

Article

Ergonomic Evaluation of Mixed Reality Interaction Modalities for Wire Harnessing Task Guidance

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Abstract

Nowadays, modern manufacturing industries still rely on the expertise and manual dexterity of highly skilled operators. In this context, Mixed Reality (MR) technologies are emerging as promising solutions for contextualized task guidance to support operators during complex activities. However, their effective adoption in production environments is still limited by the lack of ergonomic evidence regarding their impact on operators' well-being, usability, and interaction sustainability. This study investigates whether different interaction modalities with holographic instructional content influence the ergonomic suitability of a MR-based task guidance system for wire harnessing, developed in collaboration with Leonardo S.p.A. A between-subjects experimental design was adopted, involving 16 industrial workers randomly assigned to two groups: gaze and gesture interaction (Group A, $n = 8$), and gaze and voice interaction (Group B, $n = 8$). Ergonomic evaluation included both physical and cognitive aspects, assessed respectively through the Simulator Sickness Questionnaire (SSQ) and a composite usability index (UI) based on ISO 9241-11, integrating efficiency, effectiveness, and satisfaction. Results suggest comparable usability levels between the two interaction modalities ($UI_A = 0.683$; $UI_B = 0.667$). Gesture interaction was perceived as slightly more supportive of operational efficiency, whereas voice interaction was associated with lower cybersickness severity (mean $TS_A = 331.5$; $TS_B = 196.1$). Overall, the findings suggest that no single interaction modality universally outperforms the other, but rather that ergonomic suitability depends on the balance between physical workload, cognitive demands, and task characteristics. These results highlight the importance of human-centered ergonomic evaluations in the design of sustainable MR assistance systems for industrial environments.

Keywords: wire harness; task guidance; interaction modality; mixed reality



Academic Editor: Douglas O'Shaughnessy

Received: 29 May 2026

Revised: 29 June 2026

Accepted: 7 July 2026

Published: 15 July 2026

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1. Introduction

Modern manufacturing environments are increasingly characterized by the digitization of production procedures, operational knowledge, and industrial workflows, enabling higher process traceability, improved standardization, and more efficient knowledge transfer across production systems [1–3]. Within these digitally supported environments, the role of human operators is progressively evolving from simple task execution toward more knowledge-intensive and decision-oriented activities [4,5]. In this landscape, the industrial perspective is shifting from minimizing human error toward understanding and supporting the *human factor* as a fundamental contributor to process quality, operational flexibility,

and manufacturing resilience [6,7]. This vision aligns with Industry 5.0 principles, which promote human-centered production paradigms where digital technologies are designed not only to improve productivity, but also to support operator well-being, sustainable human-machine collaboration, and effective interaction within complex industrial environments [7–9]. Such a scenario is particularly representative of manufacturing processes in the aeronautical and aerospace sectors, where product quality and process reliability strongly depend on human expertise, manual dexterity, and procedural knowledge [10]. Due to the intrinsic complexity, customization, and safety-critical nature of aerospace systems, several activities are still predominantly performed manually and require continuous interaction between operators and technical documentation [5,11]. In this context, immersive technologies such as Mixed Reality are emerging as promising solutions for supporting operators by means of contextualized and interactive task guidance systems [6,12,13]. However, the effectiveness and the successful full-scale adoption of these technologies depend both on their technical capabilities and human sustainability [14,15]. The ergonomics of workers, as the end users of such innovative solutions, therefore becomes a critical aspect in the design and evaluation of industrial assistance systems, as it directly influences both human performance and production outcomes [9]. An industrial task guidance system not designed to be ergonomically satisfying for its end users can generate increased physical strain and cognitive overload, potentially affecting concentration, procedural adherence, and decision-making capabilities. These effects may ultimately reflect on critical manufacturing KPIs such as productivity, execution accuracy, defect generation, rework rates, and final product quality [16,17]. Consequently, assessing the ergonomic impact of advanced assistance technologies represents a fundamental step toward the development of sustainable and human-centered industrial systems [7].

These considerations motivate the present study, conducted in partnership with Leonardo S.p.A. We present a ‘*technological demonstrator*’ of a wearable Mixed Reality support system for aerospace wire harnessing. In particular, the study investigates the ergonomic implications of two different interaction modalities, namely voice commands and gesture-based interaction, through a comparative usability and cybersickness assessment conducted in an industrial MR environment.

1.1. Case Study

The industrial case study selected in collaboration with Leonardo S.p.A. concerns the manufacturing of an electrical wire harness installed within the empennage section of the ATR 72 regional transport aircraft, produced at the Leonardo Aerostructures facility in Pomigliano d’Arco, Italy. This process is still characterized by a high level of manual work and strong dependence on operator experience. For each ATR 72 aircraft, approximately 80 wire harnesses are manufactured, with an estimated overall production time exceeding 300 working hours per aircraft.

The production workflow can be divided into two main macro-phases: (1) harness manufacturing and certification within the dedicated wiring room, followed by (2) wire installation on the aircraft assembly line. The manufacturing phase (1) can be further subdivided into three main activities: (1.1) kit preparation (approximately 30% of the total production time), (1.2) harness routing and assembly operations (approximately 60%), and (1.3) quality control and electrical testing procedures (approximately 10%). Once completed and tested, the harnesses are packaged, identified through dedicated codes, and transferred to the final assembly area, where they are installed in a substantially plug-and-play manner. Among the manufacturing activities, the routing and assembly stage (1.2) was selected for the development of the proposed Mixed Reality demonstrator, since it represents the most operator-dependent and cognitively demanding part of the

workflow. In this phase, operators manually position and route cables on full-scale assembly boards using traditional 2D paper drawings, perform stripping and splicing operations, assemble connectors through manual crimping procedures, and install protective and identification elements. Despite the use of dedicated machinery for cable cutting and wire marking operations, most assembly activities remain manual and are performed under a self-inspection regime, in which operators autonomously verify and certify each completed operation. Consequently, the process strongly depends on operator expertise and tacit knowledge, while the fragmentation of information across multiple paper documents and the limited readability of large 2D layouts may increase assembly complexity and the risk of human error [18].

Overall, these characteristics make aircraft wire harness manufacturing a highly suitable domain for the adoption of Mixed Reality-based operator assistance systems. Furthermore, the process represents an ideal use case for developing technological demonstrators that support the Industry 5.0 transition in manufacturing companies by enhancing process standardization, operator guidance, and overall manufacturing quality.

1.2. Paper Structure

The remainder of the paper is structured as follows: Section 2 describes the relevant literature about MR environments and the state of the art of immersive digitized task guidance systems for wire harnessing, highlighting current research gap. Section 3 discusses the objectives of the study, the design of the research and formulated hypotheses. It also describes the MR technological demonstrator, further to the materials and methods adopted for the experiments execution. Sections 4 and 5 address the ergonomic suitability of implemented MR interaction modalities and connect them to formulated hypotheses, while Section 6 draws conclusions from this work.

2. Related Works

Immersive technologies have been extensively investigated over the past decades as enabling solutions for supporting humans in complex procedural task execution, ranging from everyday activities (e.g., following a recipe to cook sophisticated meals, navigating and exploring unknown indoor/outdoor environments, etc. [19–21]) to highly technical scenarios such as industrial manufacturing processes [22–24]. These types of activities are typically characterized by sequential, multi-step procedures that require users to remember and manage a large amount of information simultaneously, monitor multiple task constraints, and maintain sustained attention over time [25]. Regardless of the application domain, such conditions can lead to increased cognitive load, reduced concentration, attentional shifts, and a higher likelihood of human error, especially when tasks are performed under time pressure or involve complex spatial information [26]. In these scenarios, MR task-guidance systems have emerged as promising technologies to mitigate these limitations by providing contextualized and real-time digital assistance directly within the user's field of view, potentially reducing cognitive load and error rates, improving completion time, and increasing users' situational awareness and focus [21,27,28].

2.1. MR Task Guidance for Wire Harnessing

Wire harness manufacturing represents one of the most complex and labour-intensive assembly processes in the aerospace and aeronautical industries due to its spatial complexity, high variability, and strong dependence on highly skilled operators performing error-sensitive manual tasks. In such contexts, even small mistakes in routing or installation can significantly impact product quality, leading to rework, scrap, and production delays [29,30]. To address these challenges, MR technologies have been investigated in the

literature as enabling technologies for supporting such complex manual assembly activities. Several studies have demonstrated that AR-based instruction systems can improve spatial understanding, reduce interpretation effort compared to traditional 2D drawings, and enhance task performance in industrial assembly contexts [31,32]. Neckenich et al. [29] investigated digital support based on the 3D master method for wiring harness development, emphasizing the role of digital models in improving design-manufacturing consistency. Rice et al. proposed multiple AR-based approaches for wire routing navigation and interactive assembly guidance [30,32], demonstrating the potential of spatial overlays to reduce interpretation effort compared to traditional 2D drawings. Furthermore, comparative studies on task guidance interfaces have shown that MR systems can improve task accuracy and user confidence in wire assembly operations [31]. More recently, Szajna et al. [33] evaluated MR glasses in manual wiring production, reporting positive impacts on operator support, while also identifying limitations related to visual fatigue, and system robustness. Finally, Papetti et al. [34] investigated the application of MR to wire harness assembly tasks, reporting improvements in usability, task efficiency, and error reduction when compared to conventional instruction methods.

