

The minimal AR authoring approach: Validation in a real assembly scenario

Enricoandrea Laviola^{*}, Antonio Emmanuele Uva, Michele Gattullo

Department of Mechanics, Mathematics, and Management, Polytechnic Institute of Bari, via Orabona, 4, Bari 70125, Italy

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ABSTRACT

This work aims to validate the “minimal AR” authoring approach in a real industrial assembly scenario. It focuses on optimizing visual assets in Augmented Reality (AR) work instructions. The design of AR assembly documentation is influenced by three main variables: work instructions, affordance (dependent on equipment components and operator capabilities), and AR signifiers (combination of visual assets with their properties). In this study, we fixed the instruction complexity while exploring the relationship between affordance and AR signifiers. First, we set up a focus group of 10 experts in AR technical documentation to extract guidelines for the design of minimal AR signifiers for assembly instructions with a variable affordance. Then, we validated these guidelines through an industrial case study involving 34 participants in four assembly tasks. We verified if the candidate minimal AR signifier, obtained using the proposed guidelines, corresponded to the minimal AR signifier established by users. The results showed that in 33% of the cases, users exploited the candidate minimal AR signifier to accomplish the task successfully. Beyond the minimal AR signifier, an additional one conveying the notification about the task success must always be provided to ensure failure by those operators with reduced capabilities. We also found that, in 29% of the cases, users needed less information than the candidate minimal AR signifier due to their higher capabilities. However, as expected, this condition leads users to make more errors than with the candidate minimal AR signifier. Moreover, the study confirms that AR signifiers with redundant information or attractive appearance, such as animated product models, are unnecessary to improve task comprehension. Still, animations could be beneficial in reinforcing understanding when object properties are difficult to detect.

1. Introduction

Over the last twenty years, Augmented Reality (AR) has proven to be a promising technology in supporting industrial operators during the execution of assembly, disassembly, and maintenance tasks (Uva et al., 2018; van Lopik et al., 2020; Mourtzis et al., 2020). Georgel (Fite-Georgel, 2011) used the term Industrial Augmented Reality (IAR) to refer to the use of such technology in an industrial field. IAR enables augmenting the real world by adding referenced virtual information that can be used to understand industrial tasks better, improving workers' performance throughout the production chain (Masood and Egger, 2019; Zubizarreta et al., 2019). Nowadays, the benefits of such technology are well established, and its rapid technological advancement is prompting more and more companies to invest in AR. In addition, the emerging concept of the metaverse (Lee, 2021; Díaz et al., 2020) accelerates the transition of technologies such as AR to being used daily for various routine activities. However, although there are very strong intentions to adopt AR in the real industrial context, it is not yet widely

spread because of the complex industrial requirements to be met (Lorenz et al., 2018; Davila Delgado et al., 2020).

One of the major obstacles to spreading IAR concerns the authoring complexity. In fact, unlike traditional visualization methods, such as printed or electronic documentation, AR allows both to display procedural instructions directly on the real objects (Masood and Egger, 2019) and to provide elemental pieces of information through various visual assets (e.g., CAD models, drawings, videos) (Gattullo et al., 2022a). These advantages allow operators to reduce the cognitive load in understanding procedural instructions (Gattullo et al., 2019). However, defining which visual asset is more suitable for certain types of information is not a simple task as stated in (Gattullo et al., 2022a) in which an information model based on the decomposition of a work instruction is proposed. It requires careful instruction analysis by considering the motions involved in performing a task to reduce its complexity. However, even if the model allows to effectively decompose the instructions of a traditional documentation into elemental operations, without established guidelines, there is the risk of designing not optimized AR

^{*} Corresponding author.

E-mail address: enricoandrea.laviola@poliba.it (E. Laviola).

interfaces with an excessive authoring effort and reduced operators' performance. Unfortunately, because of the rapid growth of AR technology, companies lack high-level AR development professionals (Nebeling and Speicher, 2018; Tang et al., 2018, 2020). In addition, although there are many studies in the literature on the creation of visual assets for an industrial context (Reisinger et al., 2018; Kaipa et al., 2017; Blattgerste et al., 2019; Mourtzis et al., 2019), there is a lack of standardized guidelines to help provide optimized AR information (Rolim et al., 2015).

AR technical documentation designers should provide the proper amount of information to workers. However, they may receive incomplete or redundant information for the task to be performed. In a previous work (Laviola et al., 2022), we proposed the "minimal AR" authoring approach, which aims to provide AR work instructions with optimized visual assets (Lechner). It is based on Norman's definitions of affordance and signifier (Norman, 1988). Affordance is "the relationship between the properties of an object and the capabilities of the person that determine just how the object could possibly be used." Affordance then comes from a good object design that naturally communicates how to use it. In case of a low affordance, a secondary source of information is needed. Norman defined this source as "signifier" intended as "any mark or sound, any perceivable indicator that communicates appropriate behaviour to a person." Therefore, using the term "AR signifier" we refer to a combination of one or more visual assets that can transmit information. Each type of visual assets has the potential to convey varying amounts of information, influenced by their design properties (frame of reference, color coding, and animations). In the minimal AR approach, the virtual content that minimizes the gap between the information provided and that needed to understand the task is called "minimal AR signifier." Using AR signifiers with more information than the minimal one would not be useful for operators to understand the task but could increase the authoring effort. For example, using the CAD model of a component superimposed to the real one, to provide only the information about its location could be a disadvantageous design choice because this information can be provided through a simpler visual asset (e.g., an arrow) (Romano et al., 2023). Instead, AR signifiers with less information would lead to a performance reduction with potential errors because operators could misinterpret the instruction. However, defining a minimal AR signifier is not simple because, following the affordance definition, the minimal virtual content could differ not only depending on object properties but also on user capabilities regarding a given assembly scenario. Therefore, there is not a minimal AR signifier that works well for every context. Then, the final goal of our research is to provide the scientific community and companies with practical industrial case studies on how to design minimal AR signifiers in various assembly scenarios.

