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A Comparative Study of Handheld Augmented Reality Interaction Techniques for Developing AR Instructions using AR Authoring Tools

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ABSTRACT

Augmented Reality (AR) instructions offer companies tremendous savings potential. However, developing these AR instructions has traditionally been challenging due to the need for programming skills and spatial knowledge. To address this complexity, industry and academia are working to simplify AR development. A crucial aspect of this process is the accurate positioning of AR content within the physical environment, which requires effective AR interaction techniques that enable full 3D manipulation of AR elements. In this study, we conducted an experimental comparison of three different AR interaction techniques with 55 participants to empirically assess their performance, workload, and user satisfaction across tasks related to AR instruction development. Our findings contribute to the design of future AR instructions and AR authoring tools, emphasizing the importance of evaluating AR interaction techniques that can be utilized by users without programming experience tailored to the specific needs of the intended application domain.

1. Introduction

Over the past three decades, numerous studies have demonstrated that augmented reality (AR) is a powerful and innovative technology that supports various industrial operations, including maintenance (Henderson and Feiner, 2011) or quality control (Krenzer et al., 2019). One of the most significant use cases for AR in the industry is the utilization of AR instructions for process support (Klinker et al., 2018; Kortekamp et al., 2019). This application domain frequently leverages AR technology due to its substantial cost-saving potential. For example, implementing AR in Boeing’s cable assembly processes resulted in a 40 % productivity increase and a 25 % reduction in wiring production time (Cohen et al., 2018). These savings drive industrial organizations to transition from traditional technical documentation to AR instructions (Porter and Heppelmann, 2017). Traditional technical documentation, often presented as printed or electronic manuals, relies on comprehensive text and images (Geng et al., 2020), making it challenging to relate to the physical environment and the tasks involved (Chen et al., 2019). In contrast, AR-based technical instructions provide users with the necessary contextual information directly in the physical environment at the appropriate time (Azuma, 1997). However, as AR applications become more widespread, so do the associated challenges. One of the most significant challenges in the industry is the complexity of developing AR applications. In addition to technical expertise, advanced programming skills are required, and virtual objects and their physical placements must be created within programming environments (Ashtari et al., 2020; Nebeling and Speicher, 2018). Moreover, manually positioning AR elements in the physical environment requires AR interaction techniques that are unfamiliar to many users and demand extensive spatial knowledge (Azuma, 2016; Bräker et al., 2023). The complexity of developing AR applications has led to approximately 64 % of AR applications in the industry being custom-built solutions (Palmarini et al., 2018). These custom-built solutions developments are often impractical for small and medium-sized enterprises, as even minor changes can result in significant development costs, thereby slowing the adoption of AR in the industry (Konopka et al., 2024).

While there is a trend to ease the AR development processes so that no extensive programming knowledge or experience is required, such as in traditional software development (Matook et al., 2023) or for developing AI-based systems (Elshan et al., 2023), recent research shows that the AR authoring tools are still mainly used by experienced software developers (Ashtari et al., 2020; Krauß et al. 2021; Nebeling and

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Speicher, 2018). To further streamline the AR development process and empower domain experts, such as service technicians, to independently create AR instructions, previous research on AR development tools has primarily focused on simplifying the creation of AR content (Fortuna et al., 2024; Scurati et al., 2018). This approach enables domain experts to utilize pre-built 3D models, animations, and annotations to generate on-site AR instructions without requiring programming skills (Nebeling and Speicher, 2018). However, while the development of AR content is a critical component of these authoring tools, another crucial aspect is the need for domain experts without programming expertise to manually anchor or position the AR content within the physical environment (Bräker et al., 2023).

This task requires an interaction that allows the 3D movement of AR elements within the physical environment (henceforth referred to as the AR interaction technique). AR interaction techniques encompass the methods and mechanisms that enable users to manipulate AR elements anchored in the physical environment. While the field of human-computer interaction (HCI) broadly defines interaction as a reciprocal exchange between a user and a system, in this paper, we focus specifically on the actions a user actively performs—namely, the inputs users make within an immersive AR system (Hertel et al., 2021). Selecting the appropriate AR interaction technique is crucial for AR authoring tools, as precise and efficient positioning of AR content in the physical environment is a core component of AR instructions (Bräker et al., 2023). Although the general performance of existing AR interaction techniques has been extensively studied (Goh et al., 2019; Liu et al., 2015), an examination of current AR authoring tools reveals that those not requiring programming knowledge are typically tailored to specific application domains (Damarowsky and Kühnel, 2022; Laviola et al., 2022). Given the wide variation in application domains for immersive technologies in the industry (Buchholz et al., 2022; Dolata and Schwabe, 2023), evaluating how different AR interaction techniques perform when applied to specific use cases is important. Our study focuses on handheld devices for AR, as their widespread availability and lower costs, compared to wearable devices, make them particularly accessible and appealing for small and medium-sized enterprises (SMEs). Additionally, current research has shown that handheld devices are well-suited as AR authoring tools in the industry, as they do not require hands-free operation during the development of AR instructions, unlike their use for executing AR instructions (Hönemann et al., 2024). To the best of our knowledge, there is no clear consensus on which AR interaction technique is best suited to convert traditional technical documentation into AR instructions. Therefore, we aim to address the following research questions:

RQ1. : What are the performance, workload, and satisfaction trade-offs of AR interaction techniques for conveying traditional technical documentation into AR instructions?

RQ2. : What are the strengths, weaknesses, opportunities, and risks of using the different AR interaction techniques when creating AR instructions?

To address these research questions, we conducted an experimental comparison of three different AR interaction techniques with a total of 55 participants, aiming to empirically evaluate the trade-offs in terms of performance, workload, and user satisfaction when positioning AR elements in designated locations across tasks necessary for developing AR instructions. Satisfaction refers to the user's satisfaction with the process and the final positioning of the 3D elements in the physical environment. Additionally, we assessed the strengths, weaknesses, opportunities, and risks associated with each AR interaction technique within the specific application domain. The tasks were derived from the six information types used to convert traditional technical documentation into AR instructions (Gattullo et al. 2020). To ensure that our results are generalizable and broadly applicable, we focused on AR interaction techniques suitable for standard handheld devices and based on the most common input methods in both practice and academia—namely, device-based and touch-based interactions (Goh et al. 2019). We compared three AR interaction methods: two touch-based interactions, *Gizmo-based* and *Plane-based*, and one *Device-based* interaction. *Gizmo-based* interaction represents a widely used 3D manipulation technique found in 3D modeling tools such as Unity (Unity Technologies, 2024). *Plane-based* interaction is commonly employed in commercial AR applications like IKEA Place (IKEA, 2017). The third method, *Device-based* interaction, relies on the movement of hardware rather than touch input and is utilized in commercial applications like the Apple Measure app (Apple, 2024).

Our study contributes to the design of future AR instructions by identifying the tasks that participants found particularly challenging when creating AR instructions. Additionally, our qualitative findings provide insights into which AR interaction techniques may be suitable for applications beyond the domain of AR instructions and the risks associated with each technique. We also present empirical performance, workload, and user satisfaction data for the three AR interaction techniques evaluated. Finally, our results underscore the need to assess AR interaction techniques within AR authoring tools that are intended for users without programming experience, specifically tailored to their intended application domains.

This paper is organized as follows. First, we review the related work on AR interaction techniques, AR authoring tools, and the information types used to convey technical documentation into AR instructions. Next, we describe the laboratory experiment procedure and present the results. Finally, we conclude with a discussion of the findings.

2. Related Work

We have organized the related work into three sections: (1) Types of AR interaction techniques on handheld devices, (2) Augmented Reality Instructions, and (3) Augmented Reality Authoring Tools.

2.1. Types of AR Interaction Techniques on Handheld Devices

In AR, 3D interaction is a fundamental concept, as emphasized in its definition (Azuma, 1997). These 3D interactions require control over six degrees of freedom (6DOF), with 3DOF for object translation and 3DOF for object rotation. In handheld mobile AR, virtual object manipulation techniques can be broadly categorized into two main types widely used in science and practice: (1) Touch-based interaction and (2) Device-based interaction techniques. This section provides a detailed description of these two handheld AR interaction techniques.

2.1.1. Touch-based interaction

Touch-based interaction involves using on-screen touch inputs via fingertips to manipulate 3D objects (Goh et al. 2019). A key challenge with this interaction type is mapping 2D touch points on a screen to 3D attributes, allowing for complete 3D object manipulation consisting of 6DOF (Martinet et al. 2010). Three approaches can be considered to obtain the additional depth information necessary for manipulating objects along the Z-axis. The first approach involves using additional hardware. For instance, Wilson et al. (2008) proposed a camera capable of providing depth information per pixel, which could be used to create a comprehensive 3D model of the hand, thereby expanding interaction possibilities. However, the need for additional hardware often leads to increased costs. The second approach to achieving full 3D object manipulation is through touch-based interaction using two fingers. For example, Liu et al. (2012) proposed an interaction concept that enables 6DOF manipulation by using two fingers on the screen. This allows for 3DOF translation and 1DOF rotation with simultaneous finger movement, while an additional gesture involving one moving finger and one stationary finger can achieve 2DOF rotation. The third approach involves using translation and rotation gizmos, enabling 6DOF interaction with just one finger (Drey et al. 2023).

Table 1
Information types in AR instructions proposed by Gattullo et al. (2020).

Information Type	Description	System Models	Spatial Models	Example
Identity	To display the identity of an object.	Static	2D	An image of the object.
Location	To determine or highlight the location of an object in the users' physical environment.	Static	3D	An arrow pointing at the object.
Way-To	To visualize the operation to be carried out.	Dynamic	3D	An animation showing how to move the object
Notification	To display additional information which are necessary for an assembly step but also for different conditions or other quality indications	Static	2D	A text which displays a hint.
Order	To visualize the assembly sequence	Static	2D	A number that indicates the assembly sequence.
Orientation	To visualize the alignment of an object	Static	3D	A 3D model of the object.

2.1.2. Device-based interaction

Device-based interaction refers to techniques that utilize the physical attributes of handheld mobile devices to manipulate 3D objects. Users control 3D objects by rotating, tilting, skewing, and moving the mobile device (Goh et al. 2019). This interaction category offers several advantages: the device can be held with both hands, it is free from occlusion (Tanikawa et al. 2015), and 3D objects can generally be manipulated more quickly compared to touch-based interactions (Marzo et al. 2014; Mossel et al. 2013). However, there are also notable drawbacks. For example, larger rotations (beyond 90°) are either difficult to perform or impossible without significant effort. To address this issue, Samini and Palmerius (2016) proposed an interaction method with a hold function, allowing larger rotations by fixing the object at various positions. Another challenge is that translation and rotation cannot be performed independently—a rotation accompanies each translation, and vice versa. To mitigate this, Polvi et al. (2016) employed ray casting in conjunction with epipolar geometry, integrating the device's existing positioning technique, which tracks the device's movement by aligning the built-in camera's position with the 3D object. Object rotation is impossible in this method, so a touch-based interaction was used as a complementary technique (Polvi et al. 2016).