The academic interest in MR task guidance systems is further reinforced by first examples of industrial adoption in aerospace manufacturing. Leading companies such as Airbus and Boeing have integrated MR technologies into production and maintenance workflows. At Airbus, MR systems are used to support electrical and hydraulic installation tasks, as well as training and validation activities using digital mock-ups and holographic instructions [35–37]. Similarly, Boeing has deployed MR-based systems to assist technicians in wiring and assembly operations by overlaying 3D schematics directly in the operator's field of view, reducing reliance on 2D documentation and improving assembly performance [38–40].

2.2. Research Gap and Study Contribution

Although existing studies and recent industrial developments demonstrate the effectiveness of MR task guidance systems in controlled or pilot environments, relatively few works have systematically investigated their ergonomic implications for end-users, i.e., operators. In most cases, the primary focus of the literature has been on demonstrating improvements in task efficiency, such as reduced completion time and error rates, rather than on evaluating the cognitive and physical workload introduced by MR systems [18,29–31]. Conversely, the introduction of MR task guidance systems as alternatives to traditional solutions does not only influence task efficiency, but may also significantly affect operator workload. Even minor increases in cognitive load or usability issues may result in reduced performance and increased error rates [34]. While studies as Papetti et al. have begun to address usability-related aspects (as perceived workload, task efficiency, and user acceptance), their evaluations are typically based on comparisons between traditional paper-based instructions and innovative MR-supported conditions. As a result, existing contributions primarily demonstrate the performance benefits of MR systems, while providing limited insight into how such systems should be designed to ensure ergonomic suitability and long-term human sustainability. In addition, current MR environments are inherently multi-modal, offering multiple ways of interacting with digital content (e.g., gesture-based interaction, gaze interaction, voice commands, or controller-based input) to accommodate diverse user characteristics [41,42]. Prior research in HCI and immersive systems suggests that interaction modality significantly affects usability, workload, and cybersickness symptoms in AR/MR environments [43]. However, despite this awareness, comparative investigations of alternative interaction modalities within the same MR task guidance system remain limited, particularly in industrial contexts. Thus, identifying

which interaction paradigms—or combinations thereof—are most ergonomically suitable for real-world manufacturing application remains an open challenge [41]. This represents a critical requirement for enabling the continuous and sustainable use of MR systems in production environments, where operators are expected to rely on such technologies throughout their work shifts.

To address this gap, the present work advances the state of the art along three complementary dimensions:

- Interaction modality comparison within a controlled MR environment. Unlike prior studies that primarily compare MR systems with conventional instruction methods, this work investigates the impact of different interaction modalities (gaze and gesture vs. gaze and voice) within the same MR task guidance system, enabling an isolated evaluation of interaction design choices.
- Integrated human-centered ergonomic evaluation. The study proposes a combined assessment framework that jointly considers physical and cognitive ergonomics through the analysis of cybersickness (SSQ) and usability (ISO 9241-11 [44]: efficiency, effectiveness, satisfaction), thus providing a more comprehensive evaluation of interaction sustainability.
- Validation in a representative industrial workflow. The proposed approach is applied to a realistic aerospace wire harness manufacturing process developed in collaboration with Leonardo S.p.A., ensuring ecological validity and relevance for real-world industrial deployment.

Therefore, the present work does not only evaluate a technological demonstrator, but contributes to the understanding of how interaction modality influences the ergonomic suitability of MR-based task guidance systems in industrial environments.

3. Materials and Methods

3.1. Study Design

The study was designed to investigate whether different interaction paradigms significantly affect operators' ergonomic perception during MR-supported task guidance for wire harnessing.

To better clarify the scope and contribution of the study, the research objective and its related contributions are explicitly defined as follows:

- Research objective. The objective of this study is to quantitatively assess how different interaction modalities (gaze + gesture vs. gaze + voice) influence both physical and cognitive ergonomics in MR-supported industrial task guidance, with specific reference to wire harness assembly operations.
- Scientific contribution. The study provides empirical evidence on the role of interaction modality in shaping ergonomic outcomes in MR environments, contributing to the understanding of how different input paradigms affect usability and cybersickness in industrial task guidance scenarios.
- Methodological contribution. The work proposes an integrated human-centered evaluation framework that combines (i) cybersickness assessment through SSQ, and (ii) a composite usability index based on ISO 9241-11 [44] (efficiency, effectiveness, satisfaction), thus enabling a joint analysis of physical and cognitive ergonomics within a unified evaluation pipeline.
- Industrial contribution. The study provides practical insights for the design and deployment of MR-based assistance systems in aerospace manufacturing, identifying trade-offs between interaction efficiency and operator well-being within a realistic

wire harness assembly workflow developed in collaboration with Leonardo S.p.A. (Rome, Italy).

To address the research objective, two alternative versions of the same MR application were developed, providing identical instructional contents and holographic assets, while differing exclusively in the interaction modality adopted to navigate and control the MR interface (Figure 1):

- Condition A: Gaze + gesture interaction: users interacted with the system through gaze-based targeting combined with hand gestures for command selection and interface navigation.
- Condition B: Gaze + voice interaction: users interacted through gaze-based targeting combined with voice commands for interface control and navigation.

The choice of interaction modalities was grounded in prior research on XR interaction paradigms. Gesture-based interaction is widely adopted in MR due to its natural mapping and direct manipulation characteristics; however, it may introduce physical fatigue during prolonged use and requires reliable tracking conditions [45]. Conversely, voice interaction reduces manual effort and is particularly suitable for hands-busy environments such as assembly tasks, but it is sensitive to environmental noise and may increase cognitive load in complex procedural contexts [46]. Based on these considerations, the following hypotheses were formulated:

H1. *Gesture-based interaction may enhance operational efficiency in spatial interaction tasks, leading to reduced task completion time compared to voice-based interaction.*

This is expected due to stronger visuomotor coupling, lower cognitive translation overhead, and more direct perceptual mapping between user intent and system response in immersive environments [41].

H2. *Voice-based interaction may result less comfortable in complex procedural tasks.*

This may depend on the additional mental effort required to formulate verbal commands, manage system feedback, and maintain task focus in sequential workflows [46].

Overall, the existing literature and the hypotheses formulated in this study suggest that there is no universally optimal interaction modality for XR task guidance systems. Instead, the effectiveness of a given modality is likely to depend on the specific human factors being considered (e.g., physical workload, cognitive load, or usability) as well as the characteristics of the task context. Thus, to investigate the formulated hypotheses, a between-subjects experimental design was adopted. Participants were randomly assigned to one of the two experimental conditions and experienced a single interaction modality throughout the experiment. This design choice was made to reduce learning effects and comparative biases that could arise from repeated exposure to multiple interaction paradigms within the same MR environment [47]. However, it should be noted that the adopted design, combined with the limited sample size, prioritizes ecological validity over statistical power, and therefore supports primarily exploratory insights rather than definitive conclusions regarding interaction modality effects.

From a statistical perspective, the adopted sample size ($n = 16$, with 8 participants per group) reflects the constraints associated with conducting experimental studies with skilled industrial operators in realistic production-oriented scenarios. Such constraints limited the possibility of recruiting a larger sample while preserving ecological validity. Consequently, the study is interpreted as exploratory in nature, primarily aimed at identifying trends and generating insights rather than establishing definitive causal relationships between

interaction modalities and ergonomic outcomes. In particular, the limited sample size reduces the sensitivity of the analysis to detect small differences between conditions.

Future studies involving larger samples and longer exposure durations are required to validate and generalize the findings presented in this work.

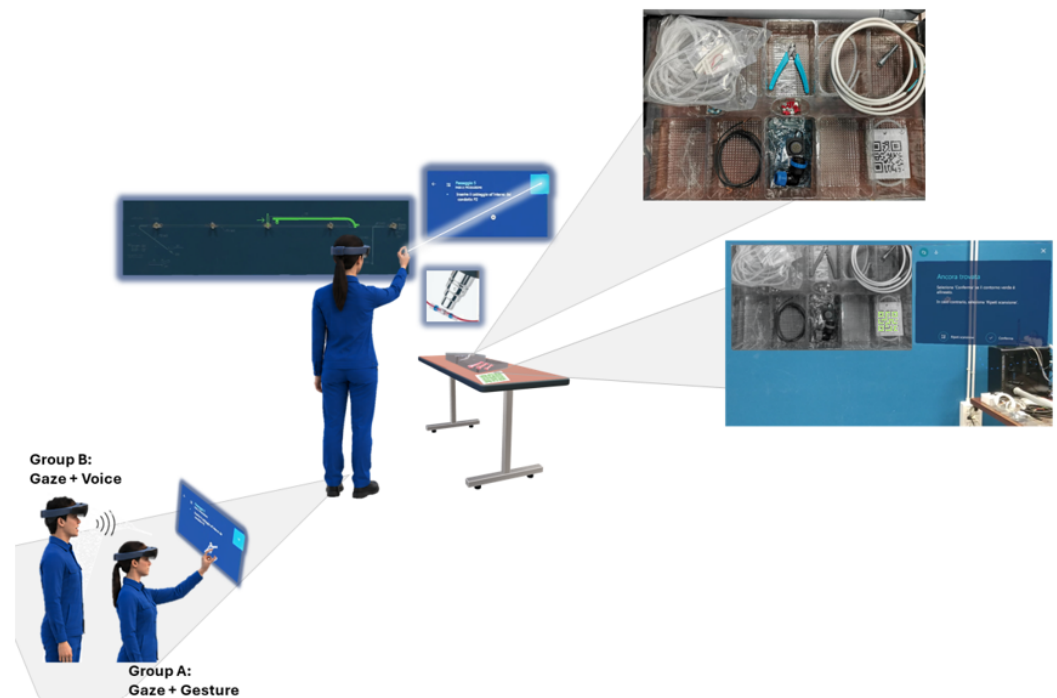


Figure 1. Overview of the MR technological demonstrator. Left: hologram of wire board is showed to the operator, that navigates the digital manual of instruction. The operator can interact by means of A-gaze and gesture or B-gaze and voice. Right: focus on the real equipment available on work table (e.g., wires, connectors and tools); focus on the dedicated QR code attached on the worktable for the anchoring of the virtual–physical worlds.

