified warehouse and in-house logistics operations related to e-commerce order fulfilment as such an area, but similar needs also exist in other sectors as manufacturing, services etc. Such operations are still challenging to be performed by robots, but human workers need cognitive and physical support. As such strengths of humans and robots are combined. This context provides a relevant setting to assess how Virtual Worlds technologies can improve robot-to-human communication, reduce learning curves, reduce cognitive workload and increase operational efficiency. The selection is further justified by the rapid growth of e-commerce in Europe, which presents new logistical challenges and underscores the need for innovation in order fulfilment in a society with societal and economic challenges (eg ageing workforce, need for healthier jobs,…).

Electronic commerce (e-commerce) refers to the sale and purchase of goods and services through the Internet or other online communication networks transactions. From 2018 to 2023, the turnover of e-commerce in the European Union has increased by 65%, and in 2023 alone, 68% of the EU-27 population bought physical goods online [1]. With the ever-spreading digitalisation of life, the steady growth of e-commerce turnover and penetration in Europe is forecasted to continue, furthering the transition from brick-and-mortar to online retailing.

However, the growing number of online purchases brings on increased numbers of purchase returns in consequence. Statistics for the year 2024 show that in the European Union, the return rates per online buyer reached 54% of transactions [2]. Returns induce losses in additional logistics expenses, as the goods must be transported back to the retailer, increased labour costs due to inspection and restocking of the returned items, as well as reduce the margin percentage if the item can be resold at all [3]. At least 5% of returns is due to incorrect or damaged goods shipped [4]. E-commerce produces over 3 times the amount of CO_2 emissions compared to brick-and-mortar retailing [5]. The major contributors

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to the increased environmental footprint are the transport of goods to customers and the additional packaging necessary in online retail [6]. Purchase returns further increase the impact on the environment as the goods are transported back to the seller; if they cannot be resold, the items become pure waste [7].

Lowering the number of returns and optimising the process of return handling to limit the footprint is one of the key points in sustainability efforts made by European SMEs, according to the European E-Commerce Report 2023 [1]. Efforts towards meeting this goal can be twofold. On the one hand, a substantial part of return causes, like items not meeting expectations or customers ordering with the intention to return, can be addressed from the level of sales and marketing. Strategies to decrease the number of returns for these reasons include reintroduction of return fees for customers, providing detailed product descriptions based on photos and videos of the item, introduction of sales of repaired or refurbished goods. On the other hand, returns often stem from order fulfilment errors and warehouse issues. Order fulfilment errors refer to incorrect items, incorrect quantities of ordered items or damaged items being delivered to the customer, and constitute the vast majority of warehouse-related reasons of purchase returns [8]. There are several approaches to limiting such errors. Widely-used methods include implementation of automated storage and retrieval systems [9] or manual paperless picking systems (handheld barcode or RFID scanners, voice picking and pick-to-light systems) [10]. Automated storage and retrieval systems follow the parts-to-picker approach. Based on paper or digital picking lists, the picker requests items, which are then retrieved from corresponding locations and transported to them in containers using cranes, carousels, conveyors or lifts.

In manual paperless picking, the picker still needs to retrieve the items from the warehouse locations themself. Replacing paper lists, picking information can be conveyed by voice over headphones (voice picking) or using lights attached to shelves and containers highlighting pick locations (pick-to-light). Confirming the picking action can be realised by using systems like speech recognition and microphones, in which the picker verbally confirms picked items (voice picking), push buttons installed at each picking location, or handheld scanners (RFID or barcode), which communicate with the warehouse system and are often able to provide audio signal feedback [10].

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Lately, Augmented Reality (AR) applications have been increasingly implemented in warehouses for worker support [11]. AR refers to environments where the real world is augmented with virtual objects, such as digital data overlays, but where the physical world is still dominant [12]. Various AR systems targeting warehouse operations have been developed, supporting workers in tasks like order picking, stocking or shelving, ranging from displays mounted on picking carts [13], flexible displays mounted on robotic arms [14] to monocular [15] and classic Head-Mounted Displays (HMDs) [16]. Such AR systems show potential to become an alternative solution to limit order fulfilment errors.

In order to investigate the ecological validity of the use of AR in order fulfilment, we conducted a survey with employees of European SMEs to explore the willingness and attitude towards using AR technology (see Appendix A). We received a total of 53 responses from 17 European countries, with an average of 4.04 years of experience in SMEs related to order fulfilment. Among the respondents, 51% indicated that their orders are picked and packaged manually, leading to higher rates of fulfilment errors. Specifically, 37% reported encountering errors in task completion often or very often. The most common sources of fulfilment errors include missing items (60.4%), incorrect items picked (47.2%), incorrect quantities (34.0%), and damaged items (32.1%).

The survey results confirmed the willingness of using AR technology in order fulfilment. Among the respondents, 13.2% have used AR in their workplace. Regarding the potential adoption, 67.9% of respondents see themselves using it in the near future, and eventually, 51% expressed a willingness to use an AR system in their workplace now. When using AR in warehouse operations, 83% of respondents expect increased productivity, 69.8% expect decreased physical workload, and 64.2% foresee reduced mental workload. They also expressed concerns related to comfort and well-being, including issues such as headaches, eye strain, and motion sickness. These were mentioned by respondents with previous AR experience and expected by those without alike. Technical malfunctions of AR devices are potential problems that could arise from implementing AR systems to address current challenges in order fulfilment.