2.2. Augmented Reality Instructions

One of the most important use cases of AR in the industry is the application of AR as a process guidance system, which is an AR instruction (Klinker et al. 2018; Kortekamp et al. 2019). These systems provide users with the right information at the right time and place in the physical environment, supporting them in performing their daily tasks in a process-compliant manner (Morana et al. 2017). These process guidance systems, in the form of AR instructions, are crucial in industrial settings due to their immense potential to facilitate the execution of complex and unfamiliar tasks (Hoffmann et al. 2020). For example, Serván et al. (2011) demonstrated a 90 % reduction in preparation time using AR instructions, which assisted service operators in wiring harness installation by displaying both the tasks to be performed and the essential operating parameters directly in the operators' physical environment. Beyond cost savings, research has also shown that AR instructions can reduce the user's mental workload (Tang et al. 2003).

The information in an AR instruction can vary in type, and no standard classification exists. Gattullo et al. (2020) proposed six information types to convey traditional technical documentation in an AR instruction to streamline the development of AR instructions and identify the necessary AR content. A unique characteristic of these information types is their inclusion of dynamic content, such as animations, alongside static content, such as 3D models. In addition to the system model, an AR instruction typically includes both 3D and 2D elements (Gattullo et al. 2020; Mohr et al. 2015). Table 1 provides an overview of these six types of information and their respective characteristics.

2.3. Augmented Reality Authoring Tools

AR authoring tools provide an environment for designing, developing, and managing AR applications and experiences by integrating virtual objects with the physical environment, which involves developing and manipulating AR elements (Nebeling and Speicher, 2018). These tools target developers with varying skill levels and address different stages of application fidelity (Ashtari et al. 2020; Krauß et al. 2021). By analyzing 60 different AR authoring tools from both scientific and practical contexts, we classified the landscape of AR authoring tools into two distinct clusters, as illustrated in Fig. 1. The left side of Fig. 1 presents a selective overview of various AR authoring tools identified in our analysis. The left-hand coordinate system in Fig. 1 classifies a selection of AR authoring tools based on their complexity (ranging from 1 – no programming knowledge required to 5 – advanced programming knowledge required) and their versatility in developing AR applications (ranging from 1 – suitable for one use case only to 5 – suitable for unlimited use cases). The right-hand coordinate system in Fig. 1 shows the distribution of AR authoring tools, where the dark blue/grey areas represent coordinates with several tools assigned, and the lighter areas indicate coordinates with only a few tools assigned.

The first cluster (grey) consists of highly complex tools that require programming and scripting knowledge (Carmigniani et al. 2011). Despite their complexity, these powerful tools can develop highly customized AR applications that can meet almost any requirement. As a result, both the complexity and versatility of these tools are very high. Developers often use gizmo interactions on desktops when creating AR applications with these tools. In practice, tools like Unity (Unity Technologies, 2024) or Unreal (Unreal Engine, 2024). are commonly used. Notably, though unsurprisingly, most of these tools are developed and marketed by large companies such as Snap Inc., Apple, and Google.

Tools in the second cluster (blue) consist of less complex tools that require little to no programming skills. However, these tools are limited in functionality and scope, often focusing on value creation within a specific application domain. Consequently, both the complexity and versatility of these tools are relatively low. The development of AR applications with tools from this cluster typically occurs on handheld devices or head-mounted displays using various interaction techniques, such as touch-based interactions (Rajaram and Nebeling, 2022) or device-based interactions (Konopka et al. 2022). An example of a tool used in practice is Microsoft Dynamics 365 Guides, which can be used to develop AR instructions (Lavric et al., 2022).

A closer examination of the second cluster reveals that, just as developers tailor AR content to specific use cases, they should also tailor the AR interaction technique to the specific use case and evaluate it accordingly.

3. Method

To investigate the AR interaction techniques and the assumptions outlined in the previous section, we designed a laboratory experiment to compare three AR interaction techniques across a set of information

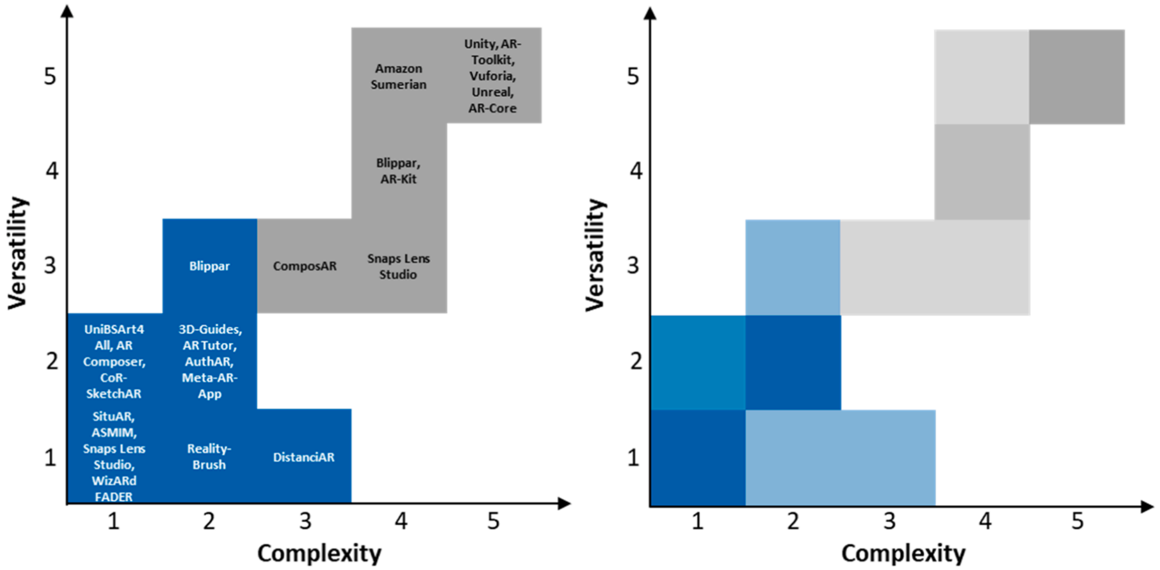

Fig. 1. Clusters of AR authoring tools.

types used to convey technical documentation into AR instructions. We first provided an overview of the (1) study design, (2) measures collected, and (3) study sample. We then detailed the (4) study procedure, (5) the three AR interaction techniques (*Plane-based*, *Gizmo-based,* and *Device-based*), and the lab experiment (6) tasks (*Order*, *Orientation*, *Way-To*, and *Location*).

3.1. Study Design

In designing this study, we adhered to the guidelines outlined by Bergström et al. (2021) for evaluating AR interaction techniques. We employed a repeated-measures within-subject design, where participants used each manipulation technique in a randomized sequence. We utilized a Latin Square design to ensure balance in the sequence of AR interaction techniques among participants.

Bergström et al. (2021) suggest limiting the number of independent variables to three, as this minimizes the influence of interpersonal variability on performance in low-level tasks. In alignment with these recommendations, we focused on two independent variables: *AR interaction techniques* (*Plane*, *Gizmo*, *Device*) and *task types* (*Order*, *Orientation*, *Way-To*, and *Location*).

Additionally, Bergström et al. (2021) recommend setting a threshold for object placement in manipulation tasks. In our study, this threshold was self-determined by participants, who positioned the AR element and confirmed the final position with a button press. A transparent version of the 3D object was used to visualize colocation, as suggested by Bergström et al. (2021). These transparent 3D objects are displayed on a virtual object that imitates the real environment to simulate an AR application.

The study also emphasized using low-level tasks, as Bergström et al. (2021) recommended, which involves separating pointing and selection from translation and rotation. Thus, our study focused exclusively on rotation and translation tasks. Furthermore, a discrete task setup was employed to maintain control over task distance, with manipulation objects starting from a consistent initial position.

Each participant used each AR interaction technique for tasks presented in a random order, except for task order, which followed realistic technical documentation. Participants began with the *Order* task (determining the assembly order of a cylinder), proceeded to the *Orientation* task (correctly positioning pistons), followed by the *Way-To* task (placing a piston on the connecting rod from the starting position), and concluded with the *Location* task (connecting the cylinder to the connecting rod with a pin). Each task included one practice trial followed by two evaluation trials.

In summary, participants engaged with three AR interaction techniques across four tasks per technique. Each task comprised three trials, including one practice trial and two evaluation trials. Thus, participants completed a total of 36 trials, with 24 designated as evaluation trials.

3.2. Measures

Through a post-survey, we collected demographic data such as age and gender to characterize the participants and assess their experience with AR, providing insight into their proficiency with AR technology. Additionally, we inquired about their 3D modeling experience to gauge their familiarity with the different AR interaction techniques.

The participants' workload and satisfaction with each AR interaction technique were assessed through a survey. Participants rated the AR interaction techniques using a seven-point Likert scale for satisfaction and a ten-point survey scale for workload. We measured workload using the RAW-TLX questionnaire (Hart, 2006) and satisfaction using the questionnaire developed by Venkatesh et al. (2011). The measurement items for satisfaction are presented in Table 2.

Following the guidelines of Bergström et al. (2021), we collected four performance measures for each evaluated trial: (1) Threshold time—the time from spawning the AR object to reaching the threshold accuracy; (2) Distance error—the deviation in millimeters (X, Y, and Z axes); (3) Path error—the path deviation in millimeters (X, Y, and Z axes); and (4) Rotation error—the deviation in degrees (X, Y, and Z axes).

We conducted a semi-structured interview to evaluate the strengths, weaknesses, opportunities, and risks associated with using the three AR interaction techniques in relation to the tasks. During the interviews, participants were asked to share their initial impressions of each AR interaction technique, including perceived strengths and weaknesses. We then asked them to identify potential opportunities and threats related to the AR interaction technique. The interviews were recorded and subsequently transcribed.

Table 2
Satisfaction measurement items (Venkatesh et al. 2011).

I am … with the use of the interaction technique.		
SAT1	Extremely displeased …	Extremely pleased.
SAT2	Extremely frustrated …	Extremely contented.
SAT3	Extremely dissatisfied …	Extremely satisfied.

3.3. Participants

We selected a student sample comprising undergraduate, graduate, and postgraduate students from the fields of business economics and engineering, as they represent future domain experts in the industry. We recruited 57 participants for our lab experiment, excluding two participants due to incomplete performance data resulting from a technical error. Thus, our study included a total of 55 participants. The gender distribution was as follows: 53 % (29 of 55) were male, 44 % (24 of 55) were female, and 3 % (2 of 55) chose not to disclose their gender. The average age of the participants was 28.7 years (SD = 9.76), with all participants providing their age information. The participants had a rather balanced overall *AR Experience*. When asked about their AR experience on a scale of 1–7 (1-No experience, 7-A lot of experience), only seven participants indicated that they had no AR experience (2: n=10; 3: n=14; 4: n=13; 5: n=4; 6: n=5; 7: n=2). The *3D Modeling Experience* of the participants, however, is somewhat lower. For example, 14 participants stated they had no 3D modeling experience at all (2: n=12; 3: n=9; 4: n=11; 5: n=5; 6: n=1; 7: n=3). Each participant received a gift of 15 euros as an incentive for participation. Additionally, to further motivate participants, the top three performers—those with the lowest average threshold time, distance error, rotation error, and path error across all AR interaction techniques and tasks—received an additional gift of 20 euros.