3.2. MR Technological Demonstrator

The task guidance procedure was developed according to the operational logic of the industrial workflow provided by Leonardo S.p.A. (Section 1.1). However, due to experimental constraints, the implemented procedure represents a simplified and time-compressed version of the actual wire harness manufacturing process, designed to preserve its structural and cognitive characteristics while enabling experimental evaluation within a controlled laboratory setting.

Specifically, the wire harness routing and assembly operations cycle was reproduced through three representative sub-phases:

- Phase 1-Kit preparation (8 actions). Through holographic instructions and interactive checklists, operators were guided in verifying the availability of tools (e.g., crimping tools, wire strippers, etc.) and assembly components (e.g., connectors, corrugated tubes, conduits, ferrules, and cables). Preliminary activities, such as cable preparation (cutting, marking, and organization) were partially simulated, focusing on procedural understanding rather than full execution.
- Phase 2-Wire harness production (6 actions). The second phase reproduce the core logic of the assembly process, including cable routing and stripping, corrugated tube installation, connector assembly, crimping procedures, and final harness completion activities. These operations were simplified and scaled down compared to the industrial process, maintaining the sequence and interaction structure while reducing execution time and physical complexity.

- Phase 3-Testing and final validation (3 actions). The final phase focused on quality control and testing procedures, which were simulated through guided validation procedures (e.g., checklist-based confirmation and reporting), without replicating the full industrial testing equipment and duration.

Overall, the implemented task consisted of 17 sequential actions and required approximately 5–7 min to complete. Although significantly shorter than the real industrial workflow—which may involve several hours of manual operations—the task was designed to retain the key cognitive and interaction demands of wire harness assembly, including sequential instruction following, spatial interpretation, and coordination between physical and digital elements.

Therefore, the experimental procedure should be interpreted as a representative task scenario aimed at evaluating interaction modalities under controlled conditions, rather than a full-scale replication of industrial production. Consequently, the results cannot be directly extrapolated to sustained industrial use over extended working shifts, and should instead be considered indicative of interaction-related ergonomic trends.

The core functionality of the application consisted of the delivery of sequential assembly instructions through holographic contents spatially integrated within the workstation. This was made by means of workspace anchoring through QR-code recognition on the worktable (Figure 1).

During task execution, the MR task guidance system provided both textual and audio instructions (in Italian, see Section 3.5), visual cues, arrows, images, videos, and 3D holographic models to support the execution of routing and assembly operations. Users navigated the instructional sequence through the interaction modality assigned to their experimental condition (Section 3.1), namely gaze and gesture interaction or gaze and voice interaction (Figure 1). Operators autonomously advanced through the procedural steps while simultaneously performing the corresponding manual assembly activities associated with the wire harness manufacturing phase described in Section 1.1.

For confidentiality reasons, the complete industrial workflow and detailed technical documentation cannot be publicly disclosed. Nevertheless, the developed MR demonstrator faithfully reproduced the procedural structure, interaction logic, and representative operational activities of the real industrial process considered in collaboration with Leonardo S.p.A.

3.3. Experts' Validation

Before conducting the experimental campaign with end users, a preliminary expert-based validation of the proposed MR demonstrator was carried out in collaboration with Leonardo S.p.A. The purpose of this phase was to assess the technical correctness, procedural coherence, and industrial suitability of the developed application before its adoption within the subsequent user study.

The validation involved 3 domain experts from Leonardo S.p.A. and 2 researchers from the academic team to coordinate the session. The industrial experts included:

- A strategic decision-maker involved in the evaluation of digital innovation technologies for manufacturing processes;
- The manager responsible for operator training activities related to wire harness manufacturing procedures;
- An expert operator with more than 10 years of experience in the execution of the specific wire harnessing workflow considered in the case study (Section 1.1).

The 3 industrial experts also presented heterogeneous levels of familiarity with MR technologies. The strategic decision-maker could be considered a novice MR user, the

training manager had limited prior exposure to MR systems, while the expert operator had previous experience with MR-related technologies through mobile-based applications.

The validation session started with a 10 min briefing provided by the 2 researchers, which aimed to summarize:

- The motivations behind the development of the technological demonstrator;
- The objectives and design of the subsequent experimental campaign;
- The industrial workflow represented within the application, including the exact sequence of assembly instructions provided to operators;
- The adopted software and hardware architecture and the implemented A/B interaction modalities;
- Finally, the purpose of their direct contribution, namely the validation of the technical and procedural reliability of the proposed MR application and identification of potential issues before final users were involved in the experimentation.

After having tested both the experimental conditions presented in Section 3.1, the experts were asked to express their opinion on 5 topics:

- Correctness of the represented workflow;
- Coherence and completeness of the instructional sequence;
- Adequacy and clarity of the MR contents;
- Comprehensibility of the interaction mechanisms;
- Suitability of the proposed solution for realistic industrial scenarios.

Such dimensions were selected from HCI and XR/MR system validation-related studies [48,49]. To this end, experts completed a short evaluation form composed of Likert-scale items associated with each validation dimension. A 5-point Likert scale was adopted, where a score of 1 corresponded to “strongly unsatisfactory”, 3 represented the minimum acceptable evaluation threshold, and 5 indicated a fully satisfactory assessment. In addition, qualitative feedback and open comments were collected at the end of the session in order to identify possible technical inconsistencies, procedural ambiguities, or interaction-related issues requiring refinement before the experimental campaign.

The outcome of this session was overall positive. The experts expressed a consistent agreement regarding the correctness and procedural coherence of the proposed workflow, confirming its alignment with the reference industrial process. The MR contents were considered clear, well-structured, and suitable for supporting operator guidance in the targeted assembly tasks. No major critical issues emerged during the evaluation session. Only minor suggestions for improvement were reported, mainly related to interface refinements and additional clarifications in specific instructional steps. Overall, the experts unanimously validated the applicability of the developed MR demonstrator in realistic industrial scenarios, supporting its suitability for the subsequent user study.

3.4. Protocol

The study protocol presented in this section was approved by the CERSUB Ethics Committee of University of Naples Federico II, Italy, and all procedures adhered to relevant ethical guidelines for research involving human subjects. Participants provided informed consent prior to experimental session, and were free to leave it at any moment.

Participants were previously and randomly assigned to one of the two experimental conditions: Condition A (gaze and gesture interaction) or Condition B (gaze and voice interaction) (Section 3.1).

Each experimental session had an approximate duration of 30 min and was conducted individually under the supervision of at least 1 researcher from the academic team. The protocol was structured as follows:

- (5 min) Participant check-in, assignment of an anonymous user ID, and brief introduction to the study objectives, the participant's role within the experimentation, and the overall session procedure.
- (5 min) Completion of the informed consent form and pre-experience profiling questionnaire.
- (5 min) Access to the experimental area, wearing of the MR headset, and calibration of the Microsoft HoloLens 2 device (Microsoft Corporation, Redmond, WA, USA), including eye-tracking configuration procedures.
- (2 min) Preliminary interaction familiarization phase. During this phase, participants were introduced to the assigned interaction modality (gaze + gesture or gaze + voice) and were required to correctly recognize and execute the basic commands needed for task progression (e.g., navigation, selection, confirmation actions). The familiarization was supervised by the researcher, who verified that each participant was able to successfully perform the required interactions before proceeding to the experimental task. It should be noted that this phase was designed to ensure operational understanding of the interaction mechanisms rather than to provide extensive training. Given the relatively low complexity and high intuitiveness of the interaction paradigms supported by the HoloLens 2 interface, this duration was considered sufficient to achieve a baseline level of user competence across participants.
- (approximately 5–7 min) autonomous execution of the assigned MR-supported wire harnessing task under researcher supervision. During the task execution, the researcher simultaneously observed both the participant's behavior and the real-time first-person view streamed from the HoloLens 2 device to an external laptop in order to monitor interaction events, task progression, and potential issues.
- (2 min) Removal of the MR headset and short post-task wellbeing verification to ensure participants did not experience discomfort or adverse effects related to the MR experience.
- (10 min) Completion of post-experience questionnaires and final participant debriefing.

More details regarding the adopted questionnaires and collected measures are provided in Section 3.8.

3.5. Participants

Considering the industrial case study developed in collaboration with Leonardo and the fact that the wiring production activities for the selected aircraft are carried out at the Leonardo plant located in Pomigliano d'Arco (Naples, Italy), all digital instructions delivered through the MR technological demonstrator (including both audio and video contents) were provided in Italian. Therefore, participants were required to be native Italian speakers in order to avoid potential comprehension issues during the execution of the experimental tasks.