Willingness to adopt AR of SMEs does not guarantee actual user acceptance. Therefore, an empirical user acceptance study is essential to assess its real-world viability and confirm its

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potential. We selected a use case in which a collaborative robot brings partially packed orders to a human worker, who checks the contents of the box against the order picking list and picks the remaining items from indicated shelf locations; upon completion of the order, the robot takes the box away. We decided to include a collaborative robot in the use case scenario following the current advancement of warehouse robotics and automated picking systems [17], and the rising trend among companies in striving for high level of automation and autonomy in warehouse operations. Furthermore, the inclusion of collaborative robots aligns with the principles of Industry 5.0, empowering the human workers. For this task, we developed a complete AR-based order fulfilment application, which is used to lead the worker to subsequent items to be picked, indicate the specific item and correct quantity, and confirm picking action. Offering intuitive and permanent guidance for the employees, a tailored AR graphical user interface remaining in the worker's field of view shows potential to streamline order checking, increase efficiency and reduce error rates [15]. The selected hardware is Head-Mounted Displays, which offer the operator freedom of motion with persistence of content characteristic of wearable devices, in contrast to camera-and-projector set-ups, and enable graphically rich, immersive 3D interfaces, yet unavailable for smart glasses. To quantitatively measure the user acceptance, we compared the user acceptance of the AR-based system with the traditional paper-based method.

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3 DESIGN OF THE AUGMENTED REALITY ORDER FULFILMENT INTERFACE

3.1 THE ORDER FULFILMENT TASK

We selected an order fulfilment task in which a user needs to complete checking three orders (boxes). The setup includes two conveyors to carry boxes before and after checking, a workplace where the user checks the items inside each box, a compartment shelf that contains items to fill in, and an UR10e robot to bring and take away boxes, see Figure 1.

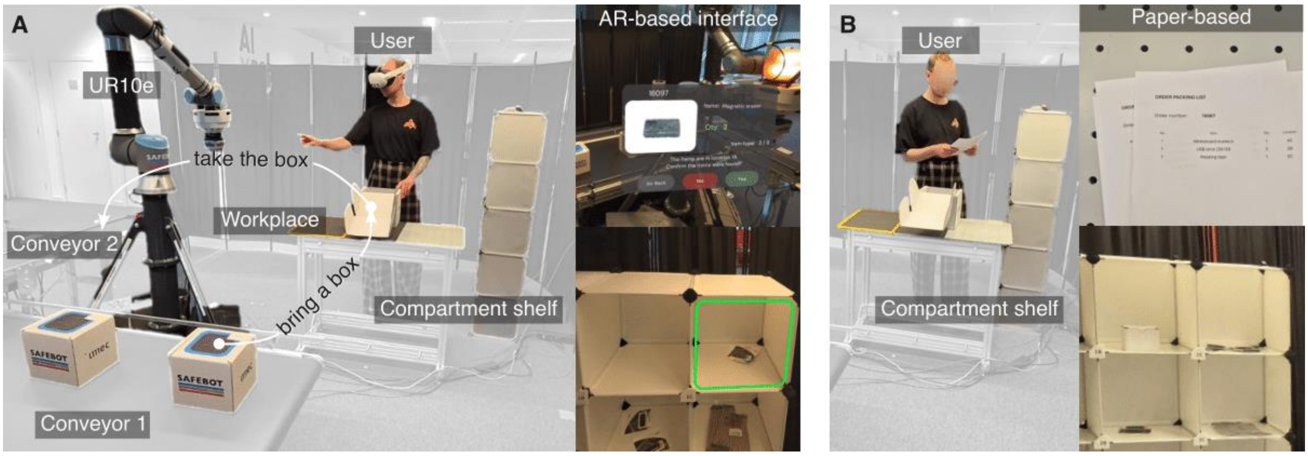

Figure 1. The experimental setup. A user checks items in each other with assistance from a UR10e robot. A compartment shelf is placed next to the workplace and contains items to fill in the boxes. (A) AR-based interface; (B) Paper-based.

The task flow is outlined in Figure 2 and demonstrated in detail in a YouTube video, available at https://youtu.be/5HAckcJIjfk. First, the participant had to request a partially fulfilled order from the robot by selecting "Start Picking" in the AR interface. Upon receiving the box from the robot from conveyor 1, the participant's task at the workplace was to verify the contents of the box against either the corresponding paper picking list, matched to the box by order ID, or by following the augmented picking list within the AR application. If an item specified on the list was not found inside the box, the participants had to locate it on the compartment shelf, pick the item in the specified quantity, and place it in the box. When an order was complete, the participants were asked to place the box within a yellow-coloured area such that it could be taken away by the robotic arm to conveyor 2 upon their confirmation. This flow must be repeated three times to complete the task.