3.4. Procedure

At the beginning of each experimental session, participants were informed about the research objective: to evaluate three different AR interaction techniques across various information types to transform technical documentation into AR instructions. The experimental procedure was also explained to them. Participants were reminded to complete the tasks as quickly and accurately as possible. Following this introduction, the experiment commenced.

At the start of the experiment, the experimenter selected the initial AR interaction technique for each participant and placed a pre-built 3D model, serving as the task foundation, on a flat surface in the participant's physical environment. Participants were then provided with a tablet device to use during the tasks. Each of the four tasks began with a practice trial that participants could initiate independently. During the practice trial, participants were encouraged to take their time to familiarize themselves with the AR interaction technique and the task at hand. They were allowed to ask the experimenter questions regarding the task and the AR interaction technique if needed. The practice trials were marked as such in the application. Following the practice trial, participants proceeded with the evaluated trials. Fig. 2 provides an overview of the study procedure in the laboratory environment.

Upon completing all four tasks using a specific AR interaction technique, a semi-structured interview was conducted. After the interview, participants were asked to complete a questionnaire assessing their workload and satisfaction of using the AR interaction techniques to complete the tasks (i.e., positioning the AR elements to the designated position). Once all tasks with all AR interaction techniques were completed, participants completed a final questionnaire collecting demographic data, AR experience, and 3D modeling experience. The entire lab experiment lasted between 45 and 60 minutes, depending on the speed at which participants completed the tasks and questionnaires.

3.5. AR Interaction Techniques

In our laboratory experiment, we compared three AR interaction techniques: two representing touch-based interaction and one representing device-based interaction. These AR interaction techniques are widely referenced and utilized in both scientific research (Goh et al. 2019) and practical applications in manufacturing and service. We focused on the following three AR interaction techniques, as illustrated in Fig. 3.

3.5.1. Plane-based (Plane)

In this technique, AR objects were moved along a surface detected by the device. By touching the plane beneath the AR objects, users could move them along the surface. As shown in Fig. 3(a), only 2DOF (degrees of freedom) was possible when translating along a surface, so we implemented a slider that allowed the object to be moved vertically (1DOF). The surface always served as the origin, and moving the object below the surface was impossible. If a new surface was detected and the AR object was moved from one surface to another, the new surface became the starting point. Rotation in this technique was achieved through a 3D touch technique. Fig. 3(b) illustrates the touch gestures that allowed AR objects to be rotated along all three axes. A horizontal movement with two fingers rotated the AR object along the Y-axis, while a vertical movement with two fingers rotated it along the X-axis. When

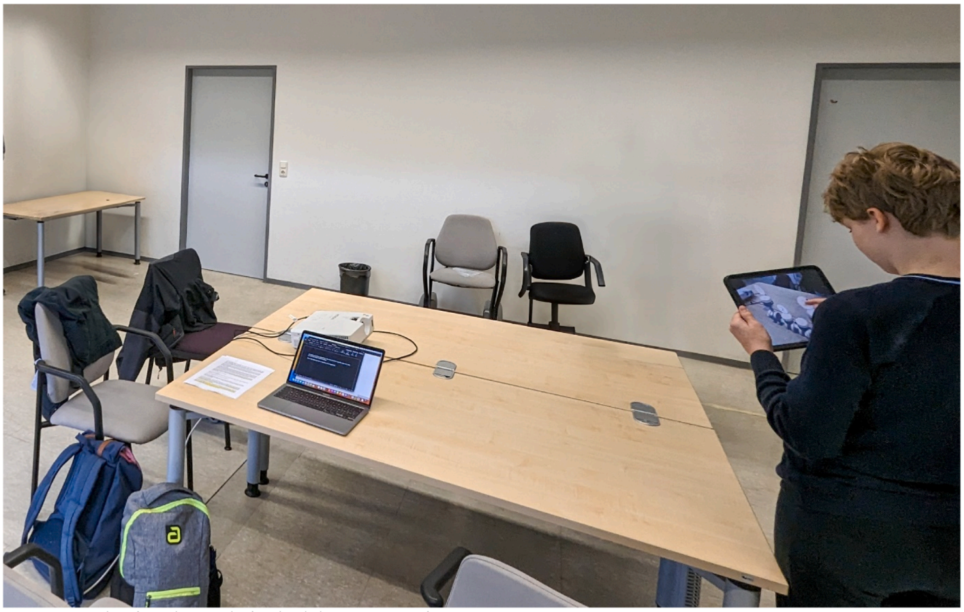

Fig. 2. Conducting the study in the laboratory environment.

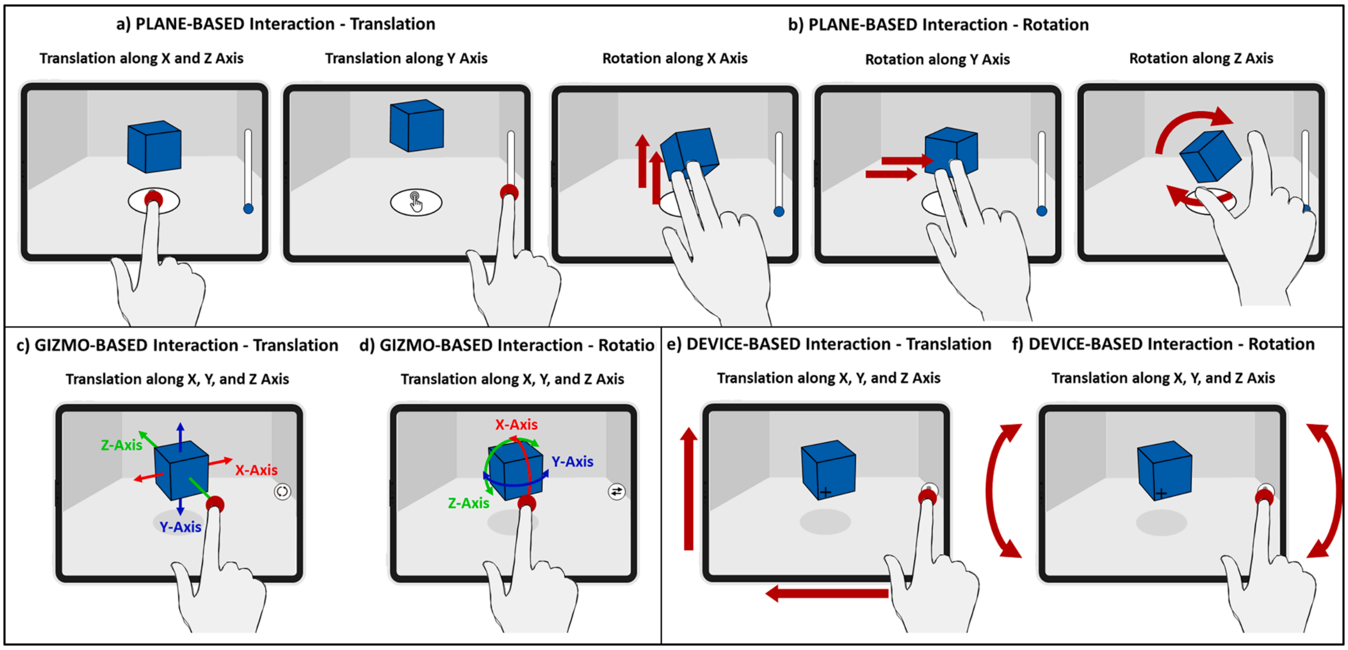

Fig. 3. Three AR interaction techniques.

fingers were moved diagonally, the AR object rotated along either the X or Y axis, depending on which axis the diagonal movement was closer to. The AR object rotated around the Z-axis when a rotation gesture was performed with two fingers, with the distance between the fingers determining the rotation speed—the closer the fingers, the slower the rotation. We chose this AR interaction because it is one of the most commonly used interactions in practice and is featured in several AR authoring tools (Nebeling et al. 2018). Practical examples include furnishing apps like IKEA Place (IKEA, 2017) or messaging apps like Snapchat (Snap AR, 2024).

3.5.2. *Gizmo-based (Gizmo)*

In this technique, AR objects were translated and rotated using gizmos. As shown in Fig. 3(c) and Fig. 3(d), the AR objects could be moved and rotated by interacting with the different gizmos attached to the objects. Given the limited screen space on the device and to simplify the interaction for participants, we separated translation and rotation functions. A button allowed users to switch between translation and rotation modes. We selected this AR interaction technique because it represents a widely used 3D object manipulation method in AR authoring tools from the first cluster described in the previous section (Unity Technologies, 2024; Unreal Engine, 2024) and is also frequently utilized in AR authoring tools referenced in academic literature (Rajaram and Nebeling, 2022).

3.5.3. *Device-based (Device)*

In this technique, the device's own attributes were used, with the device serving as a controller for the interaction. As shown in Fig. 3(e) and Fig. 3(f), to translate or rotate an AR object, participants had to align the crosshair in the center of the display with the AR object they wished to manipulate. Pressing a button initiated the interaction, and releasing the button stopped it. X, Y, and Z translations were performed by physically moving the device along the desired axis; for instance, participants could move the AR object along the Z-axis by stepping forward or backward. X, Y, and Z rotations were achieved by rotating the device along the corresponding axis, such as simulating a steering wheel movement to rotate the AR object around the Z-axis. Due to ergonomic constraints, AR objects could only be rotated by approximately 90° at a time. To achieve a full 180° rotation, participants needed to rotate the object 90°, stop the interaction, return the device to the starting position, and then perform another 90° rotation. We selected this AR interaction technique because it is widely used in practice, such as in measurement apps like Apple's Measure app (Apple, 2024), and is also featured in many AR authoring tools discussed in academic literature (Konopka et al. 2022).

3.6. *Task*

The six information types presented in the related work section served as the foundation for the tasks in our lab experiment. We focused on four of the six information types for the experiment. The two information types, *Identify* and *Notification*, were excluded from the laboratory experiment because they are displayed in AR instructions using simple 2D elements without any reference to the physical environment. As a result, these types neither required nor allowed for 3D manipulation. In practice, the *Identify* information type is typically represented by a photo or illustration of the object, while *Notification* is usually conveyed through simple text. The Order task addresses manipulating 2D texts or images in the physical environment. We designed a practical and realistic task relevant to an industrial context for each of the four selected information types, as illustrated in Fig. 4.

3.6.1. *Order*

As shown in Fig. 4(a), this task required participants to attach a 2D object (a number) to a specified location (highlighted in blue) on the model, which would later be used to visualize the assembly process. Performance in this task was evaluated based on the accuracy of the 2D object placement in the designated locations.

3.6.2. *Orientation*

As shown in Fig. 4(b), this task required participants to place a 3D object (a piston) in a specified location (highlighted in blue) relative to the model, ensuring that the 3D object's orientation would serve as the starting point for the next assembly step. Performance in this task was evaluated based on the precise placement of the 3D object in the designated location.