The recruitment process was conducted in collaboration with the company through internal e-mail communications aimed at identifying potential participants matching the required eligibility criteria. No participation fee or monetary compensation was offered.

To preserve participants' privacy, all collected data were fully anonymized. During the experimental sessions, participants were video recorded exclusively for immediate post-experience observational analysis, with the purpose of identifying potential discomfort issues or signs of cybersickness emerging during the interaction with the MR system. Since participants were also required to interact through voice commands, all recorded videos were permanently destroyed immediately after the completion of the observational analysis.

In order to reflect the actual heterogeneity of Leonardo's specialized workforce, no exclusion criteria were applied based on previous experience or familiarity with XR technologies. Consequently, both novice and expert XR users were included in the experimental campaign. Similarly, inclusiveness was also maintained with respect to years of professional experience, involving both junior and senior workers, while acknowledging that even less experienced operators in this industrial domain are still highly specialized personnel.

Finally, a participant sample of 16 workers, heterogeneous in terms of age, work seniority and XR familiarity, was involved in the experiment.

3.6. Apparatus

A schematic representation of both software and hardware architectures adopted for technological demonstration and experiment execution is provided in Figure 2.

The hardware architecture of the technological demonstrator was based on Microsoft HoloLens 2 (Microsoft Hololens 2: <https://learn.microsoft.com/it-it/hololens/hololens-commercial-features>, accessed on 13 March 2026) and a support laptop connected to the same wireless network. The HoloLens 2 headset was selected due to its standalone and spatial mapping capabilities, hand-tracking functions, and support for industrial Mixed Reality applications. The device enabled hands-free interaction with holographic contents while preserving full visibility of the physical workspace and assembly components. The laptop workstation was used for experiment supervision and real-time monitoring activities.

From the software perspective, the Microsoft "HoloLens" desktop application (Microsoft Hololens desktop app: <https://apps.microsoft.com/detail/9nblggh4qwnx?hl=it-IT&gl=IT>, accessed on 13 March 2026), freely available through the Microsoft Store, was adopted to establish a wireless connection between the MR headset and the monitoring laptop. This solution enabled real-time streaming of the user's field of view during the experimental sessions, allowing researchers to continuously observe the holographic contents visualized by the operator. Furthermore, the application allowed remote launching and closing of the MR procedure directly from the laptop workstation, simplifying experiment management and synchronization activities. Also, the MR experience was developed using Microsoft Dynamics 365 Guides (Microsoft Dynamics 365 Guides: <https://learn.microsoft.com/en-us/dynamics365/mixed-reality/guides/>, accessed on 13 March 2026), enabling the creation of interactive step-by-step assembly instructions spatially anchored to the workstation. The developed procedure included holographic visual instructions, 3D CAD models, directional arrows and virtual indicators, images and videos showing correct assembly operations, and interactive validation checklists. Since 3D CAD models of wire harnessing components were originally modeled within CATIA V5 (CATIA V5: <https://www.3ds.com/it/products/catia/catia-v5>, accessed on 15 March 2026), they were exported in .STL file format to be used within the MR platform.



Figure 2. Schema of adopted software and hardware architecture for MR-based technological demonstrator, including equipment for researchers to conduct real-time observation during experiments.

3.7. Experimental Setup

To avoid interference with regular production activities within the Leonardo Aerostructures wiring department, the experimental campaign was conducted in a dedicated laboratory environment reproducing the main operational characteristics of the industrial assembly workstation. The setup was developed inside the MARTE laboratory (Advanced Measurements in Virtual Reality) at the University of Naples Federico II.

Although the experimental environment could not fully replicate the real industrial wiring area, mainly due to space limitations and the availability of specialized equipment, the setup was designed to emulate the most relevant assembly conditions required for the validation of the proposed Mixed Reality workflow. In particular, the laboratory configuration reproduced the cable routing area, the operator workspace, and the tool/material positioning typically adopted during wire harness manufacturing activities.

The physical setup included a vertical assembly surface equipped with five equally spaced plastic supports used to simulate the routing hooks employed in the real production environment (Figure 3). The operative volume A-B-C (Figure 4) for the user was designed according to ergonomic and visual comfort constraints associated with both the selected Mixed Reality hardware and the anthropometric characteristics of potential end users:

- A-length. The operative volume represented was approximately 2.2 m to allow the complete extension and positioning of the wire harness during assembly operations. On the right side, a table was dedicated to the storage of tools, connectors, corrugated tubes, and auxiliary components required during the procedure.
- B-length. The vertical length of the operative volume was defined according to Mixed Reality ergonomic guidelines, with the aim of minimizing excessive head, neck, and eye movements during prolonged assembly activities [50]. Since wire harness manufacturing requires frequent upper-limb interactions and continuous visual attention to both physical and virtual elements [18], the holographic contents were mainly positioned within the central region of the operator's field of view: up to 15° above the horizontal line of sight and up to 35° below it approximately, corresponding to the optimal comfort area for MR interactions [50]. Anthropometric considerations based on the average stature of the Italian adult population were also adopted to define the operative height of the workstation. In particular, a reference height of approximately 173 cm was considered, corresponding to the mean value between average Italian male (178 cm) and female (165 cm) adult statures reported by ISTAT [51]. This configuration enabled users to maintain a near-neutral posture during manual assembly operations, reducing neck flexion and visual fatigue [52].
- C-length. The depth of the operative volume was defined according to the visual comfort constraints of the Microsoft HoloLens 2 device [53]. Since prolonged interactions at very short distances may generate visual discomfort due to the vergence-accommodation conflict, holographic contents should preferably be positioned around 1–2 m from the user [50]. Consequently, the experimental setup was designed with a maximum operative depth of approximately 1.5 m (i.e., mean value) from the assembly surface. This configuration allowed users to freely move within the workspace, approach the assembly board when necessary, and maintain stable and comfortable visualization of holographic contents during the assembly procedure [52].

The selected layout represented a default reference configuration automatically initialized at the startup of the MR application. Nevertheless, users retained the possibility to manually reposition holographic panels and instructional contents according to their personal comfort preferences and operational requirements during the experimental sessions.

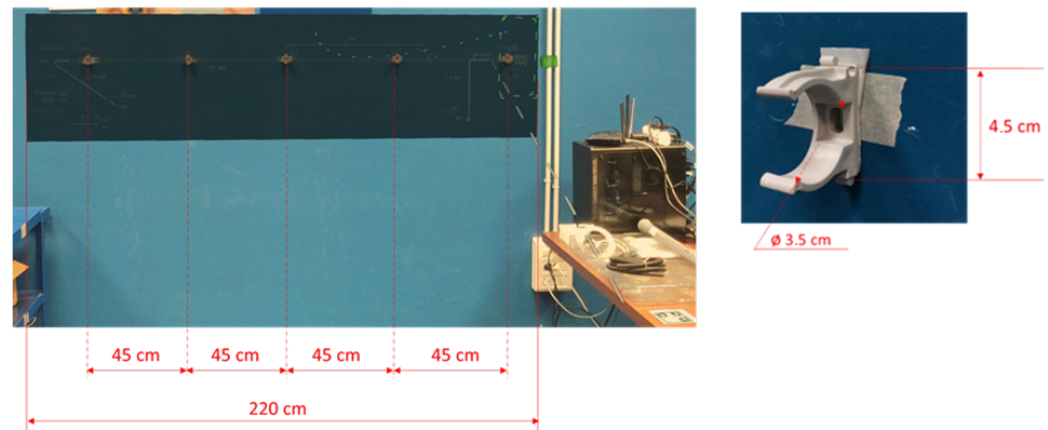


Figure 3. **Left:** front view of operative volume employed for the experimental setup, from user's perspective. **Right:** close-up of the hooks used for anchoring wires.

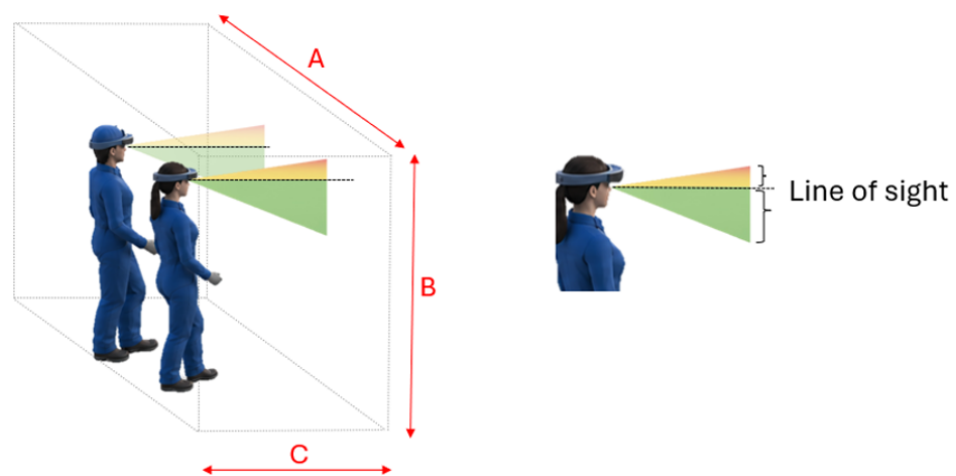


Figure 4. **Left:** operative volume of the experimental setup, designed according to the relevant literature and Microsoft HoloLens 2 guidelines for ideal hologram placement. **Right:** angular sector representing the recommended hologram placement zone, bounded by angles of -35° and $+15^\circ$ relative to the user's line of sight. Green color means high comfort, while yellow to red colors mean low to critical comfort for the user.

