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ORIGINAL RESEARCH PAPER

Is augmented reality ready for the warehouse? a comparative study of user acceptance in human–robot collaborative order fulfillment

Aleksander Burkiewicz[1,2] · Hoang-Long Cao[1,3] · Sandra Salloum[1] · Milan Amighi[1,2] · Nima Roshandel[1,2,4] · Dylan Sisavath[1,2] · Yuwen Shen[5] · Hamed Firouzipouyaei[1,2] · Constantin Scholz[1,2] · Antonio Paolillo[5] · Bram Vanderborght[1,2]

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Abstract

E-commerce has grown rapidly, but high return rates pose economic and environmental challenges, with fulfillment errors as a key factor. While augmented reality (AR) has the potential to reduce such errors, the adoption of this technology in SMEs remains limited. With inputs from our recently conducted survey of SME employees across 17 European countries, we developed an AR-based order fulfillment system to investigate the ecological validity of this technology in the warehouse. For validation, we conducted an empirical user acceptance study comparing AR-based and paper-based approaches in a human–robot collaborative order fulfillment system. Results indicate a strong interest in AR, with significant increases in perceived enjoyment and social influence. Positively, AR does not lead to a higher level of anxiety. However, the paper-based method demonstrated higher scores for task completion time and intention to use. Findings highlight the potential of AR in the warehouse, but also the need for improved interfaces and hardware to enable broader adoption.

Keywords E-commerce · Order fulfillment · Augmented reality · Human–robot collaboration · User acceptance · Almere

1 Introduction

Electronic commerce (e-commerce) refers to the sale and purchase of goods or services through the Internet and other online communication networks. From 2018 to 2023, the turnover of e-commerce in the European Union increased by 65%. In 2023, 68% of the EU-27 population bought physical goods online [1]. With the ever-spreading digitalization 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 has led to an increase in purchase returns. Statistics for the year 2024 show that in the European Union, the return rates per online buyer reached 54% of transactions [2]. Returns generate additional losses through logistics expenses, as the goods must be transported back to the retailer, increased labor costs for inspection and restocking, and reduced profit margins if the item can be resold at all [3]. At least 5% of returns are due to incorrect or damaged goods shipped [4]. E-commerce produces over three times the amount of CO_2 emissions compared to brick-and-mortar retailing [5]. The major contributors 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, and if they cannot be resold, the items become pure waste [7].

Lowering the number of returns and optimizing the process of return handling to limit the footprint are one of the key points in sustainability efforts made by European SMEs, according to the European E-Commerce Report 2023 [1]. Effort toward meeting this goal can be twofold. On the one hand, a substantial part of the causes of returns, such as items not meeting expectations or customers ordering with the intention to return, can be addressed from the level of

✉ Hoang-Long Cao
hoang.long.cao@vub.be; chlong@ctu.edu.vn

1 Brubotics, Vrije Universiteit Brussel, Brussels, Belgium

2 Imec-IMS, Vrije Universiteit Brussel, Brussels, Belgium

3 College of Engineering, Can Tho University, Can Tho, Vietnam

4 KU Leuven, Leuven, Belgium

5 Software Language Labs, Vrije Universiteit Brussel, Brussels, Belgium

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 photographs and videos of the item, introduction of sales of repaired or refurbished goods. On the other hand, returns often result from order fulfillment errors and warehouse issues. Order fulfillment 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 for 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 (e.g., 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). Confirmation of the picking action can be achieved through systems such as speech recognition with microphones, where the picker verbally verifies items (voice picking), push buttons installed at each picking location, or handheld scanners (RFID or barcode) that communicate with the warehouse system and often provide audio feedback [10].

Recently, augmented reality (AR) applications have been increasingly implemented in warehouses to support workers [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 have already displayed potential to become an alternative solution to limit order fulfillment errors [17].