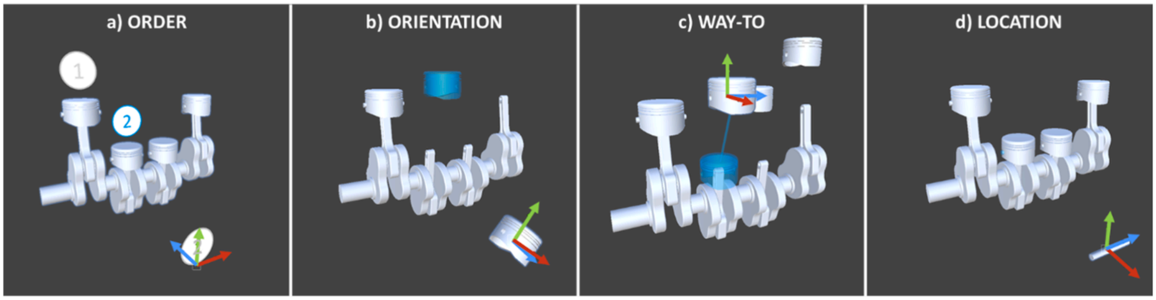

Fig. 4. Four tasks to convey technical documentation in AR instructions.

3.6.3. *Way-To*

As shown in Fig. 4(c), this task required participants to move a 3D object (a piston) along a specified pathway (highlighted in blue), representing the creation of an animation (attaching a piston to the connecting rod). Performance in this task was evaluated based on the accuracy of the 3D object's movement along the designated pathway.

3.6.4. *Location*

As shown in Fig. 4(d), this task required participants to place a 3D object (a connector pin) in a specified location (highlighted in blue) within another object, indicating the position for an assembly step. Unlike the *Orientation* task, this task involved placing objects inside another object, necessitating occluded interaction. Performance in this task was evaluated based on the precise placement of the 3D object in the designated location.

4. Results

The results section is structured as follows: (1) an analysis of the performance data collected during the evaluated trials, (2) an analysis of the workload and satisfaction data provided by participants in the questionnaire, and (3) participants' evaluations of the three AR interaction techniques in terms of strengths, weaknesses, opportunities, and risks.

4.1. *Performance*

We conducted a statistical analysis of the dependent variables collected during our lab experiment. To compare the effects on nonparametric data, such as performance, we utilized the Aligned Rank Transform (ART) method, as proposed by Wobbrock et al. (2011). This approach enabled us to perform a three-way repeated measures ANOVA with factors for AR Interaction Technique, Task, and Time. In the ART method, data is first aligned for each effect before being ranked, making it suitable for non-normally distributed data (Wobbrock et al. 2011). The variable *Time* consisted of the first and second evaluated trials. Following this, we applied Bonferroni post-hoc tests for pairwise comparisons to identify significant differences between the AR interaction techniques. When Mauchly's test indicated a violation of the sphericity assumption, we applied Greenhouse-Geisser corrections in our analysis.

4.1.1. *Threshold Time*

Fig. 5 shows the estimated marginal means of threshold time for the three interaction techniques across the four tasks during the first evaluated trial. We found a significant main effect for the variables *Task* and *Interaction*. Additionally, we observed a significant three-way interaction for *Task x Interaction x Time* (F(6324) = 9.04, $p < 0.001$). Significant two-way interactions were identified for *Task x Interaction* in both the first evaluated trial (F(6324) = 3.12, $p = 0.009$) and the second evaluated trial (F(6324) = 2.80, $p < 0.020$).

In the first evaluated trial, there was a significant simple main effect for all tasks in reaching the threshold time across the AR interaction

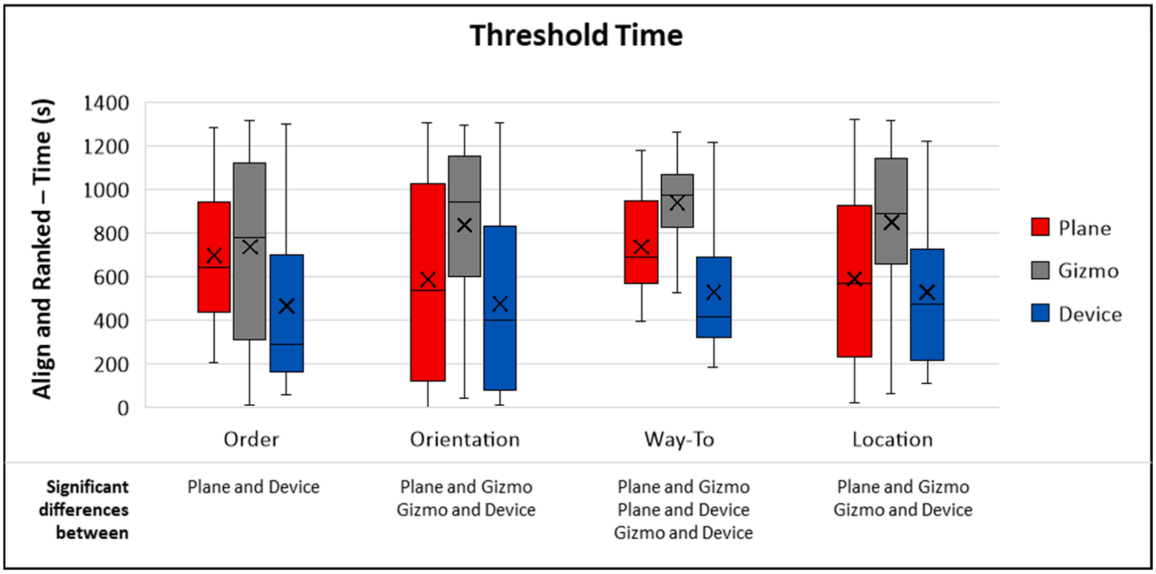

Fig. 5. Estimated marginal means of the threshold time.

techniques ($p < 0.001$). Specifically, in the *Order* task, there was a significant difference between the *Device* and *Plane* interactions and between the *Device* and *Gizmo* interactions. For the *Orientation* task, significant differences were observed between the *Plane* and *Gizmo* interactions and between the *Gizmo* and *Device* interactions. Significant differences were found between all three interaction techniques in the Way-To task. For the *Location* task, significant differences were identified between the *Plane* and *Gizmo* interactions and between the *Gizmo* and *Device* interactions.

We also found significant simple main effects for the AR interaction techniques *Plane* ($p = 0.005$) and *Gizmo* ($p < 0.008$) in reaching the threshold time between tasks in the first evaluated trial. When using the *Plane* interaction, significant differences were observed between the tasks *Order* and *Location*, *Orientation* and *Way-To*, and *Way-To* and *Location*. For the *Gizmo* interaction, significant differences were found between the tasks *Order* and *Way-To*, *Orientation* and *Way-To*, and *Way-To* and *Location*. In the second evaluated trial, the same simple main effects were observed as in the first evaluated trial.

4.1.2. *Distance Error*

Fig. 6 shows the estimated marginal means of the distance error for the three interaction techniques across the three tasks between the first and second evaluated trials. We found a significant main effect for the variables *Interaction* and *Time*. Additionally, there was a significant three-way interaction for *Task x Interaction x Time* ($F(4216) = 12.21$, $p < 0.001$). Significant two-way interactions were identified for *Interaction x Time* in the *Order* task ($F(2108) = 6.78$, $p = 0.005$), the *Orientation* task ($F(2108) = 14.05$, $p < 0.001$), and the *Location* task ($F(2108) = 10.16$, $p < 0.001$).

In the *Order* task, a significant simple main effect was found for the distance error across all AR interaction techniques between the first and second evaluated trials (*Plane* $p < 0.001$, *Gizmo* $p = 0.048$, *Device* $p = 0.003$). In the *Orientation* task, significant simple main effects were observed for the distance error with the *Plane* ($p < 0.001$) and *Gizmo* ($p < 0.001$) interactions between the first and second evaluated trials. In the *Location* task, significant simple main effects were also found for the distance error with the *Plane* ($p = 0.014$) and *Gizmo* ($p = 0.005$) interactions between the first and second evaluated trials.

Fig. 7 shows the estimated marginal means of the distance error for the three interaction techniques across the three tasks during the first evaluated trial. We identified significant two-way interactions for *Task x Interaction* in both the first evaluated trial ($F(4216) = 8.69$, $p < 0.001$) and the second evaluated trial ($F(4216) = 2.87$, $p = 0.038$). In the first evaluated trial, there was a significant simple main effect for all tasks regarding distance error between the AR interaction techniques ($p < 0.001$). In the *Order* task, significant differences were found between the *Plane* and *Gizmo* interactions and between the *Device* and *Gizmo* interactions. The same significant differences were observed in the *Orientation* task. Significant differences were identified between all AR interaction techniques in the *Location* task.

Additionally, we found a significant simple main effect for the *Plane* ($p = 0.001$) and *Gizmo* ($p < 0.001$) interaction techniques regarding distance error across tasks in the first evaluated trial. Significant differences were observed between all tasks when using the Plane or Gizmo interactions.

4.1.3. *Rotation Error*

Fig. 8 shows the estimated marginal means of the rotation error for the three interaction techniques across the three tasks between the first and second evaluated trials. We found a significant main effect for the variables *Task* and *Time*. Additionally, we observed a significant three-way interaction for *Task x Interaction x Time* ($F(4216) = 7.23$, $p < 0.001$). Significant two-way interactions were identified for *Interaction x Time* in the *Orientation* task ($F(2108) = 6.97$, $p = 0.006$) and the *Location* task ($F(2108) = 4.74$, $p = 0.025$).

In the *Orientation* task, we found a significant simple main effect for rotation error with the *Gizmo* ($p = 0.002$) and *Device* ($p = 0.028$) interactions between the first and second evaluated trials. In the *Location* task, a significant simple main effect was observed for the rotation error with the *Device* interaction ($p < 0.001$) between the first and second evaluated trials.