3.8. Measures

In this study, we aimed at investigating both the physical and cognitive ergonomics implications associated with the interaction with the MR technological demonstrator.

- From a perceptual ergonomics perspective, the study investigated the potential occurrence of **cybersickness** symptoms during MR-supported activities. Previous studies have shown that exposure to MR head-mounted displays may induce discomfort phenomena such as nausea, visual fatigue, dizziness, disorientation, and ocular strain, potentially affecting operator well-being and task execution capabilities in industrial environments [43,54]. Cybersickness symptoms experienced during the experimental sessions were assessed through SSQ post-experience questionnaire [55], administered immediately after task completion.
- From both physical and cognitive ergonomics perspectives, the study investigated the **usability** of the proposed MR solution according to the framework defined by ISO 9241-11 [44], which conceptualizes usability as a multidimensional construct composed of efficiency (E1), effectiveness (E2) and *satisfaction* (S). In MR-supported industrial environments, usability represents a key indicator of user ergonomics, since interaction quality directly affects the operator's ability to understand instructions, process

information, maintain situational awareness, and efficiently accomplish tasks while minimizing mental/physical effort and interaction-related demands [56]. Therefore, evaluating usability allows assessing how the MR system supports human cognitive and physical performance and interaction sustainability during task execution.

3.9. Data Processing and Analysis

Cybersickness. The adopted SSQ questionnaire (Italian language version [57]) consisted of 16 items, grouped into 3 standard subscales [55]: *Nausea* (N), *oculomotor disturbance* (O), and *disorientation* (D). Answers investigated symptoms commonly associated with immersive technologies, including nausea, dizziness, visual discomfort, disorientation, and general fatigue. The rating scale was defined as follows: 0-None, absence of symptoms; 1-Mild, minimal symptoms; 2-Moderate, noticeable but manageable symptoms; 3-Severe, strong symptoms with significant impact.

According to the original SSQ methodology proposed by Kennedy et al., total scores are often interpreted using qualitative severity categories (using 20 as the threshold value for severe and non-neglectable sickness occurrence) [55]. However, recent studies have highlighted that these threshold values were originally derived from military flight simulator contexts and may not be directly applicable to contemporary VR and MR systems. Weissker et al. (2020) [58] specifically questioned the universal applicability of fixed SSQ severity thresholds, arguing that SSQ scores are highly dependent on the technological context, exposure conditions, and scoring procedures adopted. Therefore, in the present study, SSQ scores were primarily used as a comparative measure between the two experimental conditions rather than being interpreted according to fixed severity categories.

SSQ data were examined from two complementary perspectives:

1. First, a symptom occurrence analysis was performed by counting how many participants reported each symptom at least once, independently from symptom intensity. This representation was adopted to provide an overview of the prevalence and distribution of cybersickness manifestations within Group A, Group B, and the overall participant population (A + B).
2. Second, a symptom severity analysis was conducted according to the revised SSQ scoring methodology, proposed by Weissker [58] (Section A). TS scores were then calculated separately for Group A and Group B to evaluate differences in overall cybersickness severity between the two experimental conditions.
3. Finally, an inferential statistical analysis was performed on TS scores to assess whether the interaction modality (Group A vs. Group B) affected users' cybersickness symptoms. Given the between-subjects design, differences between groups were evaluated using an independent-samples *t*-test. Prior to the analysis, the assumption of normality was assessed using the Shapiro-Wilk test [59]. To account for the limited sample size, a supplementary Mann-Whitney U test was also performed as a robustness check [60]. Effect sizes (Cohen's *d*) and 95% confidence intervals were additionally reported.

Usability. Raw usability data consisted of two heterogeneous sources: (i) subjective questionnaire responses and (ii) objective task completion times. About the first, usability perceptions were collected through a post-experience questionnaire (Table A2), consisting of 26 items (Q1–Q26) rated on a 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree). About the second, task completion time was considered an indicator of operational efficiency and was therefore integrated into the usability assessment framework.

The questionnaire was not derived from a single standardized usability instrument. Instead, it was specifically tailored for the evaluation of MR task-guidance systems by integrating and adapting constructs from established usability questionnaires [61–63], complemented by additional items targeting MR-specific interaction aspects. Table A3 reports

the mapping between questionnaire items and the corresponding source instruments. This design choice was motivated by the need to capture usability dimensions that are not fully addressed by traditional questionnaires. In particular, MR environments introduce additional perceptual and interaction-related characteristics, including spatially embedded information, simultaneous perception of real and virtual elements, and increased cognitive and perceptual demands during task execution [64]. Therefore, the questionnaire was extended with additional items grounded in the MR and human factors literature, targeting spatial awareness, environmental perception, physical comfort, and cognitive workload [64,65]. For this reason, internal consistency of the adopted questionnaire has been verified by means of Cronbach's alpha coefficient [66]. More details on the reliability analysis conducted on the participant sample ($n = 16$) are provided in Section 4.2.

Since the raw usability data consisted of two heterogeneous sources (questionnaire responses, on 5-point Likert scale, and task completion times, measured in seconds), collected data were normalized to the interval $[0, 1]$, to combine these heterogeneous measures into a unified usability metric (see Section B.2 for more details).

Subsequently, the multi-criteria AHP method [67] was applied to derive the relative importance of the usability criteria and associated sub-criteria. Originally proposed by Saaty [67], the AHP is a structured decision-making method designed to address complex problems through a hierarchical organization of objectives, criteria, and sub-criteria. The method relies on pairwise comparisons to determine the relative importance of each criterion and to derive weighting coefficients. Given the overall objective, that was the computation of UI for both the interaction modalities (A–B); in this study, AHP was employed on two levels, as showed in Figure 5:

- First level. The 3 usability dimensions (or criteria) (Section 3.8) [44]: efficiency (E1), effectiveness (E2), and satisfaction (S).
- Second level. The attributes of selected criteria, that are, collected raw data: questionnaire responses associated with each usability dimension and task completion times.

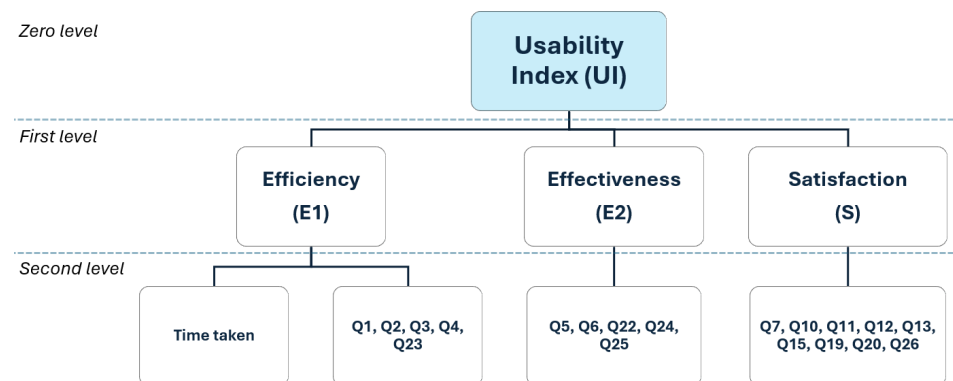


Figure 5. Hierarchical structure of the adopted AHP framework for UI computation. Second-level attributes, derived from raw experimental data collected during (time taken) and after the experiment (Q1–Q26), are aggregated to evaluate the first-level usability criteria (efficiency, effectiveness, and satisfaction), which are subsequently combined to obtain the final UI.

In this study, pairwise comparison judgments were elicited from the 3 industrial experts involved in the preliminary validation phase of the study (namely a training manager, a strategic decision-maker, and a senior wire harness operator, described in Section 3.7). The resulting weighting scheme reflects the companies' priorities and strategic vision, where operational efficiency is generally considered more critical than effectiveness and user satisfaction when evaluating MR-assisted procedures. To assess the robustness of the proposed

usability index with respect to the adopted expert-based weighting scheme, a sensitivity analysis based on alternative equal-weight configurations was additionally performed.

To ensure the transparency, robustness, and reproducibility of the proposed methodology, Section B provides a detailed description of the normalization procedure (Appendix B.2), the AHP weighting computation (Appendix B.3), and the results of the performed sensitivity analysis (Appendix B.4).