To investigate the ecological validity of AR in order fulfillment, we previously conducted a survey as part of the EU-funded Horizon Europe project OPENVERSE. While the use of AR technologies in large companies continues to rise, SMEs show a lower rate of such technology adoption [18]. The survey targeted employees of SMEs across Europe to assess their willingness and attitudes toward adopting AR technology in the workplace. 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 fulfillment. Among the respondents, 51% indicated that their orders are picked and packaged manually, leading to higher rates of fulfillment errors. Specifically, 37% reported encountering errors in task completion often or very often. The most common sources of fulfillment 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 to use AR technology in order fulfillment. 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. Technical malfunctions of AR devices are potential problems that could arise from implementing AR systems to address current challenges in order fulfillment.

Willingness to adopt AR of SMEs does not guarantee actual user acceptance, which remains a crucial factor for AR adoption in companies [18, 19]. Therefore, in this work, we conducted an empirical user acceptance study to assess its real-world viability and confirm its potential. With the advancement of robotics in warehouses, 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, and 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 [20], and the rising trend among companies in striving for high level of automation and autonomy in warehouse operations. Furthermore, the integration of collaborative robots is consistent with the core principles of Industry 5.0, which emphasize placing human well-being and safety at the center of the production process, thereby empowering workers through supportive automation [21–25]. For this task, we developed a complete AR-based order fulfillment 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, 26, 27]. The selected hardware is Head-Mounted Displays, which offer the operator freedom of motion with persistence of content characteristic of wearable devices, in contrast with cameraand-projector set-ups, and enable graphically rich, immersive 3D interfaces, yet unavailable for smart glasses.

The experimental validation was based on the Almere model, an established theory of technology acceptance in human–robot interaction [28]. The Almere model extends the Technology Acceptance Model (TAM) [29] and incorporates constructs from the Unified Theory of Acceptance and Use of Technology (UTAUT) [30]. Using the constructs of the Almere model, we aimed at measuring both instrumental beliefs (e.g., usefulness, ease of use) and social–emotional dimensions (e.g., enjoyment, trust) that shape behavioral intention and actual use of a system. We then compared the user acceptance of the AR-based system with the traditional paper-based method—the most conventional, practical, and prevalent method in today's warehouse operations, particularly within SMEs.

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.
- We designed and validated an AR interface for robot-assisted order fulfillment 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 of an AR system, comparing AR with paper-based methods, to investigate the ecological validity of introducing AR technologies in warehouse settings.

2 Design of the augmented reality order fulfillment interface

2.1 The order fulfillment task

We selected an order fulfillment task that involves verifying the contents of three separate boxes, each corresponding to a distinct customer order. The task requires the user to inspect each box, identify any missing items, and retrieve those items from a designated shelf to complete the order. This industrial use case reflects an actual order fulfillment process carried out by entry-level workers. It does not require prior experience in logistics or specialized training.

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 Fig. 1. The task flow is outlined in Fig. 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-colored area such that it could be taken away by the robotic arm to conveyor 2 upon their confirmation. This flow has to be repeated three times to complete the task.

2.2 Interface content

The application was designed to help workers check and complete the orders, addressing the most common sources of order fulfillment 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 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 colors 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 toward 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 behavior or prevent collisions and unnecessary stops due to the robot being disturbed by the human. The colors and contrast used in the interface were selected in accordance with the Web Content Accessibility Guidelines (WCAG 2) to ensure clarity and accessibility of the interface for all users [31].