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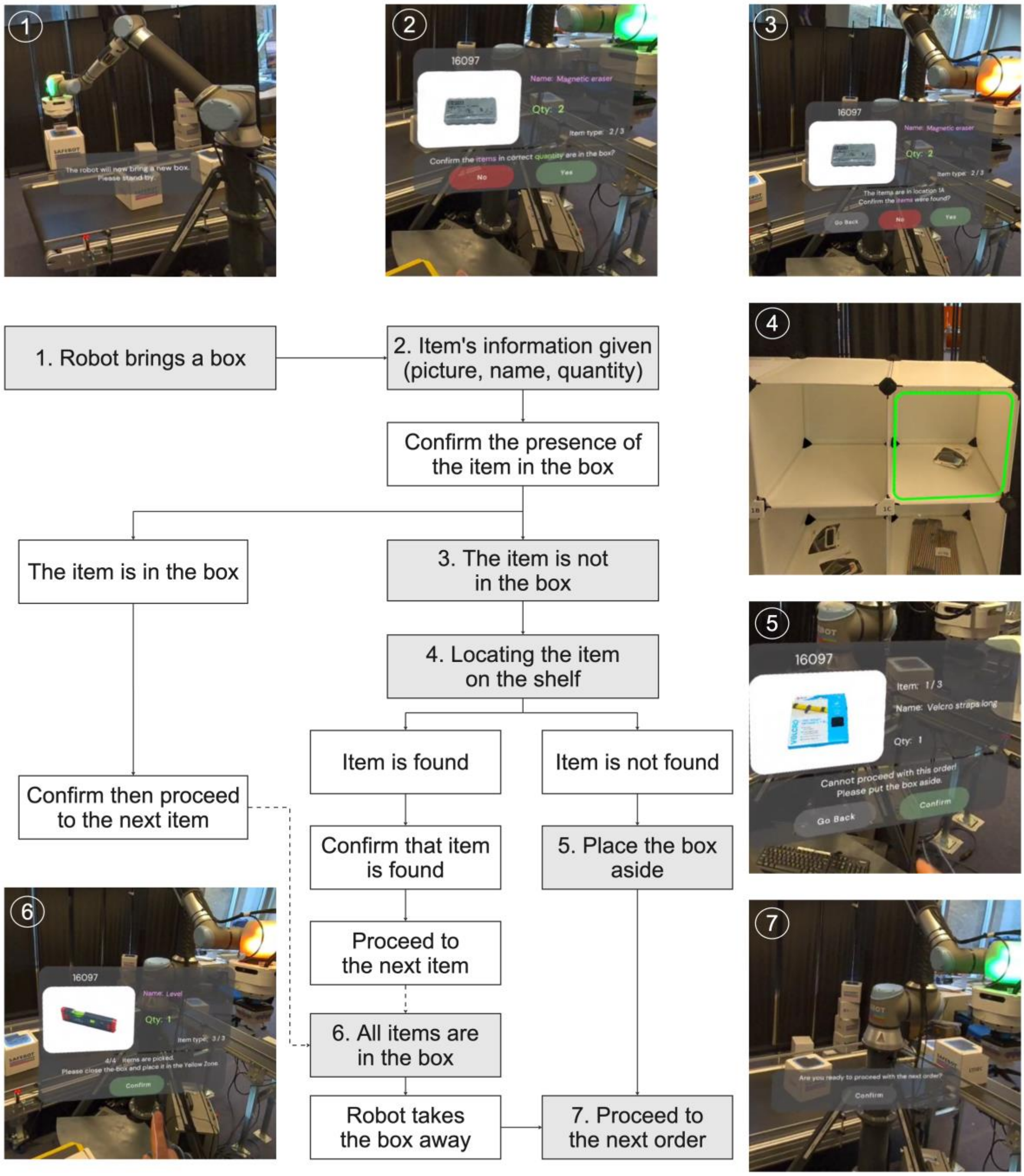

Figure 2. Task flow diagram. Relevant steps are illustrated with corresponding AR interface content.

3.2 INTERFACE CONTENT

The application was designed to help workers check and complete the orders, addressing the most common sources of order fulfilment errors, i.e. missing items, incorrect quantities or wrong items picked. For each order, an augmented list of required items was presented on an item-by-item basis. The interface displayed the order ID, the subsequent item's name

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and picture, its position in the order e.g., 1/3, 2/3 etc., and the quantity required. The item name and quantity were written in bold letters and different colours to attract the user's attention and prevent picking the wrong item or the wrong quantity. A confirmation whether the item in the correct quantity could be found in the box was necessary to proceed to the next item on the list.

If an item could not be found in the box, the application assisted the users in picking the missing items by providing augmented location indications. A panel containing the item's location was displayed and a green frame highlighted the item's location on the compartment shelf, to provide intuitive and effortless guidance towards the item. After the item was picked from the shelf, the user was prompted to double-check that the correct quantity was in the box. This double check was meant to ensure the worker was aware of the required quantity and reduce the risk of mistakes. If the order could not be completed for any reason, a panel asking to set the box aside and move on to the next order would appear.

To ensure safe and efficient human-robot collaboration, the interface provided information on the robot's movements - when bringing or taking away a box - through a dedicated panel describing the current action of the robot and asking users to stand by. In addition to serving as a robot-to-human communication layer, the purpose of these panels was to reduce potential anxiety linked to unexpected robot behaviour or prevent collisions and unnecessary stops due to the robot being disturbed by the human.

The colours used in the interface were selected in accordance with the Web Content Accessibility Guidelines (WCAG), to ensure clarity and accessibility of the interface for all users.

3.3 TECHNOLOGY STACK AND HARDWARE

We used Meta Quest 3 and Apple Vision Pro as the HMD in this study. The application was developed in the Unity 3D development software with custom C# scripts handling the application behaviour and the interface logic. The following packages provided by Unity were used for this application: the XR Interaction Toolkit package enabled the interactions with the interface, the XR Hands package allowed the interaction with the UI hands instead

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of using the controllers, to ensure a hands-free experience. The Meta XR All-in-One SDK and OpenXR SDK packages were used to ensure compatibility and streamline application deployment to the chosen HMDs.

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4 VALIDATION: USER ACCEPTANCE STUDY

4.1 EXPERIMENTAL DESIGN

We designed a within-participant experiment to investigate the effects of an AR order fulfilment interface on different aspects of technology acceptance. Each participant experienced an order completion and verification task with the robot in two conditions: *AR-based* and *paper-based*, in a counter-balanced order. The experiment was conducted at BruBotics, Vrije Universiteit Brussel, Belgium, and obtained ethical approval from the institutional ethics committee (ECHW_594).

4.1.1 Ethical Considerations

Data Protection:

- Data collected during the study are confidential and the participant's privacy is guaranteed during the publication of results in accordance with the General Data Protection Regulation (GDPR).
- The videos recorded during the experiment, documenting each participant's performance, will be used to extract task completion time and number of errors of each participant, and deleted immediately afterwards.
- The institution responsible for processing the participant's data is Vrije Universiteit Brussel (VUB) and no other institution will be involved in the process.
- The data is collected and processed for the needs of a scientific study. The legal basis for collection and processing of personal data lies in the participant's explicit permission to do so by signing the Informed Consent Form.

Harm and Discomfort:

- Researcher attempts to ensure participants feel relaxed and avoid confusion. The experimenter does not see the details of the interaction and cannot say whether participants make mistakes or not. Collected data is anonymized, and any mistakes cannot be tied to any specific person.

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- During the experiment the researcher asks participants to announce any discomfort or inconvenience. There is no possibility of long-term consequences.
- Any questions are encouraged during the session. While participants can contact us at any time after participation, no specific support or counselling should be necessary.