Processed usability data were analyzed from different perspectives:

1. First, a descriptive usability analysis was performed by examining the distribution of questionnaire responses for the whole participant sample to retrieve an overview of how the MR technological demonstrator has been perceived by users.
2. Second, an inferential statistical analysis was performed to assess whether the interaction modality (Group A vs. Group B) affected users' task completion times. Consistent with SSQ scores, differences between groups were evaluated using an independent-samples *t*-test. Prior to the analysis, the assumption of normality was assessed using the Shapiro-Wilk test [59]. To account for the limited sample size, a supplementary Mann-Whitney U test was also performed as a robustness check [60]. Effect sizes (Cohen's *d*) and 95% confidence intervals were additionally reported.
3. Finally, usability index computation was performed for both groups, to identify potential optimal interaction modality. The computation procedure followed the hierarchical structure illustrated in Figure 5. First, second-level attributes were aggregated to obtain the three first-level criteria (efficiency, effectiveness, and satisfaction):

$$X_j = \sum_{k=1}^{m_j} p_{jk}^{II} \bar{\mu}_{jk} \quad (1)$$

where:

- X_j is the aggregated score of the first-level usability criterion j ;
- $j \in \{E_1, E_2, S\}$ identifies the first-level criteria, namely efficiency, effectiveness, and satisfaction, respectively;
- k identifies the second-level attributes associated with criterion j ;
- m_j denotes the number of second-level attributes associated with criterion j (as described in Figure 5);
- p_{jk}^{II} represents the local AHP weight assigned to attribute k within criterion j at the second hierarchical level (see Section B.3 for more details);
- $\bar{\mu}_{jk}$ denotes the average normalized value of attribute k associated with criterion j (see Section B.2 for more details).

Specifically, the normalized values associated with each attribute were aggregated using the corresponding local AHP weights. For efficiency (E1), two attributes were considered: normalized task completion time and the average normalized score of questionnaire items Q1, Q2, Q3, Q4, and Q23. In the same way, effectiveness (E2) and satisfaction (S) were computed from the average normalized scores of their respective questionnaire items, as shown in Figure 5.

Then, the overall usability index was calculated separately for both experimental groups, by using first-level criteria:

$$UI = \sum_{j=1}^3 p_j^I X_j \quad (2)$$

where:

- p_j^I denotes the global AHP weight associated with the first-level usability criteria (see Section B.3 for more details);
- X_j denotes the aggregated score of each criterion obtained from the second-level attributes (Equation (1)).

4. Results

4.1. Cybersickness

The SSQ results were analyzed from two complementary perspectives. First, symptom occurrence frequencies were evaluated to estimate how many participants experienced each cybersickness symptom at least once during the experiment (Table 1). Second, symptom severity was assessed through the SSQ subscales (N,O,D) and the overall TS, as reported in Table 2.

1. From a **symptom occurrence** perspective (Table 1), the results indicate that cybersickness symptoms were generally mild to moderate across both groups. The most recurrent disturbances belonged to the oculomotor dimension, particularly difficulty focusing, blurred vision, eye strain, and concentration difficulties. In contrast, nausea-related symptoms were less frequent and mostly limited to mild manifestations, while severe symptoms were only sporadically reported.

The predominance of oculomotor symptoms is consistent with existing literature on AR/MR technologies, where visual fatigue and focusing difficulties are commonly identified as the primary sources of discomfort [68].

2. From a **symptom severity** perspective (Table 2), Group A exhibited higher average SSQ scores compared to Group B, with $TS_A = 331.5$ and $TS_B = 196.1$, respectively. This suggests a generally higher cybersickness burden within Group A (gaze + gesture), although symptom distribution remained heterogeneous across participants. Indeed, several users reported very low or null symptomatology, whereas a limited number of participants showed markedly higher SSQ values, contributing substantially to the group averages.
3. Finally, the assumption of normality for SSQ scores was assessed using the Shapiro-Wilk test and was not violated ($W = 0.935$, $p = 0.291$). Therefore, an independent-samples t -test was conducted to compare cybersickness scores between the two interaction modalities. The analysis revealed no statistically significant difference in SSQ total scores between the gesture-based interaction modality (Group A; $M = 331$, $SD = 312$) and the voice-based interaction modality (Group B; $M = 196$, $SD = 145$), $t(14) = 1.11$, $p = 0.285$). Although participants in the voice-based condition reported lower mean cybersickness scores, the observed mean difference of 135 points was not statistically significant ($95\%CI[-126, 396]$). The effect size was moderate (Cohen's $d = 0.556$). A supplementary Mann-Whitney U test, performed to account for the limited sample size, yielded consistent results ($U = 26$, $p = 0.563$).

The dataset used for these analyses is provided in the Supplementary Materials, within the *DataAnalysis* Jamovi v2.7.17 project file, while the corresponding statistical outputs are also reported in the Excel file entitled *Processed Data*.

Table 1. Cybersickness symptoms frequency across Group A, Group B, and Total. Heatmap is provided to highlight symptoms' intensity: yellow for mild, light and dark orange for moderate and severe symptoms respectively.

Symptom	Group A (n = 8)			Group B (n = 8)			Total: A + B (n = 16)		
	Mild	Moderate	Severe	Mild	Moderate	Severe	Mild	Moderate	Severe
General discomfort	3/8	-	-	2/8	-	-	5/16	-	-
Fatigue	-	-	-	1/8	-	-	1/16	-	-
Headache	3/8	-	-	1/8	-	-	4/16	-	-
Eye strain	2/8	1/8	1/8	6/8	-	-	10/16	1/16	1/16
Difficulty focusing	4/8	1/8	1/8	3/8	1/8	-	7/16	2/16	1/16
Increased salivation	1/8	-	-	-	-	-	1/16	-	-
Sweating	1/8	-	-	-	-	-	1/16	-	-
Nausea	3/8	-	-	2/8	1/8	-	5/16	1/16	-
Difficulty concentrating	5/8	-	-	2/8	-	-	7/16	-	-
Fullness of head	4/8	-	-	1/8	1/8	-	5/16	1/16	-
Blurred vision	1/8	3/8	-	5/8	-	-	6/16	3/16	-
Dizzy (eyes open)	-	1/8	-	1/8	-	-	1/16	1/16	-
Dizzy (eyes closed)	1/8	1/8	-	2/8	-	-	3/16	1/16	-
Vertigo	-	1/8	-	2/8	-	-	2/16	1/16	-
Stomach awareness	3/8	-	-	1/8	-	-	4/16	-	-
Burping	-	-	-	-	-	-	-	-	-

Table 2. Cybersickness symptoms severity: SSQ subscales (N, O, D) and Total Score (TS) for Group A and Group B participants, computed according to [58].

Group A-Gesture				
User	N	O	D	TS
User01	19.08	15.16	41.76	284.24
User02	47.70	37.90	41.76	476.33
User03	0.00	0.00	0.00	0.00
User04	85.86	53.06	111.36	936.05
User05	47.70	30.32	55.68	500.04
User06	19.08	0.00	0.00	71.36
User07	9.54	0.00	0.00	35.68
User08	28.62	22.74	41.76	348.27
Mean	32.198	10.898	36.54	331.5
Group B-Voice				
User	N	O	D	TS
User09	0.00	7.58	13.92	80.41
User10	0.00	15.16	13.92	108.76
User11	9.54	15.16	13.92	144.44
User12	57.24	22.74	27.84	403.25
User13	0.00	7.58	0.00	28.35
User14	38.16	30.32	41.76	412.30
User15	9.54	15.16	13.92	144.44
User16	38.16	0.00	27.84	246.84
Mean	19.08	14.213	19.14	196.1

4.2. Usability

Processed usability data were analyzed according to the three complementary perspectives described in Section 3.9.

1. Questionnaire-based usability evaluation. Overall, participants reported a positive perception of the proposed MR technological demonstrator, particularly in terms of ease of use, intuitiveness and task guidance. As anticipated in Section 3.9, to assess the internal consistency of the proposed questionnaire, a reliability analysis was conducted separately for the three usability criteria (E1,E2,S) by means of Cronbach's alpha test [66]. The obtained internal consistency values are $\alpha = 0.877$ for efficiency,

$\alpha = 0.934$ for effectiveness, and $\alpha = 0.968$ for satisfaction, indicating good to excellent internal consistency for the adopted instrument [69].

Regarding general usability and ease of interaction (Q1, Q5, Q6, and Q7 of the questionnaire, in Table A2), most participants considered the solution easy to use and intuitive. In particular, 20% of participants rated the interface as “very easy to use”, while 45% rated it as “fairly easy to use”. Furthermore, 80% of participants positively evaluated the capability of the system to facilitate task execution through visual information support.

The MR solution was also positively evaluated in terms of physical comfort during task execution. Specifically, 45% of participants considered the system comfortable to use, while 25% described it as “very comfortable”. Nevertheless, some critical observations emerged from the qualitative feedback collected after the experiment. A subset of participants reported that prolonged use of the headset could potentially induce headache or visual fatigue. Additional suggestions concerned the need for a wider field of view and the adoption of shorter and more practical interaction commands in order to further improve operational efficiency.

Overall satisfaction toward the adopted technology was generally high. In particular, 20% of participants declared themselves “very satisfied”, while 50% reported being “fairly satisfied” with the proposed solution. Moreover, 65% of participants believed that the MR system could improve task execution efficiency compared to traditional approaches and considered the interaction workflow sufficiently smooth and compatible with operational practices (Q19–Q20).

Concerning learning support and task comprehension (Q25–Q26), 65% of participants reported that the application improved their understanding of the assigned tasks, while 80% expressed satisfaction with the system as a learning and training tool.