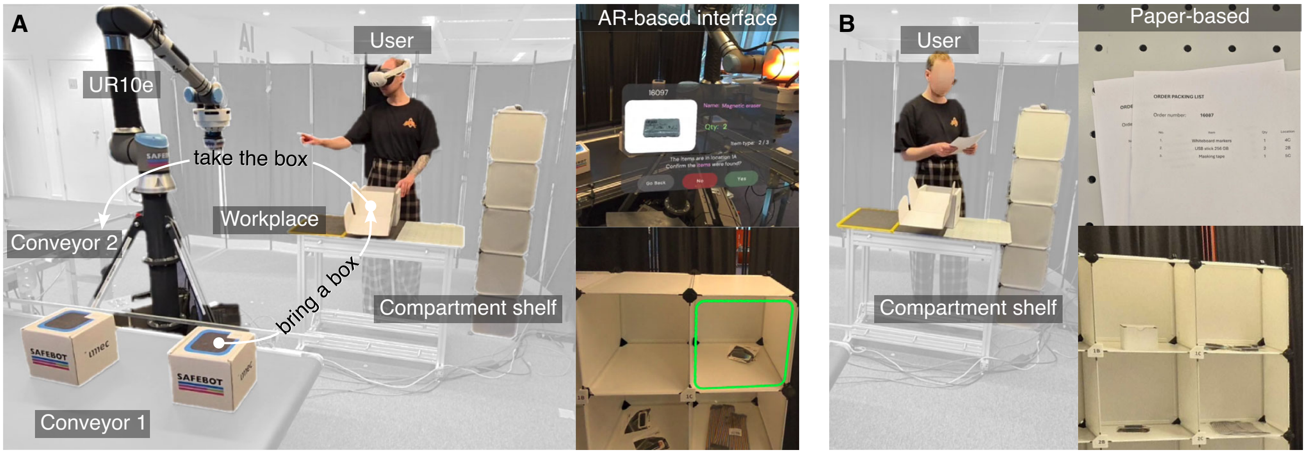

Fig. 1 Experimental setup. A user checks items in each other with assistance from a UR10e robot. A compartment shelf is placed next to the workplace and contains items to fill in the boxes. **A** AR-based interface; **B** paper based

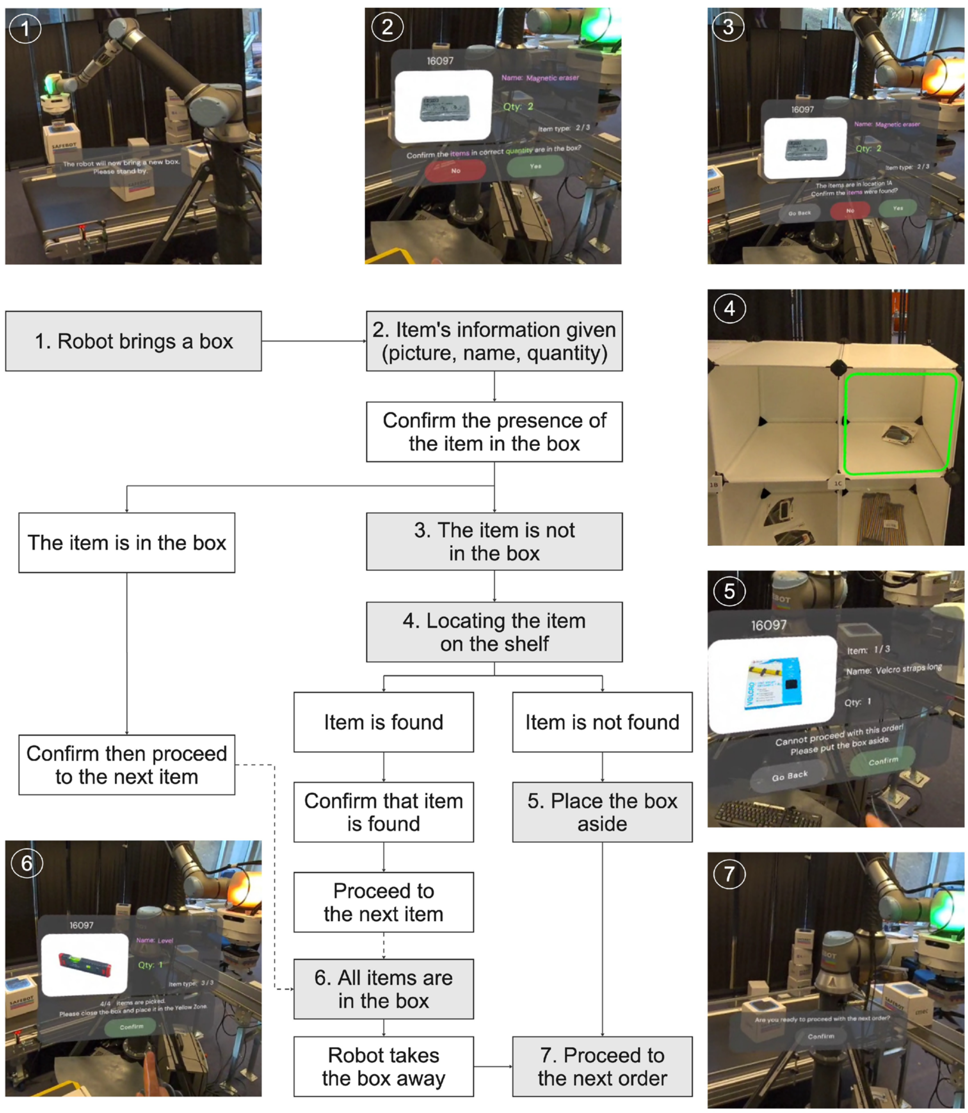

Fig. 2 Task flow diagram. Relevant steps are illustrated with corresponding AR interface content