Fig. 9 shows the estimated marginal means of the rotation error for the three interaction techniques across the three tasks. We identified significant two-way interactions for *Task x Interaction* in both the first evaluated trial ($F(4216) = 8.23$, $p < 0.001$) and the second evaluated trial ($F(4216) = 3.78$, $p = 0.018$). In the first evaluated trial, we found a significant simple main effect for the *Order* ($p < 0.001$) and *Orientation* ($p = 0.037$) tasks regarding rotation error between the AR interaction techniques. In the *Order* task, significant differences were observed between the *Plane* and *Gizmo* interactions and between the *Device* and

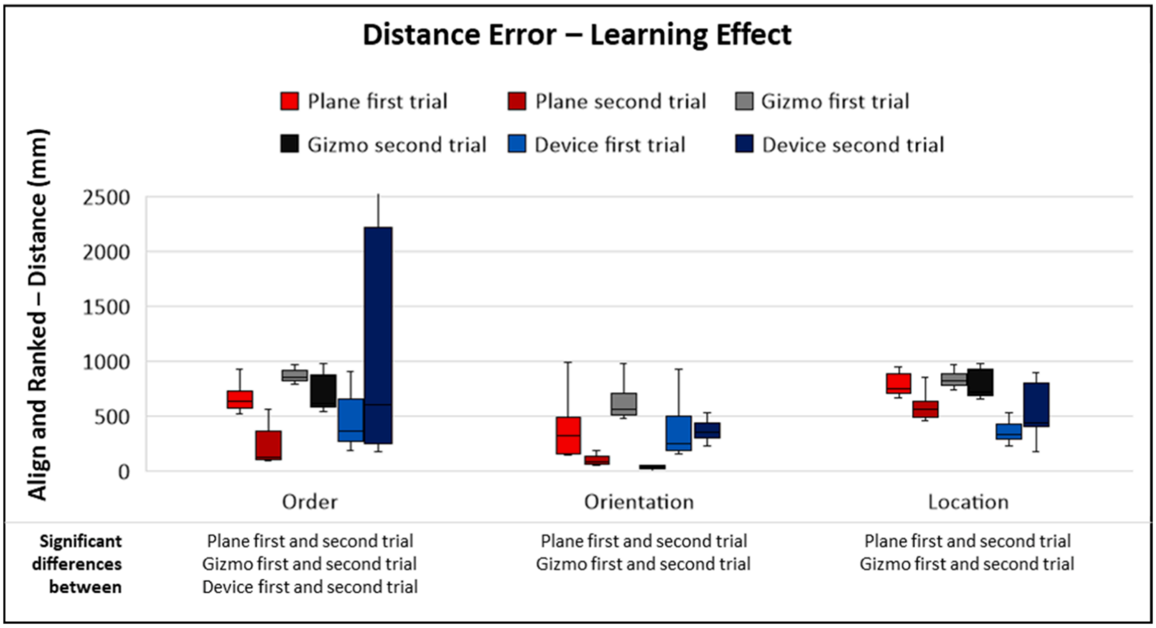

Fig. 6. Estimated marginal means of the distance error between the first and second evaluated trail.

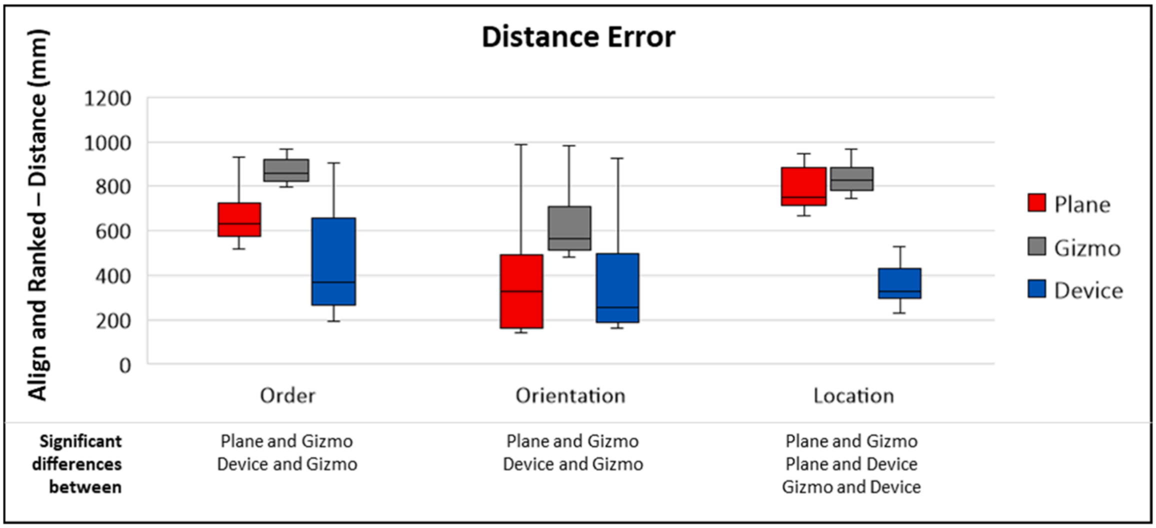

Fig. 7. Estimated marginal means of the distance error.

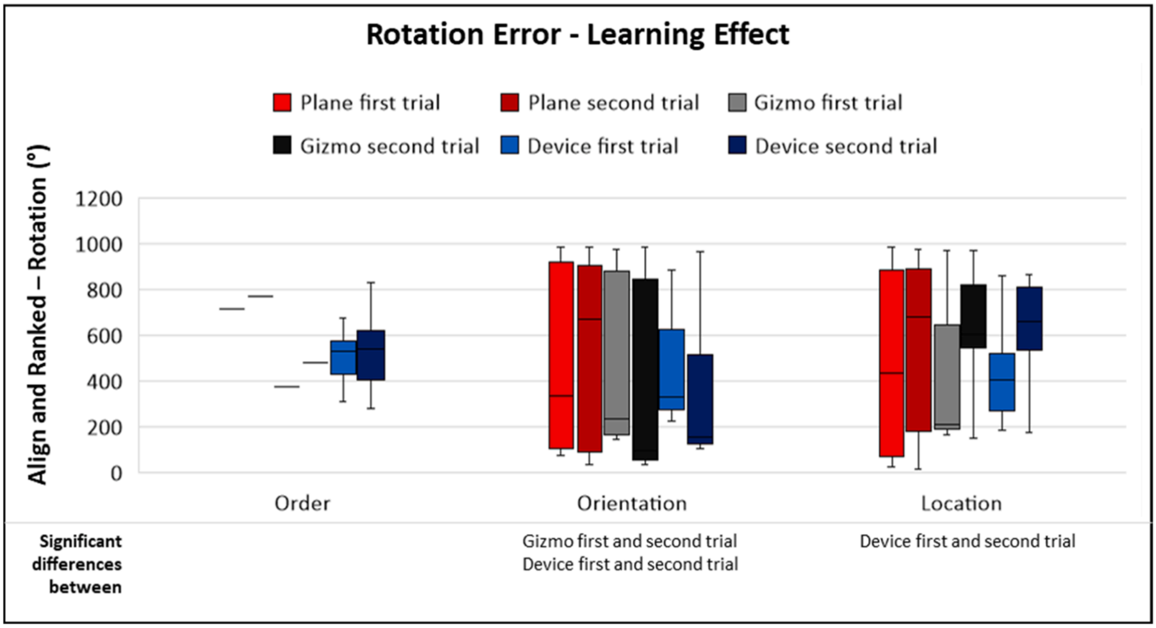

Fig. 8. Estimated marginal means of the rotation error between the first and second evaluated trail.

Gizmo interactions. The same significant differences were found in the *Orientation* task.

Additionally, we found a significant simple main effect for the *Plane* ($p = 0.001$) and *Gizmo* ($p = 0.016$) interaction techniques regarding rotation error across tasks in the first evaluated trial. When using the *Plane* interaction, significant differences were observed between the *Order* and *Orientation* tasks and between the *Order* and *Location* tasks. Similar significant differences were found when using the *Gizmo* interaction.

4.1.4. *Path Error*

Since path error was only measured in one task (Way-To), we conducted a two-way repeated measures ANOVA after aligning and ranking the data. We then applied Bonferroni post-hoc tests for pairwise comparisons to identify significant differences between the AR interaction techniques. Fig. 10 shows the mean values of the path error for the three interaction techniques in the Way-To task. We found a significant main effect of Time ($F(1,54) = 13.91$, $p < 0.001$) on path error. The post-hoc analysis revealed a significant difference in path error between the first and second evaluated trials, as well as a significant difference between the *Gizmo* and *Device* interactions.

4.2. *Workload and Satisfaction*

Based on the participants' workload and satisfaction ratings when using the different AR interaction techniques—measured on a seven-point Likert scale for satisfaction and a ten-point survey scale for workload—we conducted an ANOVA to compare the main effects of the AR interaction techniques. We then applied Bonferroni post-hoc tests for pairwise comparisons to identify significant differences between the AR interaction techniques.

4.2.1. *Workload*

Fig. 11 shows the mean perceived workload of the three AR interaction techniques. We found a significant main effect of the AR interaction techniques on mental demand ($F(2162) = 10.19$, $p < 0.001$),

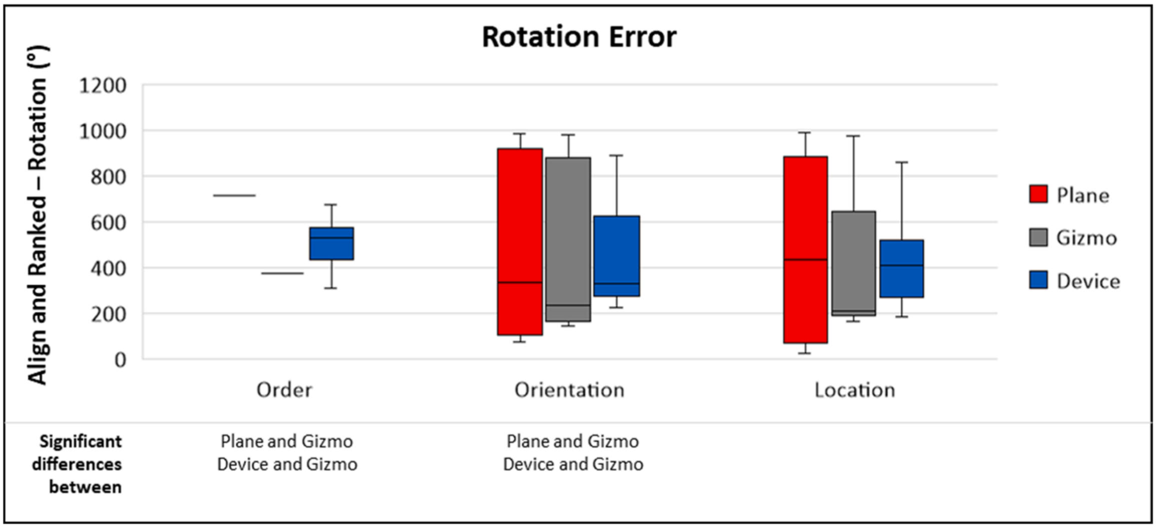

Fig. 9. Estimated marginal means of the rotation error.

Fig. 10. Mean values of the path error.