2. Task completion time analysis. Time taken was analyzed to evaluate whether the interaction modality influenced operational efficiency. Mean completion times were comparable between the two groups, with the voice-based interaction modality showing slightly longer completion times (Group A: $t_A = 483.5$ s; Group B: $t_B = 491$ s). The assumption of normality was assessed using the Shapiro-Wilk test and was not violated ($W = 0.942$, $p = 0.374$). Therefore, an independent-samples t -test was performed, revealing no statistically significant difference in task completion times between the two interaction modalities ($t(14) = -0.097$, $p = 0.924$). The observed mean difference between groups was -7.5 s (95% CI $[-174, 159]$), with a negligible effect size (Cohen’s $d = -0.048$). A supplementary Mann-Whitney U test confirmed these findings ($U = 31$, $p = 0.959$), indicating that the interaction modality did not significantly influence task completion time.
3. UI evaluation. Usability index was computed for both groups as described in Section 3.9. The obtained indexes ($UI_A = 0.683$; $UI_B = 0.667$) indicate comparable overall usability levels between the two interaction modalities. The only relevant difference emerged within the efficiency criterion E1 (Table 3), where the gesture-based interaction modality achieved slightly higher scores. In particular, participants interacting through the voice-command interface reported marginally less positive evaluations for Q23 (Table A3). Consequently, the gaze-based interaction (Group A) was perceived as slightly more supportive of work performance and operational efficiency compared to voice command (Group B).

Table 3. For both interaction modalities, final UI scores and respective values of the usability attributes, normalized and calculated with AHP method.

Criteria	Attributes	Group A-Gesture	Group B-Voice
Efficiency	Average time $\bar{t}$	0.420	0.420
	Average score $Q(E1)$	0.725	0.715
Effectiveness	Average score $Q(E2)$	0.720	0.720
Satisfaction	Average score $Q(S)$	0.680	0.680
UI		0.683	0.667

5. Discussion

The obtained results are now discussed in relation to the proposed research hypotheses (formulated in Section 3.1) and interpreted considering the previous literature on MR interaction paradigms, usability, and operator ergonomics in industrial environments.

H1. *Gesture-based interaction may enhance operational efficiency in spatial interaction tasks, leading to reduced task completion time compared to voice-based interaction.*

The experimental results do not support this hypothesis. Task completion time analysis showed comparable performance between the two groups ($t_A = 483.5$ s; $t_B = 491$ s), and no statistically significant differences in completion times were observed between the two interaction modalities. However, an interesting distinction emerges when considering subjective perception. Despite similar objective performance, participants reported slightly higher perceived efficiency when interacting through gesture-based input, although this difference was not reflected in objective performance metrics. This suggests that gesture interaction may be associated with an increased perceived sense of control and natural interaction, without necessarily translating into measurable performance improvements. Such interpretation should be considered exploratory in nature and should be further investigated.

These findings are consistent with previous works [70–72], indicating that the benefits of gesture-based interaction are often context-dependent and may be reduced in procedural task scenarios where interaction primarily involves navigation and information retrieval rather than continuous spatial manipulation.

H2. *Voice-based interaction may result less comfortable in complex procedural tasks.*

This hypothesis is not supported by the experimental findings. No statistically significant differences in SSQ total scores were observed between the two interaction modalities. Nevertheless, participants using the voice-based modality reported lower mean cybersickness scores compared to those using gesture-based interaction ($TS_B = 196.1$, $TS_A = 331.5$), corresponding to a moderate effect size (Cohen's $d = 0.556$).

Although these findings do not allow definitive conclusions regarding the superiority of one interaction modality over the other in terms of comfort, they suggest a possible tendency toward reduced cybersickness when using voice interaction. One possible explanation is that voice-based interaction reduces the need for sustained visuomotor coordination and prolonged mid-air hand movements, which have been associated with increased physical workload and muscular fatigue in gesture-based interfaces [73,74]. Consequently, reducing such interaction demands may reduce the physical demands associated with interaction, potentially resulting in a more comfortable user experience.

However, given the limited sample size and the absence of statistically significant differences, this interpretation should be considered exploratory. Further studies involving

larger participant samples are needed to determine whether the observed trend reflects a genuine effect of the interaction modality on user comfort.

Summary

From a confirmatory perspective, the experimental evidence does not support the initial hypotheses (H1 and H2) as originally formulated. However, the observed trends provide useful exploratory insights into the trade-offs between interaction modalities, suggesting that perceived efficiency and physical comfort may be influenced by different interaction mechanisms. Overall, the results suggest that the relationship between interaction modality and comfort is complex and may depend on the interplay between cognitive demands and physical workload. While voice interaction may introduce additional cognitive effort, it simultaneously reduces physical interaction requirements, potentially influencing users' perceived comfort. These findings should therefore be interpreted as indicative rather than conclusive, and warrant further investigation with larger samples and extended exposure conditions.

6. Conclusions

This work investigated the ergonomic implications of different interaction modalities within a Mixed Reality task-guidance system for industrial wire harness manufacturing, developed in collaboration with Leonardo S.p.A. Although MR technologies are increasingly adopted to support complex industrial procedures, the current literature still provides limited evidence regarding the ergonomic sustainability of different interaction paradigms in real manufacturing-oriented scenarios.

In this context, the present study assessed the ergonomics sustainability of two interaction modalities: gaze + gesture (Group A) and gaze + voice (Group B) interaction modalities. No universally optimal interaction modality was found; instead, the ergonomic suitability of a specific interaction paradigm resulted to depend on the balance between physical workload, cognitive demands, interaction naturalness, and task characteristics.

From an industrial and scientific perspective, the study aimed to contribute to the ongoing transition toward human-centered Industry 5.0 environments by providing an experimentally validated MR technological demonstrator and a replicable evaluation methodology for XR-supported manufacturing assistance systems. In particular, the proposed framework may support future investigations aimed at assessing the ergonomic sustainability of immersive technologies in realistic industrial contexts.

Nevertheless, the study presents some limitations. First, the experimental campaign involved a limited number of participants ($n = 16$), reflecting constraints in recruiting skilled industrial operators. Therefore, the study should be interpreted as exploratory, with findings indicative of trends rather than generalizable conclusions. Second, the experiment was conducted in a controlled laboratory environment and based on a simplified and time-compressed version of the real wire harnessing workflow. Although the task preserved key procedural and cognitive aspects, several operations were partially simulated and the duration (5–7 min) does not reflect real production conditions. Thus, results cannot be directly extrapolated to prolonged industrial use or full working shifts. In particular, the evaluation of cybersickness should be interpreted as a short-term assessment, as potential cumulative effects associated with prolonged exposure to MR systems were not investigated in this study. Finally, additional real-world factors were not fully addressed, including the impact of industrial noise on voice interaction and the potential effects of prolonged headset use (e.g., physical discomfort). In particular, the controlled laboratory environment may have reduced environmental disturbances such as background noise and visual distractions, which are typically present in real production settings. This condition may have influenced

the performance of the voice-based interaction modality, as speech recognition systems are known to be sensitive to noise. Consequently, the comparative results between interaction modalities should be interpreted with caution, as their relative performance may vary under actual industrial conditions. Future studies should therefore involve larger participant samples, longer exposure duration, and validation in real industrial environments to verify whether users' objective performances and/or subjective perceptions may vary.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16147120/s1>, including 3 files: Processed data.xlsx, Report on Cybersickness.pdf and Data Analysis.omv. Processed data.xlsx provides all participants' sample collected data during and after the experiments (usability and sickness), Report on Cybersickness.pdf provides additional info about post-experience answers to SSQ, Data Analysis.omv is the Jamovi file used to perform analyses on processed data (Cronbach alpha and Mann-Whitney U test).

Author Contributions: S.B. methodology, software, data curation, writing; A.T. methodology, conceptualization, software, supervision; F.M. investigation, software; G.D.G. conceptualization, funding acquisition, supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the 'TOP-Technology One Piece' (TOP project: <https://www.daccampania.com/it/progetto-top/>, accessed on 13 April 2026) and 'NEMESI—New Engineering & Manufacturing Enhanced System Innovation' (NEMESI project: <https://www.leonardo.com/it/focus-detail/-/detail/progetto-nemesi-un-passo-verso-industria-digitale>, accessed on 13 April 2026) projects, promoted by Leonardo.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by CERSUB, the Ethics Committee of University of Naples Federico II (approval code: no approval code issued, date of approval: 24 February 2026).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Collected anonymized data and further documentation are provided at <https://osf.io/5w6jk> (accessed on 6 July 2026).

Acknowledgments: This work was conducted within the 'TOP-Technology One Piece' and 'NEMESI-New Engineering & Manufacturing Enhanced System Innovation' projects, promoted by Leonardo. We would like to thank all colleagues working at the Pomigliano d'Arco (Naples, Italy) plant, including wire harnessing operators, who contribute every day to making Leonardo an excellent manufacturer. We sincerely appreciate their professionalism, technical contributions, and constant availability during meetings and discussions aimed at improving the application. Among all, we are profoundly grateful to Davide Santoro, whose guidance and continuous support represented the key enabling element in the collaboration with Leonardo. His deep technical expertise, strategic vision, and constant availability greatly contributed to our understanding of the production cycle, operational mission, and industrial requirements underlying the project, fostering an effective and constructive communication between the research team and the company. We would also like to thank Giovanni Cavallo and Alessandro Guerra, members of the design and development team at the University of Naples Federico II, for their strong technical contribution to the success of the project. In particular, we thank them respectively for the management of the digitization of the wire harnessing process and for the development of the MR experience used in the experiments.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic hierarchy process
AR	Augmented Reality
CI	Consistency index
CR	Consistency ratio
HCI	Human-computer interaction
ISTAT	Istituto nazionale di statistica
KPI	Key performance indicator
RI	Random index
SSQ	Simulator Sickness Questionnaire
TS	Total severity
UI	Usability index
UX	User experience
XR	Extended reality

Appendix A. Cybersickness

Table A1. SSQ symptom grouping into nausea (N), oculomotor (O), and disorientation (D) subscales following Kennedy et al. [55].