2.3 Technology stack and hardware

We used Meta Quest 3 as the HMD in this study. The application was developed in the Unity 3D development software with custom C# scripts handling the application behavior 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 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 HMD.

3 Validation: user acceptance study

3.1 Experimental design

We designed a within-participant experiment to investigate the effects of an AR order fulfillment 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 paper-based condition was selected as the baseline because it reflects the most conventional, practical, and widely used method in current warehouse operations, especially among SMEs. The experiment obtained ethical approval from the institutional ethics committee (ECHW_594).

3.2 Participants

We recruited participants through our professional networks and affiliated communities. Eligibility criteria required individuals to be of working age and representative of entry-level workers, ensuring alignment with the target user profile for the industrial task. The sample size was estimated by using G*Power [32]. 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 and 34. In total, we recruited 27 participants, including 20 men and 7 women, with a mean age of 25.3 years (SD=3.44). All participants were volunteers who provided informed consent, fully understood the purpose of the study, and confirmed that they did not suffer from any mental or physical disorders, neurological conditions, epilepsy, or color blindness. They did not have experience working with AR systems.

3.3 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 to compare different technologies in order fulfillment 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 fulfillment 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 using a 5-point Likert scale: anxiety, intention to use, perceived enjoyment, perceived ease of use, perceived usefulness, facilitating conditions, attitude, social influence, and trust [28]. 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 are pseudonymized and securely stored at the VUB Institutional Data Repository.

3.4 Data analysis

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

3.5 Results

We conducted ten paired-sample tests on the collected data, see Fig. 3. Depending on the results of the Shapiro–Wilk test for normality and Bartlett's test for homogeneity of variances, either a paired t-test or the non-parametric Wilcoxon signed-rank test was applied to each construct. 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 (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; $p < 0.05$; Cohen's d = 0.49) and completion time (M_{Paper} = 6.31, SD = 0.64; M_{AR} = 7.81, SD = 0.94; t(26) = 9.98; $p < 0.001$; Cohen's d = 1.84).