4.2 PARTICIPANTS

We recruited participants through our research group's networks and communities. The sample size was estimated by using G*Power [18]. With an effect size from medium to large (d: 0.5-0.8), an alpha level of 0.05, and a power of 0.8, the suggested sample size should be between 15-34. In total, we recruited 27 participants, including 20 men and 7 women, with a mean age of 25.3 years (SD=3.44). The majority of participants have a bachelor's or a master's degree. All participants were adults within the working age range (18 to 70 years old) and volunteers who fully understood the purpose of the study and confirmed that they did not suffer from any mental or physical disorders, neurological conditions, epilepsy, or colour blindness. They did not have experience working with AR systems.

4.3 PROCEDURE AND MEASUREMENTS

Before the start of the experiment, participants received information leaflets and informed consent forms. We informed them of the general purpose of the experiment, which was the comparison of different technologies in order fulfilment scenarios with collaborative robots. The participants had the opportunity to ask questions about the experiment and the informed consent form. Upon signing the informed consent form, we asked them to fill in basic demographic information.

In the experiment, a participant performed the order fulfilment task with the robot in two conditions: AR-based and paper-based, each lasting up to 10 mins. The participants were asked to complete three orders by verifying the contents of the box brought to them by the robot and picking the missing items from the compartment shelf. After each condition, we assessed their opinion on nine constructs of the Almere robot acceptance model: anxiety,

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intention to use, perceived enjoyment, perceived ease of use, perceived usefulness, facilitating conditions, attitude, social influence, and trust [19]. In addition, we also measured the completion time. Concluding the session, we provided a detailed explanation of the purpose of the experiment. After the experiment, the participants have the right to withdraw from the study by requesting erasure of their data. The collected data is pseudonymised and securely stored at the VUB Institutional Data Repository.

4.4 DATA ANALYSIS

Data analysis was conducted using Python using *scipy* and *pingouin* packages. Normality and homogeneity were assessed using the Shapiro-Wilk and Bartlett tests. The significance level was set at 0.05.

4.5 RESULTS

We conducted ten paired-sample tests on the collected data, see Figure 3. The results showed that the AR-based condition received significantly higher ratings on perceived enjoyment ($M_{Paper} = 3.25$, $SD = 1.09$; $M_{AR} = 4.19$, $SD = 0.76$; $W = 18.5$; $p < 0.001$; $rbc = 0.87$) and social influence[1] ($M_{Paper} = 3.57$, $SD = 0.87$; $M_{AR} = 3.91$, $SD = 0.69$; $W = 32.5$; $p < 0.05$; $rbc = 0.5$). In contrast, the paper-based conditions received significantly higher ratings in intention to use ($M_{Paper} = 3.64$, $SD = 1.09$; $M_{AR} = 3.07$, $SD = 1.17$; $t(26) = 2.41$; $p < 0.05$; $d = 0.49$) and completion time ($M_{Paper} = 6.31$, $SD = 0.64$; $M_{AR} = 7.81$, $SD = 0.94$; $t(26) = 9.98$; $p < 0.001$; $d = 1.84$).

[1] = The degree to which an individual perceives that important others believe he or she should use the new system

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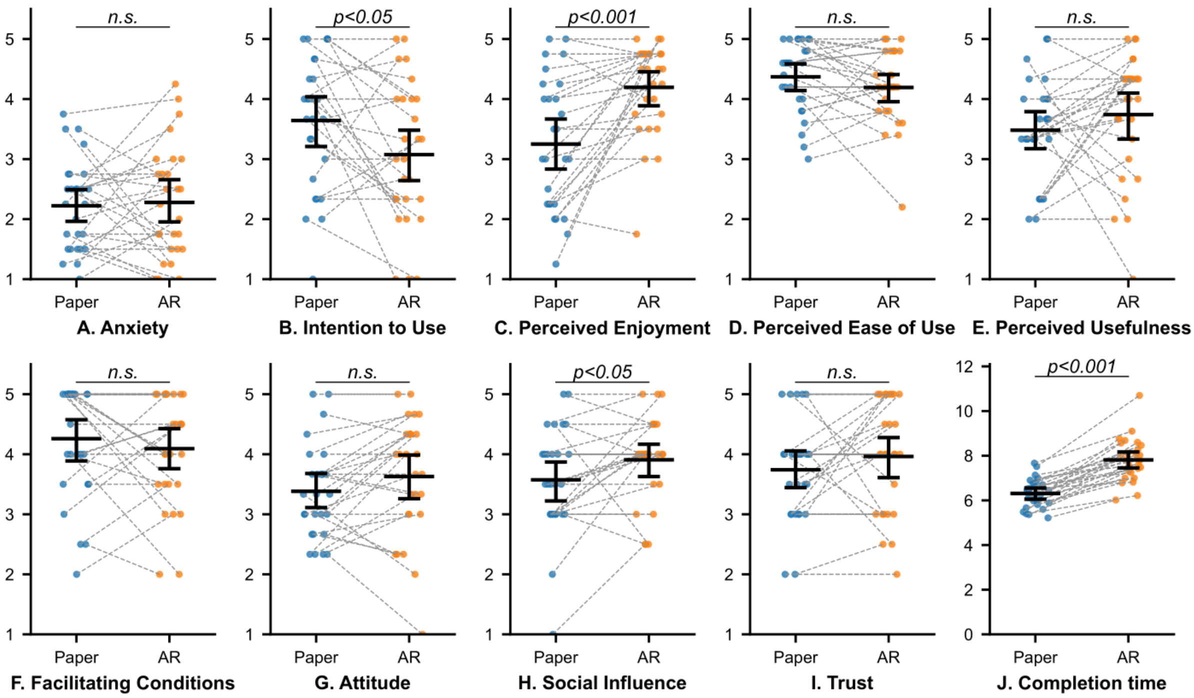

Figure 3. Experimental results. Participants demonstrated a higher level of perceived enjoyment and social influence in the AR-based condition but a lower level of intention to use and completion time.