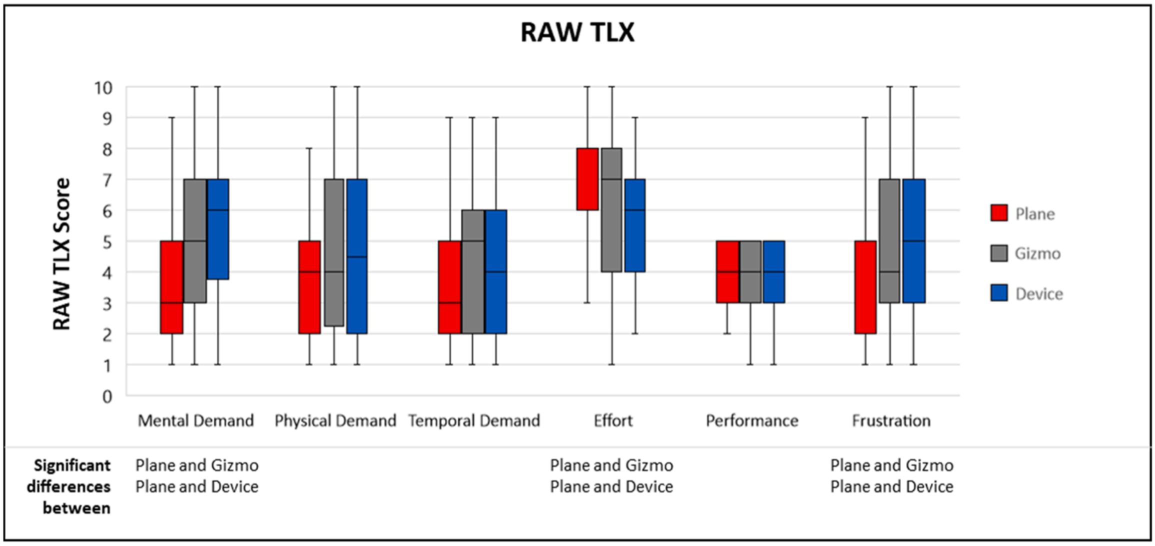

Fig. 11. Workload grouped by the AR interaction techniques.

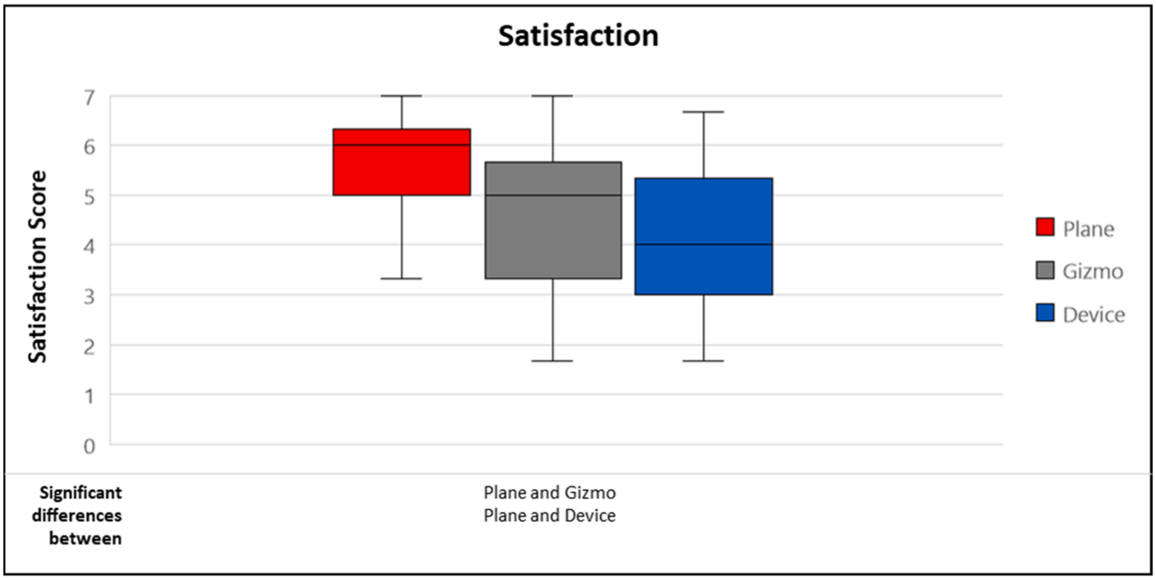

Fig. 12. Satisfaction grouped by the AR interaction techniques.

Table 3
Summary of the SWOT Analysis Regarding the Plane Interaction.

Plane				
Helpful		**Harmful**		
Familiar Interaction	*"[…] with the touch control it is reasonably intuitive […] especially the control with one or two fingers is very familiar […]"*	Difficulties with the rotation of the AR objects	*"The rotation has caused me problems. I haven't quite figured out which gestures to use to initiate which axis rotation. […]"*	**Internal origins**
Fast translation of the AR Objects	*„I found it very good for the translation and also much faster. You only had to position the object below the position and then move it up […]"*	Inaccuracy of the rotation of AR objects	*"The rotation has caused me problems. I have not found out with which gestures I initiate which rotation, […]. "*	
Suitable for occluded interactions	*"I found it worked well in the last task because the shadow (plane) was displayed below the object, and I, therefore, knew whether the position was roughly correct."*	Unsuitable for small AR objects	*"[…] If you click on the object to move it, you can no longer see the object, and then it feels more like a matter of luck whether it does what it is supposed to do."*	**External origins**
Suitable for placing AR objects on a flat surface (4 DOF)	*"[…] to create a navigation in 2D. So a path can be created for the technicians to show where the container door is so they can position themselves correctly."*	Initiating a rotation requires two fingers, which increases fatigue.	*"There is a risk of fatigue and thus the risk of dropping the tablet, as you can only hold it in one hand, as the interaction requires two fingers."*	

effort (F(2162) = 11.32, $p < 0.001$), and frustration (F(2162) = 8.68, $p < 0.001$). The post hoc analysis revealed that the mental demand of using the *Plane* interaction technique was significantly lower than that of *Gizmo* (t(162) = −1.56, p = 0.001) and *Device* (t(162) = −1.82, p = 0.001). It also showed that the effort required for using *Plane* was significantly higher than for *Gizmo* (t(162) = 1.36, p = 0.001) and *Device* (t(162) = 1.67, $p < 0.001$). Additionally, the frustration associated with using *Plane* was significantly lower than that of *Gizmo* (t(162) = −1.40, p = 0.009) and *Device* (t(162) = −1.86, $p < 0.001$). No significant differences were identified between the *Gizmo* and *Device* interaction techniques.

4.2.2. Satisfaction

Fig. 12 shows the mean perceived satisfaction with the three AR interaction techniques. We found a significant main effect of the AR interaction techniques on satisfaction (F(2162) = 14.75, $p < 0.001$). The post hoc analysis revealed that the *Plane* interaction technique resulted in significantly higher user satisfaction compared to both *Gizmo* (t(162) = 0.96, $p < 0.001$) and *Device* (t(162) = 1.33, $p < 0.001$).

4.3. Qualitative Results

The objective of the semi-structured interviews was to evaluate the utility of different AR interaction techniques for the task types used to translate technical documentation into AR instructions. We employed a deductive approach to analyze the rich interview data (Sarker et al. 2013). Participants' opinions on the various AR interaction techniques were coded using open coding, with short descriptive statements summarizing the core idea of each text passage (Wiesche et al. 2017). We then analyzed the codes using the framework of SWOT analysis. SWOT analysis is a widely recognized method for systematic thinking and thorough assessment of factors related to new products, technologies, management, or planning (Weihrich, 1982). The following SWOT analyses summarize the most frequently mentioned strengths, weaknesses, opportunities, and threats of the different AR interaction techniques. The *Plane* interaction technique was found to be the most familiar to users, though it presented the greatest challenge when initiating 3D rotation. Table 3 provides a summary of the SWOT analysis for the *Plane* AR interaction technique.

The *Gizmo* interaction technique was found to be the least intuitive, but after a brief adjustment period, it led to the greatest learning effect among the participants. Table 4 provides a summary of the SWOT analysis for the *Gizmo* AR interaction technique.

The *Device* AR interaction technique offers the most natural interaction, as AR elements can be positioned through the user's physical movement. However, this also presents the greatest challenge in achieving precise placement. Table 5 provides a summary of the SWOT analysis for the *Device* AR interaction technique.

Table 4
Summary of the SWOT Analysis Regarding the Gizmo Interaction.

Gizmo				
Helpful		**Harmful**		
Precise placement of the AR objects	*"[…] I found it very good that the translation and the rotation are separated from each other, so I can customize exactly the axes I need."*	Difficult interaction due to limited space on mobile devices	*"I found the arrows too small. They were very difficult to grasp. You always had to turn the tablet in the right direction so that you could only see the arrow that you wanted to select […]."*	**Internal origins**
		Time-consuming	*"Since you have to adjust each axle individually, it takes a very long time."*	
Suitable for technical constructions due to high precision and reliability	*"Rather in the area of construction to represent the position between objects. The focus here is not on movement but rather on the final position, so I would say construction rather than maintenance or assembly […]"*	Unsuitable for creating animations	*"[…] because it is less about the movement, such as when you install or remove a part, and more about the final positioning."*	**External origins**
Suitable for occluded interactions since the gizmos are a great visual aid.	*"With the arrows, you can imagine exactly in which direction the object can be moved."*			

Table 5
Summary of the SWOT Analysis Regarding the Device Interaction.

Device				
Helpful		**Harmful**		
Intuitive and natural interaction	*"[…] the strength is that I have control over it, that it does exactly what I want it to do because I can move it in a 3D environment, and I'm not locked into the screen […]"*	Difficulties with the precise positioning of the AR objects	*"Only all axes can be manipulated at the same time. If I want to move the object just a little bit to the left, then I move all axes, and then there is a chance that it will be positioned worse than before."*	**Internal origins**
Fast positioning of the AR objects	*"[…] due to the fact that I could do both the translation and the rotation at the same time through this interaction, this interaction was much faster […]."*			
Suitable for creating Animations	*"[…] especially for the task of moving the object along the blue line, the interaction seems very suitable."*	Unsuitable for occluded interactions	*"[…] if the elements are placed in another object […] then there is no visual display that indicates whether the object is currently aligned."*	**External origins**
Suitable to move the AR objects over large areas	*"You could use this in a large room if you want to move large components […] this is much easier."*	Unsuitable for positioning 2D elements	*"The positioning of 2D objects did not work well. I found it difficult to position the 2D objects on the same layer as indicated."*	
		The interaction takes up a lot of space, and people can get hurt	*"You only look at the tablet and concentrate on the exact positioning, which means I don't really notice the surroundings, and there's a risk of bumping my head or similar."*	

4.4. Design Guidelines

Our experiment demonstrated the performance, workload, and satisfaction trade-offs across a series of tasks involved in creating AR instructions. In subsequent interviews, we identified the strengths, weaknesses, opportunities, and risks associated with different AR interaction techniques. Below, we consolidate our quantitative and qualitative findings into design guidelines to support the development of future AR instructions and AR authoring tools.

- **When focusing on time when creating the AR application, implement a device-based interaction.** By using device-based interaction, the AR objects can be positioned significantly faster in almost any task without a significant loss in positional accuracy in the physical environment.
- **When focusing on precision when creating the AR application, implement a gizmo-based interaction.** By using a gizmo-based interaction, AR objects can be positioned with the smallest rotation error in the physical environment by taking more time, as users can adjust each translation and rotation axis individually without affecting the other axes.
- **When creating an AR application with only 3DOF manipulation (i.e., 2 DOF translation and 1DOF rotation), implement a plane-based interaction.** The use of plane-based interaction provides a familiar interaction with the least effort and the highest satisfaction. Implementing full 3D manipulation (6DOF) causes the AR elements to be placed with a significantly larger rotation error due to an illusion of control.
- **When creating an AR application with many occluded objects, implement a gizmo-based interaction.** By using the gizmo-based interaction, the gizmos, which are always visible, provide a visual aid that indicates the orientation of the AR objects to the users.
- **When creating an AR application over a large area, implement a device-based interaction.** By using device-based interaction, users can manipulate all translation and rotation axes simultaneously, making moving AR objects over long distances easier and faster.
- **When creating an AR application with many animations, implement a device-based interaction.** By using device-based interaction, users can manipulate all translation and rotation axes simultaneously, allowing them to create animations faster and more naturally.
- **Avoid using 2D objects anchored to the physical environment in AR instructions.** The 2D objects are manipulated using a 3D interaction technique, which resulted in the 2D objects behaving differently than users expected.
- **Avoid using occluded interactions in AR instructions.** The orientation and exact position of the AR objects to be manipulated are no longer visible to the user. Users are dependent on visual cues, as with gizmo-based interaction.