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 =

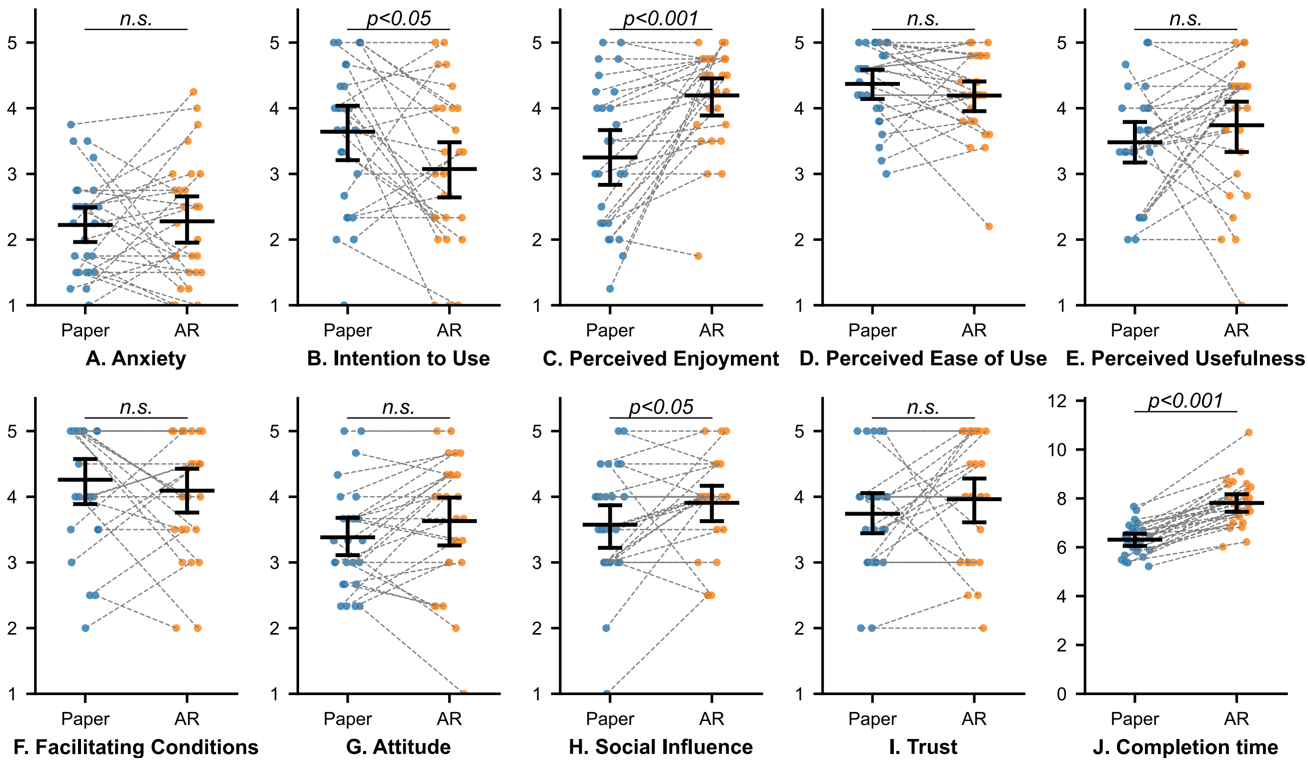

Fig. 3 Experimental results. Participants demonstrated a higher level of perceived enjoyment and social influence in the AR-based condition but a lower level of intention to use and completion time

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).

4 Discussion

In this study, we explored the potential of the implementation of AR systems in order fulfillment 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 a 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 they 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 with large effect sizes. 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. Beyond immersion, AR can also be perceived as a novelty and innovation, which can stimulate curiosity and motivate users to explore the system more actively. The visual richness and real-time feedback offered by AR may have contributed to stronger perceptions of competence and control, reinforcing enjoyment. Additionally, the use of AR also had a positive impact on social influence. Participants may have felt that adopting AR aligns them with modern practices and peer expectations, thereby increasing its perceived value. 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 method was still higher than in the paper-based method with a large effect size. This can be linked to participants having no experience in working with AR technology and highlights the necessity of a learning process. Previous studies have indicated that the level of tech savviness in employees is an important factor in user performance and resulting job satisfaction when using AR devices. Additional training to improve tech savviness in employees and technology familiarization are crucial for successful adoption [17, 18]. Completion time can be improved when users grow accustomed to the AR interface content and layout, as well as controlling the AR interface. As users become familiar with the application, they would no longer need additional time to orient themselves and read through prompts and the interface. Their interactions with the user interface elements would become 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 toward this goal 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.

Intention to use, however, still remained higher for the paper-based method, with a medium effect size. Further developments in hardware (e.g., AR contact lenses or lighter AR glasses) could translate to an increased intention to use of AR. Both experiment participants and survey respondents mentioned comfort concerns when asked about the use of current AR hardware, such as classic HMDs. Eye strain and adverse effects on eyesight, nausea, headaches, or neck pain were frequently mentioned. Lighter and more compact devices, such as smart glasses, that offer the capabilities of current HMDs are expected to significantly enhance users' intention to adopt AR, as reflected in the survey results. Another possible explanation is participants' initial unfamiliarity with AR hardware and interfaces, which may have influenced both comfort and usability perceptions. With repeated exposure, users are likely to adapt more readily, leading to improved task efficiency and stronger acceptance over time.