No significant differences were found in other constructs: anxiety (M_{Paper} = 2.22, SD = 0.74; M_{AR} = 2.28, SD = 0.92; t(26) = 0.28; n.s), perceived ease of use (M_{Paper} = 4.37, SD = 0.59; M_{AR} = 4.19, SD = 0.62; W = 112; n.s), perceived usefulness (M_{Paper} = 3.48, SD = 0.83; M_{AR} = 3.74, SD = 1.02; W = 100; n.s), facilitating conditions (M_{Paper} = 4.26, SD = 0.92; M_{AR} = 4.09, SD = 0.9; W = 51.5; n.s), attitude (M_{Paper} = 3.38, SD = 0.76; M_{AR} = 3.63, SD = 0.98; t(26) = 1.71; n.s), and trust (M_{Paper} = 3.74, SD = 0.82; M_{AR} = 3.96, SD = 0.91; W = 42.5; n.s).

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5 DISCUSSION

In this study, we explored the potential of the implementation of AR systems in order fulfilment tasks by a survey of European SME employees and a technology acceptance study. Our findings revealed positive effects of AR on workers, but also the need for the technology to mature for broader adoption.

In the survey, respondents showed positive attitudes and strong interest in adopting AR technology in the workplace, expecting improvements in efficiency and accuracy. They viewed AR as a valuable tool for enhancing task performance and reducing errors and would like to adopt the technology in the near future and even now. However, many raised concerns about the current hardware's impact on health and well-being, citing issues like eye strain, discomfort, and fatigue from prolonged use. These concerns highlight the need for more ergonomic and user-friendly AR devices to support sustainable adoption in professional settings.

In the comparative study of technology acceptance, the AR system demonstrated a significant positive impact by increasing perceived enjoyment and social influence among users. Participants found the AR experience more engaging and entertaining than traditional systems, likely due to its immersive and interactive nature, which enhances user satisfaction and emotional involvement. Additionally, the use of AR also had a positive perceived impact on social influence, as users may have perceived the technology as innovative and socially valued, thereby encouraging adoption through peer approval or perceived prestige. Importantly, despite being a novel technology for most participants, the AR system did not result in heightened anxiety. This suggests that when thoughtfully designed, AR interfaces can feel intuitive and user-friendly, mitigating the stress often associated with unfamiliar digital tools. These findings indicate that AR has strong potential for promoting user acceptance by combining enjoyable experiences with social encouragement, without the drawback of increased technological anxiety.

However, the task completion time in the AR-based condition was slightly higher than in the paper-based one. This can be linked to participants having no experience in working with AR technology and highlights the necessity of a learning process. Completion time can be

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improved when the users grow accustomed to the AR interface content and layout, as well as controlling the AR interface. Becoming familiar with the application, the workers would no longer need the additional time to orient themselves and read through prompts and interface; their interactions with the user interface elements would grow more natural and require less focus and attention diverted from the task itself. Furthermore, improving the design of the interface itself would also contribute to reducing the task completion time. Foreseen changes towards this goal, based on participants' feedback, would include reducing the number of confirmations necessary to complete one order and allowing a better overview of the entire order instead of providing necessary information solely on an item-by-item basis.

Further developments in hardware (e.g. AR contact lenses or lighter AR glasses) could translate to increased intention to use. Both experiment participants and survey respondents mentioned comfort concerns when asked about the use of current AR hardware like classic HMDs—eye strain and adverse effects on eyesight, nausea, headaches or neck pain were frequently mentioned. These ergonomic and health-related issues not only reduce comfort but may also undermine user trust in the reliability and long-term safety of AR hardware in workplace settings. Lighter, more compact devices, like smart glasses, offering the capabilities of current HMDs are expected to significantly improve the intention to use aspect, which was reflected in the survey results.

The work carried in this task provides several broader insights into how Virtual Worlds may shape the future of industrial collaboration in Europe:

- **Enhancing worker engagement and acceptance.** Even at their current maturity level, immersive technologies can improve user engagement and enjoyment in human-robot collaboration. Virtual Worlds could therefore serve not only as technical tools but also as cultural and social enablers, ensuring automation is perceived as augmentation rather than substitution of human work.

- **Human skills and training**. Augmented Reality (AR) can play a crucial role in compensating for limited robot skills and accelerating their training in collaborative

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environments. By overlaying contextual guidance and adaptive instructions onto the physical workspace, humans are supported and cognitive workload reduced.

- **The need for user-centric hardware innovation.** Adoption is limited by concerns about comfort, ergonomics, and health impacts. Persistent discomfort and ergonomic limitations can decrease user trust, reinforcing the urgency of developing hardware that is both reliable and conducive to long-term use in industrial contexts. Investment in lighter, safer, and more accessible XR devices—tailored for industrial settings—will be crucial. Supporting European SMEs and manufacturers in this effort could strengthen Europe's competitiveness while ensuring technological sovereignty.

- **Building trust frameworks.** While SMEs show strong interest in AR adoption, they also highlight concerns about reliability and technical malfunctions. Such concerns highlight that adoption is not only a question of technical performance but also of building confidence through trust frameworks that ensure reliability, accountability, and clear safeguards for immersive human-robot collaboration. This underlines the need for robust trust frameworks that combine technical reliability with regulatory, ethical, and legal safeguards. The EU could play a leading role by establishing standards for safety, transparency, and accountability in immersive human-robot interaction.

- **Supporting industrial sustainability.** Many workers are receptive to immersive technologies when these visibly reduce workload, enhance job quality, and foster enjoyable experiences. Virtual Worlds could therefore become integral to Europe's industrial sustainability, helping to reduce waste, improve precision, and promote worker well-being. Beyond niche applications, the EU may consider positioning Virtual Worlds as strategic drivers of the green and digital transitions.

Taken together, these insights highlight both the near-term challenges of AR adoption and the long-term potential of Virtual Worlds as enablers of sustainable and human-centric industrial transformation.