5. Discussion

Our findings can potentially enhance AR utilization in the industry by revealing previously unexplored aspects of AR authoring tools. We evaluated the performance of three AR interaction techniques relevant to practical applications. We highlighted the importance of assessing these techniques within AR authoring tools that belong to the second cluster, specifically tailored to the intended application domain. In our case, this domain is the manufacturing industry in the service sector, particularly for creating AR instructions. Our study produced performance results that differ somewhat from those in the existing literature, which often assessed AR interaction techniques without considering specific application domains. These findings have theoretical and practical implications for companies as they adopt or design future AR authoring tools, whether for creating AR instructions or

5.1. *Theoretical Implications*

First, we contribute to understanding users' performance, perceived workload, and satisfaction when using different AR interactions for industrial applications, specifically in positioning AR elements within the physical environment. Recent studies indicate that time is one of the most critical factors in the adoption of new technology in the service sector (Allmendinger and Lombreglia, 2005; Kundu and Ramdas, 2022). In this regard, the *device-based* technique appears to be the most suitable for creating AR instructions—our chosen application domain—since it enables participants to position AR elements significantly faster across almost any task.

Second, the performance of AR interaction techniques has traditionally been evaluated using general threshold tasks (Bergström et al. 2021). However, an analysis of 60 AR authoring tools from both practice and research shows that tools in the second cluster—those that enable the creation of AR applications without programming knowledge—are typically designed for a specific application domain. Therefore, we propose evaluating the AR interaction techniques used in these second-cluster AR authoring tools with respect to their intended application domain. Our study provides initial evidence supporting this proposal, as we found performance results that differ from existing studies that did not consider the application domain. Consistent with the literature, our results show that across all tasks, participants were the fastest at placing AR elements using the *device-based* technique (Grandi et al. 2018; Marzo et al. 2014; Mossel et al. 2013). However, contrary to previous studies, our findings do not indicate that AR elements placed with touch-based interactions (*Plane* and *Gizmo*) are significantly more precise (in terms of distance error and rotation error) than those placed with the device-based interaction (Grandi et al. 2018; Marzo et al. 2014; Mossel et al. 2013). Additionally, while traditional threshold tasks only compare the final positions of AR elements, AR instructions often involve dynamic AR elements, such as animations (Gattullo et al. 2020; Hoffmann et al. 2021). Our results demonstrated that the *device-based* technique also achieved the lowest path deviation in such tasks.

5.2. *Practical Implications*

Third, it is notable that the *Orientation* task appeared to be the easiest for participants, who demonstrated the greatest accuracy in positioning AR elements (in terms of distance and rotation error) using most of the AR interaction techniques. These findings have important implications for the future design of AR instructions. For example, the results indicate that positioning 2D elements (*Order* task) using various AR interaction techniques was more challenging for participants than positioning 3D elements (*Orientation* task). As a result, we recommend that future AR instructions use 3D texts to visualize the assembly sequence (*Order* task) and, if possible, avoid occluded interactions (*Location* task). Additionally, our results show that the workload for touch-based interactions is lower than for device-based interactions, and touch-based interactions generate higher satisfaction levels among participants. This effect is likely due to participants' familiarity with touch-based interactions, whereas device-based interaction represents a new form of interaction for them (Beer and Mulder, 2020). Therefore, when incorporating device-based interactions into AR authoring tools, we suggest implementing a short tutorial to ease users' initial experience with this new form of interaction.

Finally, our results contribute to overcoming the barriers to adopting and using AR authoring tools in the industry. Our study provides concrete design guidelines for future AR authoring tools, particularly for creating AR instructions. Moreover, the qualitative results extend beyond this specific application domain, addressing one of the most challenging aspects of designing AR applications: the physical design of immersive experiences (Ashtari et al. 2020). Additionally, our research helps dispel misconceptions about AR hardware, particularly the tendency to overestimate hardware and software performance while overlooking hardware-specific limitations (Krauß et al. 2021). For instance, several participants expected to be able to place AR content in the physical environment with millimeter precision and persistence without additional hardware. Others assumed that complete 3D translation and rotation on a 2D display would be intuitive, given their daily use of mobile devices (Langer, 1975). However, this is not the case, as such interactions represent a new skill that most users must learn.

5.3. *Limitations and Future Research*

Although our lab experiment adhered to established guidelines, some potential limitations warrant further research. First, a virtual 3D model was used as the basis for the tasks in the lab experiment, replacing the physical model on which AR instructions would typically be created. The use of a physical model may impact task processing, potentially leading to different results. Second, the selected tasks in the lab experiment, reflecting the four information types proposed by Gattullo et al. (2020), may differ from the real tasks encountered in developing AR instructions. However, we believe the chosen tasks have significant practical relevance and can be generalized to various industrial operations. Third, participants used the AR interaction techniques for only a limited period. Over several hours, the prolonged use of AR interaction techniques in everyday work could yield different results, as factors such as fatigue might significantly influence performance. A long-term study conducted in a manufacturing company could provide valuable new insights. Finally, we administered the cognitive workload and satisfaction survey after the short interviews, which may have affected the accuracy of the measurements.

Although our study has shown that device-based interaction is well suited to convey traditional technical documentation into AR instructions, some open questions allow different research directions. First, our results are based on the largest handheld device known to us, a tablet. It remains unclear how display size might affect the performance of different 3D object manipulation techniques and tasks. Additionally, as the development of wearable devices such as HMDs becomes increasingly important, the question of which 3D object manipulation techniques are best suited for this hardware is raised. In evaluating the different manipulation techniques, we used a threshold-based approach where the final position of the 3D object was visually displayed to the user. In the actual development of AR instructions, novice users independently decide where to anchor the 3D objects in the real environment, making their own decisions about translations and rotations. Assessing novice users during the development of an AR technical guide could provide valuable insights into how they prefer to interact with the authoring tool.

6. Conclusion

In this paper, we compare three AR interaction techniques across four tasks relevant to AR instruction development, demonstrating the performance, workload, and satisfaction trade-offs associated with using these techniques to position AR elements in the physical environment. The tasks in our study design were derived from AR instruction literature, and the three AR interaction techniques represent those frequently mentioned and used in both science and practice. Our results show that participants were able to place AR elements the fastest across all tasks using the *device-based* interaction technique, which is particularly relevant for our chosen application domain, the service sector. Additionally, our findings indicate that participants experienced the lowest workload and highest satisfaction with the touch-based Plane interaction technique when placing 3D elements in specified positions in the physical environment, likely due to familiarity with this interaction technique. Our results also offer valuable insights for the future design of AR instructions by identifying tasks that participants found particularly challenging, such as occluded interactions in the Location task or positioning 2D objects as in the Order task. Our design guidelines provide direction for researchers and practitioners in designing and implementing AR interaction techniques for their specific application domains and in the future development of AR instructions.

CRediT authorship contribution statement

Björn Konopka: Writing – review & editing, Methodology, Investigation, Conceptualization. **Kay Hönemann:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Michael Prilla:** Writing – review & editing, Methodology. **Manuel Wiesche:** Writing – review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kay Hoenemann reports financial support was provided by German Federal Ministry for Education and Research in the project WizARd under reference 02K18D180. Bjoern Konopka reports financial support was provided by German Federal Ministry for Education and Research in the project WizARd under reference 02K18D180. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

References

Allmendinger, G., Lombreglia, R., 2005. Four strategies for the age of smart services. Harv. Bus. Rev. 83 (10), 131–145.

Apple. 2024. "Use the Measure app on your iPhone, iPad, or iPod touch," available at ⟨https://support.apple.com/en-us/102468⟩, accessed on Apr 8 2024.

Ashtari, N., Bunt, A., McGrenere, J., Nebeling, M., Chilana, P.K., 2020. Creating augmented and virtual reality applications: current practices, challenges, and opportunities. CHI Conf. Hum. Factors Comput. Syst. 1–13.

Azuma, R.T., 1997. A survey of augmented reality. Presence. Teleoperators Virtual Environ. 6 (4), 355–385.

Azuma, R.T., 2016. The most important challenge facing augmented reality. Presence.: Teleoperators Virtual Environ. 25 (3), 234–238.

Beer, P., Mulder, R.H., 2020. The effects of technological developments on work and their implications for continuous vocational education and training: a systematic review. Front. Psychol. (11), 918.

Bergström, J., Dalsgaard, T.S., Alexander, J., Hornbæk, K., 2021. How to evaluate object selection and manipulation in VR? Guidelines from 20 years of studies. 2021 CHI Conf. Hum. Factors Comput. Syst. 1–20.

Bräker, J., Hertel, J., and and Semmann, M. 2023. "Empowering Users to Create Augmented Reality-Based Solutions – Deriving Design Principles for No-Code AR Authoring Tools," in *44th International Conference on Information Systems (ICIS)*.

Buchholz, F., Oppermann, L., Prinz, W., 2022. There's more than one metaverse. i-Com. 21 (3), 313–324.

Carmigniani, J., Furht, B., Anisetti, M., Ceravolo, P., Damiani, E., Ivkovic, M., 2011. Augmented reality technologies, systems and applications. Multimed. Tools Appl. 51 (1), 341–377.

Chen, H., Chen, C., Sun, G., and Wan, B. 2019. Augmented reality tracking registration and process visualization method for large spacecraft cable assembly," *in 6th International Conference on Advanced Composite Materials and Manufacturing.*

Cohen, L., Duboé, P., Buvat, J., Melton, D., Khadikar, A., and Shah, H. 2018. "Augmented and Virtual Reality in Operations: A guide for investment," available at ⟨https://www.capgemini.com/in-en/wp-content/uploads/sites/18/2022/05/AR-VR-in-Operations1-4.pdf⟩, accessed on Apr 24 2024.

Damarowsky, J., Kühnel, S., 2022. Conceptualization and design of a workflow management system front end for augmented reality headsets. 30th Eur. Conf. Inf. Syst.

Dolata, M., Schwabe, G., 2023. What is the Metaverse and who seeks to define it? Mapping the site of social construction. J. Inf. Technol. 38 (3), 239–266.

Drey, T., Montag, M., Vogt, A., Rixen, N., Seufert, T., Zander, S., Rietzler, M., Rukzio, E., 2023. Investigating the effects of individual spatial abilities on virtual reality object manipulation. *2023 CHI Conf. Hum. Factors Comput. Syst.* 1–24.