In this study, we focused on comparing AR with a paper-based method, which is a suitable baseline in SMEs, to investigate whether AR offers genuine benefits compared to the traditional approach before expanding to broader comparisons. In future phases, we plan to systematically compare AR with established digital solutions, including handheld scanners and voice-picking systems, to more comprehensively evaluate its advantages and limitations. We anticipate that AR will still demonstrate stronger effects on perceived enjoyment, social influence, and user engagement compared to these digital tools, given its immersive, interactive, and novel nature. In the short term, we also expect that handheld scanners and voice-picking systems still outperform AR in terms of task completion time, particularly due to their lightweight hardware.

5 Conclusion

This study investigated the potential of AR to support warehouse workers in order fulfillment 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 fulfillment 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 the paper-based method still outperformed in task completion time and intention to use. These findings indicate that while AR holds promise for improving fulfillment 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. In addition, future research should adopt longitudinal designs to capture how performance and intention to use evolve over time, offering a clearer picture of AR's long-term potential in warehouse operations. Finally, as this study was conducted within European SMEs, larger and more diverse samples across different regions and organizational contexts are needed to strengthen generalizability.

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Author Contributions All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by A.B., S. S., H.F., and H.L.C. The first draft of the manuscript was written by A.B., S. S., 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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Data Availability Data are available from the corresponding author upon reasonable request.

Declarations

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

Ethical approval The authors declare that this research was conducted in full accordance with the Declaration of Helsinki and has obtained ethical approval from the Vrije Universiteit Brussel (ECHW_594). Informed consent was obtained from all individual participants involved in the study.

Declaration of Generative AI We used Microsoft Copilot during the preparation of this manuscript to assist with language refinement. All content was reviewed and verified by the authors to ensure accuracy and integrity.