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6 CONCLUSION

This study investigated the potential of AR to support warehouse workers in order fulfilment tasks and reduce errors in e-commerce operations, particularly within European SMEs. Survey results revealed strong interest in AR among SME employees, with expectations of increased productivity and reduced workload. We developed a complete AR-based order fulfilment system and conducted a user acceptance study to investigate the ecological validity of AR technology in the warehouse. Our user study confirmed higher perceived enjoyment and social influence for AR-based systems, though paper-based methods still outperformed in task completion time and intention to use. These findings indicate that while AR holds promise for improving fulfilment accuracy, significant barriers remain in hardware usability. Future efforts should focus on refining interface design and addressing ergonomic concerns to support wider adoption of AR in warehouse environments.

If advances continue to align with user needs, immersive tools could become valuable enablers of Europe's digital and green transition, improving not only industrial workflows but also job quality and sustainability.

The findings of the research carried out within this task will be reported in a scientific publication: *"Is Augmented Reality ready for the warehouse? A comparative study of user acceptance in order fulfillment"* authored by *Aleksander Burkiewicz, Hoang-Long Cao, Sandra Salloum, Milan Amighi, Nima Roshandel, Dylan Sisavath, Yuwen Shen, Hamed Firouzipouyaei, Constantin Scholz, Antonio Paolillo, Bram Vanderborght*.

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7 ETHICS COMPLIANCE SIGN-OFF

Deliverable D3.3 – Demonstration Case on Virtual Worlds-Enabled Robotics
Project: OPENVERSE – Grant Agreement No. 101135701
Deliverable Lead: Vrije Universiteit Brussel (VUB)
Work Package: WP3 – Governance and Ethics
Version Reviewed: 1.3 (final)
Date of Ethics Review: 25 October 2025
Reviewed by: OPENVERSE Ethics Advisor (UNEXT Ltd.)

7.1 1. ADHERENCE TO ETHICAL REQUIREMENTS OF THE EU

Deliverable D3.3 demonstrates strong alignment with EU fundamental ethical principles, as defined by:

- The EU Charter of Fundamental Rights (human dignity, privacy, non-discrimination).
- The General Data Protection Regulation (GDPR) (Articles 5–6 and 35 on lawfulness and impact assessment).
- The AI Act (2024/1689) provisions for limited-risk AI systems (Articles 11–14 on transparency, human oversight, and risk management).
- The deliverable includes explicit ethical considerations for human participants under section 4.1.1. It confirms:
    - Institutional ethics approval (VUB reference ECHW_594).
    - Use of informed consent forms detailing purpose, voluntary participation, and data handling.
    - No special category data collected (biometric, genetic, or health data excluded).
    - Data minimisation and pseudonymisation applied to video and survey data.
    - Deletion of raw videos post-analysis in line with GDPR storage-limitation principles.

From an AI Act perspective, the use of AR/VR and robotics interfaces was classified as limited risk, with full human-in-the-loop supervision and traceable testing environments.
Compliance Rating: ▨ High – Fully aligned with EU ethics and AI governance standards.

7.2 2. MITIGATION ACTIONS REQUIRED

Area	Identified Gap / Risk	Mitigation Action	Responsible Partner
Data Protection	Video recordings of participants before deletion could pose temporary risk of re-identification	Ensure explicit DPIA summary and documented deletion log	VUB / WP7 Data Manager
Participant Well-being	Possible eye strain or motion fatigue with AR hardware	Include ergonomic monitoring and post-session comfort report	VUB
Informed Consent Archiving	Ensure retention and audit of consent forms separate from data files	Maintain secure consent repository	VUB / UNEXT
AI Transparency	Graphical user interface and robotic logic not yet fully documented in ethics annex	Publish public AI transparency note in D3.5	WP3 lead (VUB)
Independent Oversight	Ongoing monitoring needed for data reuse and AI tool evolution	Biannually Ethics Committee review	Ethics Advisor

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7.3 3. OVERALL ETHICAL ACCEPTABILITY EVALUATION

Deliverable D3.3 is ethically acceptable under Horizon Europe standards. The work complies with the GDPR and AI Act frameworks and has undergone institutional ethics review. No ethical violations or non-conformities were identified. Minor mitigation measures relate to documentation of AI transparency and ergonomic monitoring.

Final Evaluation: ◍ High – Ethically compliant, low residual risk, continued oversight recommended.

7.4 PUBLIC BRIEF DATA PROTECTION IMPACT ASSESSMENT (DPIA)

Deliverable D3.3 – Demonstration Case on Virtual Worlds-Enabled Robotics

7.5 CONTEXT AND PURPOSE OF PROCESSING

Deliverable D3.3 presents a demonstration case integrating virtual worlds and robotic interaction for research and experimentation purposes within the OPENVERSE project. Processing of personal data occurs in limited circumstances, primarily involving research participants (voluntary test users, researchers, and operators) interacting with robotic systems in controlled environments. No automated decision-making or profiling is conducted. All data processing supports research transparency, reproducibility, and ethical validation of virtual-world-enabled robotics scenarios.

7.6 LAWFUL BASIS AND LEGAL COMPLIANCE

Processing activities are carried out under:

- Article 6(1)(a) GDPR – explicit consent of the participant for experimental participation and data use.
- Article 6(1)(e) GDPR – processing necessary for scientific research in the public interest under the Horizon Europe Grant Agreement.
- Article 89 GDPR – safeguards for scientific research (anonymisation, pseudonymisation, and restricted access).
- EU AI Act (2024/1689) – robotic and AI systems classified as limited-risk, requiring transparency, traceability, and human oversight.

All participants sign an informed consent form approved by the VUB Ethics Committee (Ref. ECHW_594).