Elshan, E., Ebel, P., Söllner, M., Leimeister, J.M., 2023. Leveraging Low Code Development of Smart Personal Assistants: An Integrated Design Approach with the SPADE Method. J. Manag. Inf. Syst. 40 (1), 96–129.

Fortuna, S., Barbieri, L., Marino, E., Bruno, F., 2024. A comparative study of Augmented Reality rendering techniques for industrial assembly inspection. Comput. Ind. (155), 104057

Gattullo, M., Dammacco, L., Ruospo, F., Evangelista, A., Fiorentino, M., Schmitt, J., Uva, A.E., 2020. "Design preferences on Industrial Augmented Reality: a survey with potential technical writers,". IEEE Int. Symp. . Mixed Augment. Real. Adjun. (ISMAR-Adjun.) 172–177.

Geng, J., Song, X., Pan, Y., Tang, J., Liu, Y., Zhao, D., Ma, Y., 2020. A systematic design method of adaptive augmented reality work instruction for complex industrial operations. Comput. Ind. 119 (103229).

Goh, E.S., Sunar, M.S., Ismail, A.W., 2019. 3D object manipulation techniques in handheld mobile augmented reality interface: a review. IEEE Access (7), 40581–40601.

Grandi, J.G., Debarba, H.G., Bemdt, I., Nedel, L., Maciel, A., 2018. Design and assessment of a collaborative 3D interaction technique for handheld augmented reality. IEEE Conf. Virtual Real. 3D Use Interfaces 49–56.

Hart, S.G., 2006. Nasa-Task Load Index (NASA-TLX); 20 years later. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 50 (9), 904–908.

Henderson, S., Feiner, S., 2011. Exploring the benefits of augmented reality documentation for maintenance and repair. IEEE Transactions on Visualization and Computer Graphics 17 (10), 1355–1368.

Hertel, J., Karaosmanoglu, S., Schmidt, S., Braker, J., Semmann, M., Steinicke, F., 2021. A taxonomy of interaction techniques for immersive augmented reality based on an iterative literature review. 2021 IEEE Int. Symp. Mixed Augment. Real. 431–440.

Hoffmann, C., Büttner, S., Prilla, M., Wundram, K., 2020. Impact of augmented reality guidance for car repairs on novice users of AR. In: Preim, B., Nürnberger, A., Hansen, C. (Eds.), in Proceedings of the Conference on Mensch und Computer, pp. 279–289.

Hoffmann, C., Prilla, M., Wundram, K., Emmermann, B., 2021. Augmented reality guidance for car repairs: immediate and long-term effects. *Mensch und Comput. 2021* 110–119.

Hönemann, K., Konopka, B., Wiesche, M., 2024. The importance of separation in the creation and usage phases of augmented reality content using social cognitive theory. *57th Hawaii Int. Conf. Syst. Sci.*

IKEA. 2017. "IKEA Place app launched to help people virtually place furniture at home," available at ⟨https://www.ikea.com/global/en/newsroom/innovation/ikea-launches-ikea-place-a-new-app-that-allows-people-to-virtually-place-furniture-in-their-home-170912/⟩, accessed on Apr 8 2024.

Klinker, K., Berkemeier, L., Zobel, B., Wüller, H., Huck-Fries, V., Wiesche, M., Remmers, H., Thomas, O., and Krcmar, H. 2018. "Structure for innovations: A use case taxonomy for smart glasses in service processes," in *Multikonferenz Wirtschaftsinformatik*.

Konopka, B., Hönemann, K., Wiesche, M., 2024. Investigation of key barriers regarding adoption and implementation of augmented reality in industrial organizations: a delphi study. *57th Hawaii Int. Conf. Syst. Sci.*

Konopka, B., Hönemann, K., Brandt, P., Wiesche, M., 2022. WizARd: a no-code tool for business process guidance through the use of augmented reality. Demonstr. Resour. Track, Best. BPM Diss. Award, Dr. Consort. BPM 2022 Co. -located 20th Int. Conf. Bus. Process Manag.

Kortekamp, S.S., Werning, S., Ickerott, I., Thomas, O., 2019. The future of digital work - Use cases for augmented reality glasses. 27th Eur. Conf. Inf. Syst.

Krauß, V., Boden, A., Oppermann, L., Reiners, R., 2021. Current practices, challenges, and design implications for collaborative AR/VR application development. CHI Conf. Hum. Factors Comput. Syst. 1–15.

Krenzer, A., Stein, N., Griebel, M., Flath, C., 2019. Augmented intelligence for quality control of manual assembly processes using industrial wearable systems. 40th Int. Conf. Inf. Syst.

Kundu, A., Ramdas, K., 2022. Timely after-sales service and technology adoption: evidence from the off-grid solar market in Uganda. Manuf. Serv. Oper. Manag. 24 (3), 1329–1348.

Langer, E.J., 1975. The illusion of control. J. Personal. Soc. Psychol. 32 (2), 311–328.

Laviola, E., Gattullo, M., Manghisi, V.M., Fiorentino, M., Uva, A.E., 2022. Minimal AR: visual asset optimization for the authoring of augmented reality work instructions in manufacturing. Int. J., Adv. Manuf. Technol. 119 (3-4), 1769–1784.

Lavric, T., Bricard, E., Preda, M., Zaharia, T., 2022. ATOFIS, an AR training system for manual assembly: a full comparative evaluation against guides. IEEE Int. Symp. . Mixed Augment. Real. 558–567.

Liu, J., Au, O.K.-C., Fu, H., Tai, C.-L., 2012. Two-finger gestures for 6DOF manipulation of 3D objects. Comput. Graph. Forum 31 (7), 2047–2055.

Liu, Y., Shen, Y., Chan, H., Lu, Y., Wang, D., 2015. Touching the future: the effects of gesturebased interaction on virtual product experience. Int. Conf. Inf. Syst.

Martinet, A., Casiez, G., Grisoni, L., 2010. The design and evaluation of 3D positioning techniques for multi-touch displays. IEEE Symp. . 3D Use Interfaces 115–118.

Marzo, A., Bossavit, B., Hachet, M., 2014. Combining multi-touch input and device movement for 3D manipulations in mobile augmented reality environments. in *2nd ACM symposium on Spatial user interaction*. ACM, pp. 13–16.

Matook, S., Wang, Y.M., Koeppel, N., Guerin, S., 2023. Metacognitive skills in low-code app development: Work-integrated learning in information systems development. J. Inf. Technol. 39 (1), 41–70.

Mohr, P., Kerbl, B., Donoser, M., Schmalstieg, D., Kalkofen, D., 2015. Retargeting Technical Documentation to Augmented Reality. *CHI Conf. Hum. Factors Comput. Syst.*

Morana, S., Schacht, S., Scherp, A., Maedche, A., 2017. A review of the nature and effects of guidance design features. Decis. Support Syst. (97), 31–42.

Mossel, A., Venditti, B., Kaufmann, H., 2013. 3DTouch and HOMER-S. Virtual Real. Int. Conf.: Laval Virtual 1–10.

Nebeling, M., Nebeling, J., Yu, A., Rumble, R., 2018. ProtoAR: rapid physical-digital prototyping of mobile augmented reality applications. *CHI Conf. Hum. Factors Comput. Syst.* 1–12.

Nebeling, M., Speicher, M., 2018. The trouble with augmented reality/virtual reality authoring tools. *IEEE Int. Symp. . Mixed Augment. Real. Adjun.* 333–337.

Palmarini, R., Erkoyuncu, J.A., Roy, R., Torabmostaedi, H., 2018. A systematic review of augmented reality applications in maintenance. Robot. Comput. -Integr. Manuf. (49), 215–228.

Polvi, J., Taketomi, T., Yamamoto, G., Dey, A., Sandor, C., Kato, H., 2016. SlidAR: A 3D positioning method for SLAM-based handheld augmented reality. Comput. Graph. (55), 33–43.

Porter, M.E., Heppelmann, J., 2017. Why every organization needs an augmented reality strategy. Harv. Bus. Rev. (2017:ember-December), 1–13.

Rajaram, S., Nebeling, M., 2022. Paper Trail: An Immersive Authoring System for Augmented Reality Instructional Experiences. *CHI Conf. Hum. Factors Comput. Syst.* 1–16.

Samini, A., Palmerius, K.L., 2016. A study on improving close and distant device movement pose manipulation for handheld augmented reality. *22nd ACM Conf. Virtual Real. Softw. Technol.* 121–128.

Sarker, S., Xiao, X., Beaulieu, T., 2013. Qualitative studies in information systems: a critical review and some guiding principles. MIS Q. 37 (4), iii–xviii.

Scurati, G.W., Gattullo, M., Fiorentino, M., Ferrise, F., Bordegoni, M., Uva, A.E., 2018. Converting maintenance actions into standard symbols for Augmented Reality applications in Industry 4.0. Comput. Ind. (98), 68–79.

Serván, J., Mas, F., Menéndez, J.L., Ríos, J., 2011. Using augmented reality in AIRBUS A400M shop floor assembly work instructions. The 4th Manufacturing Engineering Society International Conference. AIP, pp. 633–640.

Snap A.R. 2024. “World Tracking Planes,” available at ⟨https://docs.snap.com/lens-studio/references/templates/world/world-tracking-planes#world-tracking-planes-api⟩, accessed on Apr 8 2024.

Tang, A., Owen, C., Biocca, F., Mou, W., 2003. Comparative effectiveness of augmented reality in object assembly. *SIGCHI Conf. Hum. Factors Comput. Syst.* 73–80.

Tanikawa, T., Uzuka, H., Narumi, T., Hirose, M., 2015. Integrated view-input ar interaction for virtual object manipulation using tablets and smartphones. *12th Int. Conf. Adv. Comput. Entertain. Technol.* 1–8.

Unity Technologies. 2024. “Gizmos menu,” available at ⟨https://docs.unity3d.com/Manual/GizmosMenu.html⟩, accessed on Apr 8 2024.

Unreal Engine. 2024. “Landscape Gizmos: Guide to the Gizmos available for modifying Landscapes.,” available at ⟨https://docs.unrealengine.com/4.26/en-US/BuildingWorlds/Landscape/Editing/Gizmos/⟩, accessed on Apr 8 2024.

Venkatesh, V., Thong, J.Y.L., Chan, F.K.Y., Hu, P.J.-H., Brown, S.A., 2011. Extending the two-stage information systems continuance model: incorporating UTAUT predictors and the role of context. Inf. Syst. J. 21 (6), 527–555.

Weihrich, H., 1982. The TOWS matrix—a tool for situational analysis. Long. Range Plan. 15 (2), 54–66.

Wiesche, M., Jurisch, M.C., Yetton, P.W., Krcmar, H., 2017. Grounded theory methodology in information systems research. MIS Q. 41 (3), 685–701.

Wilson, A.D., Izadi, S., Hilliges, O., Garcia-Mendoza, A., Kirk, D., 2008. Bringing physics to the surface. *21st Annu. ACM Symp. Use Interface Softw. Technol.* 67–76.

Wobbrock, J.O., Findlater, L., Gergle, D., Higgins, J.J., 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. *CHI Conf. Hum. Factors Comput. Syst.* 143–146.