References

1. Lone S, Weltevreden J (2023) European e-commerce report 2023. Amsterdam University of Applied Sciences & E-commerce Europe, Amsterdam/Brussels, p 105
2. Statista: How Common Are Online Returns? (2025). https://www.statista.com/chart/27584/how-common-are-online-returns-gcs/ Accessed 2025-05-09
3. Retail A, Federation NR (2021) Consumer returns in the retail industry 2021. Source: Appriss Retail and National Retail Federation 2021 Returns Survey
4. Eurostat Source: https://doi.org/10.2908/ISOC_EC_IPRB21, 2024-10-02 (2024)
5. Escursell S, Llorach-Massana P, Roncero MB (2021) Sustainability in e-commerce packaging: a review. J Clean Prod 280:124314. https://doi.org/10.1016/j.jclepro.2020.124314
6. Mangiaracina R, Marchet G, Perotti S, Tumino A (2015) A review of the environmental implications of b2c e-commerce: a logistics perspective. Int J Phys Distrib Logist Manag 45(6):565–591. https://doi.org/10.1108/IJPDLM-06-2014-0133
7. Frei R, Jack L, Brown S (2020) Product returns: a growing problem for business, society and environment. Int J Oper Prod Manag 40(10):1613–1621
8. Helm M, Malikova A, Kembro J (2024) Rooting out the root causes of order fulfilment errors: a multiple case study. Int J Prod Res 62(11):3853–3871. https://doi.org/10.1080/00207543.2023.2251060
9. Roodbergen KJ, Vis IFA (2009) A survey of literature on automated storage and retrieval systems. Eur J Oper Res 194(2):343–362. https://doi.org/10.1016/j.ejor.2008.01.038
10. Battini D, Calzavara M, Persona A, Sgarbossa F (2015) A comparative analysis of different paperless picking systems. Ind Manag Data Syst 115(3):483–503
11. Grosse EH (2024) Application of supportive and substitutive technologies in manual warehouse order picking: a content analysis. Int J Prod Res 62(3):685–704. https://doi.org/10.1080/00207543.2023.2169383
12. Adriana Cárdenas-Robledo L, Hernández-Uribe Reta C, Antonio Cantoral-Ceballos J (2022) Extended reality applications in industry 4.0—a systematic literature review. Telemat Inform 73:101863. https://doi.org/10.1016/j.tele.2022.101863
13. Guo A, Raghu S, Xie X, Ismail S, Luo X, Simoneau J, Gilliland S, Baumann H, Southern C, Starner T (2014) A comparison of order picking assisted by head-up display (hud), cart-mounted display (cmd), light, and paper pick list. In: Proceedings of the 2014 ACM international symposium on wearable computers. ISWC '14, 71–78. Association for Computing Machinery, New York, NY, USA . https://doi.org/10.1145/2634317.2634321
14. Scholz C, Cao H-L, El Makrini I, Niehaus S, Kaufmann M, Cheyns D, Roshandel N, Burkiewicz A, Shhaitly M, Imrith E, Genoe J, Rottenberg X, Gerets P, Vanderborght B (2025) Improving robot-to-human communication using flexible display technology as a robotic-skin-interface: a co-design study. Int J Intell Robot Appl 9(1):146–163. https://doi.org/10.1007/s41315-024-00343-0
15. Weaver KA, Baumann H, Starner T, Iben H, Lawo M (2010) An empirical task analysis of warehouse order picking using head-mounted displays. In: Proceedings of the SIGCHI conference on human factors in computing systems, pp 1695–1704
16. Wang W, Wang F, Song W, Su S (2020) Application of augmented reality (AR) technologies in inhouse logistics. E3S Web Conf 145:02018. https://doi.org/10.1051/e3sconf/202014502018
17. Windhausen A, Heller J, Hilken T, Mahr D, Di Palma R, Quintens L (2024) Exploring the impact of augmented reality smart glasses on worker well-being in warehouse order picking. Comput Hum Behav 155:108153. https://doi.org/10.1016/j.chb.2024.108153
18. Jalo H, Pirkkalainen H, Torro O, Pessot E, Zangiacomi A, Tepljakov A (2022) Extended reality technologies in small and medium-sized European industrial companies: level of awareness, diffusion and enablers of adoption. Virtual Reality 26(4):1745–1761
19. Windhausen A, Heller J, Hilken T, Mahr D, Di Palma R, Quintens L (2024) Exploring the impact of augmented reality smart glasses on worker well-being in warehouse order picking. Comput Hum Behav 155:108153
20. Yang X, Hua G, Hu L, Cheng T, Huang A (2021) Joint optimization of order sequencing and rack scheduling in the robotic mobile fulfilment system. Comput Oper Res 135:105467
21. Chu TS, Culaba AB, Jose JAC (2022) Robotics in the fifth industrial revolution. In: 2022 IEEE 14th international conference on humanoid, nanotechnology, information technology, communication and control, environment, and management (HNICEM). IEEE, pp 1–6
22. Huang S, Wang B, Li X, Zheng P, Mourtzis D, Wang L (2022) Industry 5.0 and society 5.0-comparison, complementation and co-evolution. J Manuf Syst 64:424–428
23. Scholz C, Cao H-L, Imrith E, Roshandel N, Firouzipouyaei H, Burkiewicz A, Amighi M, Menet S, Sisavath DW, Paolillo A (2024) Sensor-enabled safety systems for human-robot collaboration: a review. IEEE Sens J 25(1):65–88
24. Sajja GS, Addula SR (2024) Automation using robots, machine learning, and artificial intelligence to enhance production and quality. In: 2024 second international conference computational and characterization techniques in engineering & sciences (IC3TES). IEEE, pp 1–4
25. Vanderborght B (2020) Unlocking the potential of industrial human-robot collaboration: a vision on industrial collaborative robots for economy and society. Publications Office of the European Union
26. Fang W, An Z (2020) A scalable wearable AR system for manual order picking based on warehouse floor-related navigation. Int J Adv Manuf Technol 109(7):2023–2037
27. Reif R, Günthner WA (2009) Pick-by-vision: augmented reality supported order picking. Vis Comput 25(5):461–467
28. Heerink M, Kröse B, Evers V, Wielinga B (2010) Assessing acceptance of assistive social agent technology by older adults: the Almere model. Int J Soc Robot 2(4):361–375
29. Davis FD (1989) Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Q, pp 319–340
30. Venkatesh V, Morris MG, Davis GB, Davis FD (2003) User acceptance of information technology: Toward a unified view. MIS quarterly, pp 425–478
31. World Wide Web Consortium: Web Content Accessibility Guidelines 2.0 (WCAG 2.0). http://www.w3.org/TR/WCAG20 (2008)
32. Faul F, Erdfelder E, Buchner A, Lang A-G (2009) Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. Behav Res Methods 41(4):1149–1160