7.7 CATEGORIES OF DATA AND PROCESSING

Data Category	Description	Purpose	Storage & Retention
Participant Identification	Name, professional affiliation, contact (optional)	Registration, consent traceability	Secure EU-based servers, deleted post-project
Video / Sensor Data	Short video/audio recordings of interactions	Behavioural analysis of human-robot interfaces	Pseudonymised; raw videos deleted after analysis
Questionnaire Data	Voluntary feedback on comfort, usability, and experience	Evaluation of system usability and ergonomics	Stored pseudonymised until project completion
System Logs	Non-personal operational and performance data	Reproducibility and AI safety validation	Retained for audit under FAIR principles

7.8 RISK IDENTIFICATION AND MITIGATION

Potential Risk	Impact	Likelihood	Mitigation Measure
Re-identification through recorded imagery	Moderate	Low	Pseudonymisation, secure deletion log
Incomplete consent awareness	Low	Low	Plain-language consent forms and withdrawal procedure
Data leakage or unauthorised access	High	Very Low	Encryption, access control, EU-based storage

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Misuse of AI model outputs	Low	Low	Full human-in-the-loop oversight and transparency annex
Ergonomic or psychological discomfort	Low	Low	Real-time monitoring, optional withdrawal at any stage

7.9 DATA SUBJECT RIGHTS

Participants are informed of and may exercise their rights to:

- Access, rectification, and erasure of personal data;
- Restriction of processing and withdrawal of consent;
- Lodge a complaint with their national Data Protection Authority (DPA).
- Contact for all privacy inquiries: privacy@openverse-project.eu

7.10 DATA TRANSFERS AND PROCESSORS

No personal data are transferred outside the European Economic Area. All processors operate under GDPR-compliant Data Processing Agreements (DPAs).

7.11 RESIDUAL RISK AND OVERALL EVALUATION

After implementing mitigation measures, the residual risk level is Low. The D3.3 demonstration is fully compliant with the GDPR and AI Act principles of transparency, human oversight, and data minimisation. The deliverable is deemed ethically acceptable for public dissemination, with ongoing monitoring by the OPENVERSE Ethics Committee and Ethics Advisor (UNEXT Ltd.).

Final Evaluation: ▨ Ethical Compliance – High | ▨ GDPR Risk Level – Low | ▨ AI Act Risk Classification – Limited-Risk System

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ADDITIONAL PUBLICATION

In addition to the work presented in this deliverable, the BruBotics research group has contributed to another peer-reviewed publication acknowledging funding from the OPENVERSE project (Grant Agreement No. 101135701):

Omidi, M., De Winter, J., De Pauw, K. *et al.* Investigating the effects of an augmented reality-based warning system on safety and trust in human-robot collaboration. *Int J Adv Manuf Technol* 138, 3593–3602 (2025). https://doi.org/10.1007/s00170-025-15784-5

This article examines how an Augmented Reality–based warning system can improve operator safety and foster trust in collaborative robot environments. Although not directly related to the demonstrator described in this deliverable, it contributes to the broader OPENVERSE objectives by advancing understanding of human-robot trust, situational awareness, and safe interaction within use cases enabled by AR technology and in industrial Virtual Worlds contexts.

Abstract:

Human-robot collaboration (HRC) in manufacturing environments relies on mutual understanding and trust between humans and robots. This study investigates the impact of an augmented reality-based warning system on operator safety perception, task performance, and trust in collaborative robots. Experimental results demonstrate that AR-delivered safety cues enhance user awareness of robot intentions and improve trust calibration without compromising efficiency. The findings highlight the potential of AR interfaces to support safe and transparent HRC, providing guidance for the design of trustworthy Virtual Worlds–enabled robotic systems.

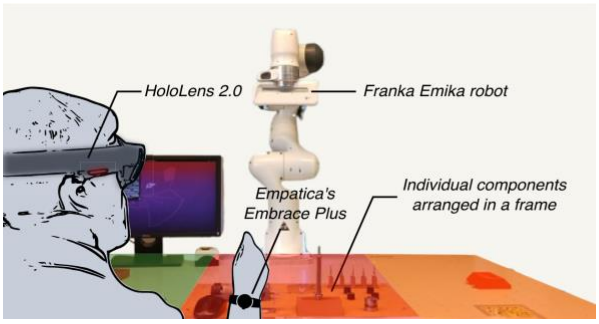

Figure 4. The experimental setup from the study consists of a Franka Emika robot and components for the assembly operation. A person wears a HoloLens with AR visualization of workspace zones based on safety conditions.

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APPENDIX A – EXPERT AND STAKEHOLDER SURVEY

VRIJE UNIVERSITEIT BRUSSEL

PERSONAL DATA - INFORMED CONSENT FORM

You are asked to participate in scientific research.

Please take your time to decide whether you want to participate.

You can stop your participation at any time, without giving a reason.

You will find more information about the research below. Do not hesitate to ask questions to the researcher if something is not clear.

1. **Description of the research**
    - **Title**: Survey on order fulfilment practices and attitude towards Augmented Reality systems in European SMEs
    - **Researchers**: Aleksander Burkiewicz (aleksander.burkiewicz@vub.be),
      Constantin Scholz (constantin.scholz@imec.be),
      Hoang-Long Cao (hoang.long.cao@vub.be)
    - **Supervisor**: Bram Vanderborght (bram.vanderborght@vub.be)
    - **Research group or department**: R&MM
    - **Purpose of the research**: exploring the existing (or non-existence of) solutions for XR-enhanced robotics in logistics and warehouse applications in European SMEs
    - **Practical conduct**: online survey, time required to complete ca. 5 minutes, research period 11.2024 – 11.2025

2. **Responsible data controller**

VUB (Vrije Universiteit Brussel), Pleinlaan 2, 1050 Brussels, Belgium, company number 449.012.406.

3. **Description of risks and benefits**

Your participation will not involve any risks.

Your participation will not involve any benefits.

4. **Confidentiality**

We will keep the collected data confidential and respect the privacy legislation, including the European General Data Protection Regulation (GDPR).

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5. Data – Purpose – Retention Time – Transfer

For this research, we will collect the following personal data:
age, gender, country, IP address, position, years of experience in the field, information observed or requested, such as "your opinion on Augmented Reality systems", "your experiences with order fulfilment processes", "your experience with Augmented Reality systems".

We will only process your data for the purpose of scientific research.

We will store your data for ten years after the end of the research.

Your data may be re-used for the purposes of scientific research in the general interest, under the condition that protection measures are taken.