Symptom	N	O	D
General discomfort	X	X	
Fatigue		X	
Headache		X	
Eyestrain		X	
Difficulty focusing	X	X	X
Increased salivation	X		
Sweating	X		
Nausea	X		X
Difficulty concentrating	X	X	
Fullness of head			X
Blurred vision		X	X
Dizzy (eyes open)			X
Dizzy (eyes closed)			X
Vertigo			X
Stomach awareness	X		
Burping	X		

$$N = (\sum \text{Nausea Items}) \times 9.54 \quad (\text{A1})$$

$$O = (\sum \text{Oculomotor Items}) \times 7.58 \quad (\text{A2})$$

$$D = (\sum \text{Disorientation Items}) \times 13.92 \quad (\text{A3})$$

$$TS = (\sum N + \sum O + \sum D) \times 3.74 \quad (\text{A4})$$

Appendix B. Usability

Appendix B.1. Usability Questionnaire

Table A2. Usability post-experience questionnaire. Responses were collected using a 5-point Likert scale: 1 = Strongly disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly agree.

Question	Statement
Q1	The solution is easy to use.
Q2	It is intuitive to use this type of command within the solution.
Q3	The visualization of guiding elements on the screen is clear and understandable.
Q4	The application's user interface is intuitive to use.
Q5	Task execution is facilitated by providing visual information.
Q6	The solution supports work practices seamlessly.
Q7	Using the solution to perform the assigned task is comfortable.
Q8	Using the solution to perform the assigned task does not require cognitive effort.
Q9	I am familiar with AR/MR devices.
Q10	My overall feeling when using the solution is positive.
Q11	I enjoy working with the solution.
Q12	I would like to use the solution in the future.
Q13	The solution is physically pleasant to use.
Q14	The solution is mentally pleasant to use.
Q15	I would reuse the solution to perform the same task.
Q16	I find the solution safe to use.
Q17	I can maintain the necessary environmental awareness while using the solution.
Q18	The solution provides a clear view of the surrounding environment during use.
Q19	Overall, I am satisfied with this technology for carrying out the task.
Q20	The solution improves task execution efficiency compared to traditional methods.
Q21	I believe the guided procedure is understandable for a non-expert user.
Q22	It is simple to perform the assigned activity as proposed.
Q23	Using the solution would improve my work performance.
Q24	This type of command is useful for performing the assigned activity.
Q25	The application helped improve my understanding of the tasks.
Q26	I am satisfied with the solution as a learning method.

Table A3. Mapping of 26 selected items with usability standardized questionnaires and respective measured constructs.

Standard Questionnaire	Dimension (Objective)	Questionnaire Items
SUS [62]	Ease of use, global usability	Q1, Q7, Q8, Q12
QUIS [61]	Interface intuitiveness, interaction quality	Q2, Q3, Q4, Q10, Q11, Q15, Q21, Q24
PSSUQ [75]	System performance, information quality, efficiency	Q3, Q5, Q6, Q19, Q20, Q23, Q25
PUTQ [76]	System learnability, task simplicity	Q21, Q22, Q25, Q26
WAMMI [63]	User satisfaction, enjoyment, perceived attractiveness	Q11, Q12, Q26
MR/AR literature [64]	Cognitive load, spatial awareness, physical comfort, safety	Q8, Q9, Q13, Q14, Q16, Q17, Q18

Appendix B.2. Data Normalization

Collected data were normalized to eliminate scale differences between heterogeneous measures. In particular, questionnaire responses were expressed on a 1–5 Likert scale, whereas task completion time was measured in seconds.

Since different variables contributed either positively or negatively to usability, two normalization approaches were adopted.

For negatively correlated variables (e.g., task completion time):

$$Val_{norm} = \frac{Val_{max} - Val_{obs}}{Val_{max} - Val_{min}} \quad (A5)$$

For positively correlated variables (e.g., questionnaire scores):

$$Val_{norm} = \frac{Val_{obs} - Val_{min}}{Val_{max} - Val_{min}} \quad (A6)$$

where:

- Val_{obs} is the observed value;
- Val_{min} is the minimum value;
- Val_{max} is the maximum value;
- Val_{norm} is the normalized value.

All questionnaire scores were normalized within the interval $[0, 1]$.

Appendix B.3. AHP Weighting Procedure for Usability Index

As described in Section 3.9 about usability raw data processing, usability weights were derived using the AHP method [67]. The procedure followed a two-level hierarchical structure consistent with the ISO 9241-11 framework [44].

Level 1: Usability criteria weighting

At the first level, pairwise comparisons were performed among the three usability criteria: efficiency (E), effectiveness (F), and satisfaction (S). The comparison matrix $M^{(I)}$ was defined using the Saaty scale [67]:

$$M^{(I)} = \begin{bmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{bmatrix}$$

The resulting normalized priority vector was

$$p^{(I)} = \begin{bmatrix} 0.633 \\ 0.260 \\ 0.106 \end{bmatrix}$$

Consistency analysis

The consistency of the matrix was evaluated using the principal eigenvalue method. The maximum eigenvalue was

$$\lambda_{\max} = 3.039$$

The Consistency Index CI was computed as:

$$CI = \frac{\lambda_{\max} - n}{n - 1} = 0.019$$

For $n = 3$, the Random Index RI was set to 0.52, resulting in the Consistency Ratio, CR :

$$CR = \frac{CI}{RI} = 0.037$$

Since $CR < 0.1$, the pairwise comparisons were considered consistent.

Level 2: Efficiency sub-criteria weighting

At the second level, efficiency was decomposed into two sub-criteria: task completion time (T) and questionnaire-based efficiency (Q_E). The pairwise comparison matrix $M^{(II)}$ was defined as

$$M^{(II)} = \begin{bmatrix} 1 & 1/3 \\ 3 & 1 \end{bmatrix}$$

The resulting weight vector was

$$p^{(II)} = \begin{bmatrix} 0.25 \\ 0.75 \end{bmatrix}$$

For a 2×2 matrix, consistency is always satisfied, yielding

$$\lambda_{\max} = 2, \quad CI = 0, \quad CR = 0$$

Summary of AHP weights

The final weights used for usability index computation are summarized as follows:

- Level 1 weights:

$$p^{(I)} = [0.633, 0.260, 0.106]$$

- Level 2 weights (Efficiency):

$$p^{(II)} = [0.25, 0.75]$$

These weights were used to aggregate normalized measurements into the final usability index UI, as described in Section 3.9.

Appendix B.4. Sensitivity Analysis of the AHP Weighting Scheme

Since the weighting coefficients derived through AHP (Appendix B.3) depend on expert judgments and may vary according to specific industrial contexts, operational priorities, or business objectives, a sensitivity analysis was performed to assess the robustness of the proposed usability index with respect to alternative weighting schemes. Sensitivity analysis is commonly recommended in the literature on multi-criteria decision analysis and composite indicator construction to evaluate the influence of weighting assumptions on the final results and rankings [77,78].

Following common practice, additional weighting scenarios based on equal weights were considered ('Equal L1 + L2', Table A4). Equal weighting is frequently adopted as a benchmark configuration in sensitivity studies, as it represents the absence of prior preferences among criteria [77]. Thus, equal weights were assigned at both hierarchical levels, i.e., to the first-level usability dimensions (E1,E2,S) and to the second-level efficiency sub-criteria (task completion time and questionnaire-based efficiency).

Table A4 summarizes performed sensitivity analysis and results. The adoption of equal weights slightly modifies the absolute values of the usability indices, reducing the difference between the two interaction modalities from 0.016 to 0.002. A quantitative analysis has been conducted by comparing the differences between the usability indices obtained under the various weighting configurations. Specifically, for each weighting scheme w , the usability difference between the two interaction modalities was computed as follows:

$$\Delta^{(w)} = UI_A^{(w)} - UI_B^{(w)} \quad (A7)$$

The relative variation with respect to the equal-weight configuration was then evaluated as follows:

$$S = \frac{\Delta^{(w)} - \Delta^{(eq)}}{\Delta^{(eq)}} \times 100 \quad (A8)$$

where $\Delta^{(eq)}$ denotes the usability difference obtained under the equal-weight configuration.

In the present study, the relative variation resulted in approximately 7%, which corresponds to a moderate sensitivity according to commonly adopted empirical guidelines [77,78]. However, despite this variation, the relative ranking between the two in-

teraction modalities remained unchanged ($UI_A > UI_B$), demonstrating that the overall conclusions of the study are robust with respect to the adopted weighting scheme [77].

Table A4. Sensitivity analysis of the usability index under alternative weighting schemes.

Scenario	p_1 (E1,E2,S)	p_2 (Time,Q)	UIA	UIB	$\Delta(UI_A - UI_B)$
Weighted AHP	(0.633,0.260,0.106)	(0.25,0.75)	0.683	0.667	0.016
Equal L1 + L2	(0.333,0.333,0.333)	(0.50,0.50)	0.658	0.656	0.002

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