Otherwise, your data will not be transferred to any third parties, unless with your explicit consent or due to a legal obligation.

6. Citations

Without your express consent, you will not be cited in any publications.

7. Security

The storage of your data will offer a high degree of protection, in accordance with the guidelines of VUB (VUB Charter of the Researcher, ICT Security policy). Your data will not be stored on a personal computer, an external hard disk or a USB stick, unless encrypted.

We will pseudonymize your data as soon as possible. This means that we will replace data that can directly identify you, such as your name and e-mail address, by codes. A "translation key" will be necessary to convert the codes back to the original data. Only the researchers and the supervisor have access to this key.

We will anonymize your data as soon as possible. This means that it will no longer be possible to identify you by means of the data.

8. Your rights

You have the right to access, correct and erase your data, request information on the way we handle your data, request a copy of your data, limit the way we handle your data and ask us to transfer your data to third parties.

You are entitled to withdraw the consent to process your data at any time, without having to justify your request.

Please note that the exercise of your rights may be limited whenever the data are anonymous.

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9. **Contact**

If you have questions or if you wish to exercise your rights, you can contact Aleksander Burkiewicz (aleksander.burkiewicz@vub.be) or the data protection officer of VUB (dpo@vub.be).

10. **Complaints**

If you wish to complain about the way we handle your data, you can contact the researchers, the supervisor or the DPO (cf. above).

Or you can file a complaint with the data protection authority:

Drukpersstraat 35, 1000 Brussel

Tel. +32 2 274 48 00

email: contact@apd-gba.be

website: www.dataprotectionauthority.be

You also have the right to file a suit at the competent court.

Consent of the participant

I agree to participate in the research.

I confirm that I fulfil the conditions to participate, being that I work at/ speak on behalf of a European SME.

I understand that my participation in this research is voluntary and that I can stop my participation at any time, without having to give a reason.

I agree with the collection of the following data for the research:

age, gender, IP address, position, years of experience in the field, information observed or requested, such as "your opinion on Augmented Reality systems", "your experiences with order fulfilment processes", "your experience with Augmented Reality systems".

Please note that your acceptance to the collection of all the above-mentioned data is essential. If you do not agree, you will not be able to participate in the research.

I consent to the disclosure of the research results in a publication, conference or otherwise, without revealing my name or any other data that could identify me.

Please note that your consent to disclosing research results in a publication, conference or otherwise is essential. If you do not agree, you will not be able to participate in the research.

→

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Survey on order fulfilment practices and attitude towards Augmented Reality systems in European SMEs

This survey will ask about your warehouse practices and challenges in order fulfilment.

You'll then watch a brief video on an Augmented Reality (AR) system used in robotics, and we'll ask for your opinion on its potential use in your workplace.

The survey will take **less than 5 minutes**.

Your responses are anonymous and used only for research purposes.

Your feedback is key to help us to identify areas for improvement and further development insights.

Thank you for your time.

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What is your gender?

- Male
- Female
- Non-binary
- Other
- Prefer not to say

How old are you?

What is your role?

- Warehouse - Logistics worker
- Business owner - Manager - Planner
- Other (please describe)

How many years have you been working in your current field?

What is the country of your employment?

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How do you or your employees currently pack and check orders?

- Manually (ex: Pick-by-Paper)
- Semi-Automated (ex: Pick-by-Light)
- Automated (ex: robotic arms with minimal or no human intervention)

How often do you or your employees face errors in accomplishing your tasks? (incorrect items picked, wrong quantity, damaged items...)

- Very often
- Often
- Sometimes
- Rarely
- Never

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What is the source of errors?
Multiple selection is allowed.

- Incorrect item picked
- Incorrect quantity
- Damaged item picked
- Missing items
- Additional item
- Other (please specify below)

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Please watch this video until the end.

It offers a brief overview of Augmented Reality (AR) applications in warehouse operations and robotics.

The systems presented will help familiarize you with the key concepts and potential uses of AR in these contexts.

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Do you have experience with Augmented Reality (AR) technology?

- No
- Yes, in workplace
- Yes, in leisure (such as in gaming applications)
- Yes, others (please specify below)

Do you think that implementing an AR system will reduce **physical** workload compared to traditional warehouse processes? (such as reducing walking and movement, avoiding unnecessary movements...)

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

Do you think using AR systems will increase productivity (faster task completion, fewer errors, ...)?

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

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Do you think that implementing an AR system will reduce **mental** workload compared to traditional warehouse processes? (such as reducing the need for consistent attention to detail, providing clear instructions for workers...)

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

Would you see yourself using an AR system in the workplace now?

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

Would you see yourself using an AR system in the workplace in the near future?

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree

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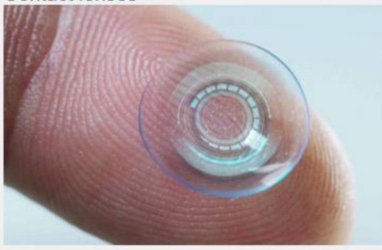
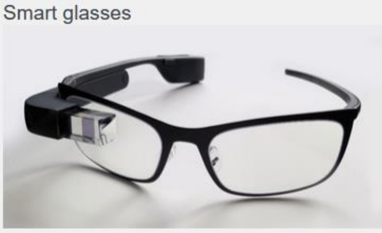
What kind of AR system would you like to use?

Contact lenses

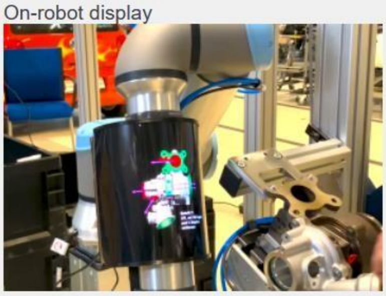


Smart glasses



Classic Head-Mounted Displays

On-robot display



Camera and Projector set-ups

None

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If an AR system is implemented to solve the existing issues in packaging, what other **problems** do you think could arise? (optional question)

If an AR system is implemented to solve the existing issues in packaging, what other **advantages** do you think it could bring? (optional question)

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