Considering our previous work (Laviola et al., 2022), the three main variables which affect the design of an AR assembly documentation are i) the assembly work instructions, which can contain a variable type and amount of information for operators; ii) the affordance, which depends on the relation between the components of the equipment involved in the assembly and the operator capabilities; iii) the AR signifiers, which can contain a combination of different visual assets whose properties can also be varied (e.g., animated/static). Given the complex relations among these three variables, we evaluated them separately by keeping one fixed and changing the other two. In our previous work (Laviola et al., 2022), we fixed the affordance and evaluated the relationship between AR signifiers and instruction complexity. We selected tasks with an increasing amount of information needed and proposed AR signifiers that provided an increasing amount of information, including the minimal AR signifier. The results supported the minimal AR approach. In fact, we found no increase in user performance (completion time, mental workload, and errors) by providing AR signifiers with more information than the minimal one.

In this work, we fixed the instruction complexity and explored the relationship between affordance and AR signifiers. Therefore, we

formulated the following research question: "Is it possible to provide guidelines for designing AR signifiers for assembly tasks with a variable affordance?". Affordance is difficult to evaluate and the only way to understand how it affects the design of AR signifiers is through the observation of real industrial case studies. The first contribution of this work is then a workflow useful to design a minimal AR signifier for assembly instructions with a variable affordance. The workflow was derived from guidelines proposed by a focus group of experts in the design of AR technical documentation who were instructed on the minimal AR approach. Thus, they provided guidelines on the design of minimal AR signifiers exploring different assembly scenarios with a variable affordance. Following these recommendations, we designed the minimal AR signifiers for complex assembly instructions of a real equipment. We chose as a case study a gas-fired radiant heating system used for the climatization of big industrial areas. This example of assembly procedure is representative of our target scenario because the tasks involved required the comprehension of all the elemental operations provided by work instructions. Then, a second contribution of this work is the validation of the proposed guidelines through a user study. The goal is to verify if the candidate minimal AR signifier obtained following the proposed guidelines corresponded to the minimal AR signifier established by users.

This paper is organized into 7 sections. Section 2 reports the related work on previous authoring approaches for the design of AR signifiers, while Section 3 describes the proposed guidelines for the design of minimal AR signifiers. In Section 4, the user study design is reported to validate our recommendations. Section 5 shows the results of the user study discussed in Section 6. Finally, in Section 7, a conclusion is provided with considerations about future works.

2. Related work

In the literature, choosing the most suitable virtual content according to the industrial task to be performed is a widespread challenge (Geng et al., 2020; Radkowski et al., 2015; Tainaka et al., 2020; MacAllister et al., 2017). Marques et al (Marques et al., 2022). stated that the AR signifier choice for each instruction is not properly evaluated before the AR application is effectively used in the industrial field. For this reason, many industrial AR applications require long development times and have scalability constraints (Chen et al., 2022).

Visual assets need to be easily understood and accepted by the operators; therefore, it is important to conduct in-depth studies on the properties that virtual content should have to convey information most effectively. In this regard, Gattullo et al (Gattullo et al., 2022a). conducted a comprehensive literature review on visual assets employed within industrial contexts. Their study introduced a classification system based on the content displayed, the visual asset properties (such as frame of reference, color coding, and animation), and the reasons behind their use (locating, operating, checking, and warning). Finally, their research revealed that product models emerged as the most used visual asset in these contexts. Even if a clear classification is provided, the literature lacks clear guidelines on choosing visual assets for authoring AR information in work instructions.

As a result, many works state that visual assets used to convey information are a choice that is solely up to technical writers. For instance, Li et al (Li et al., 2019). proposed a classification of visual assets based on the process information that needs to be expressed, providing recommendations that may leave space for multiple interpretations. Lavric et al (Lavric et al., 2022). support a low-cost authoring by avoiding the use of product models with an approach that associates a visual asset to each of the three basic questions in problem solving (what, where, and how). Both works propose an association between visual assets and tasks that is up to the technical writer without explaining the choices made.

Another viable solution is to leave the choice of the visual asset to both expert and novice operators. For example, Chu et al (Chu et al., 2020). compared two systems for assembling Dougong Chinese

structures, starting from technical considerations to overcome the limitations of paper-based instructions. Alves et al (Alves et al., 2021). proposed an AR system capable of generating virtual content by a detection algorithm that extracts 3D points. In both works, the final choice was left to the primary users. A similar study was conducted by Tainaka et al (Tainaka et al., 2020), who elaborated an information-presentation method by decomposing assembly tasks into subtasks proposing a list of candidate visual assets to be selected by users. However, these studies focused on defining an approach based on empirical observations that are difficult to scale in an industrial scenario.

Other works described AR systems able to recommend visual assets to be provided based on user capabilities. Wolfartsberger et al (Wolfartsberger et al., 2019). proposed a human-centered AR application that automatically adapts conveyed information distinguishing between beginners and experienced workers. Even in (Syberfeldt et al., 2016; Holm et al., 2017) a framework was described with the assumption that AR instructions should depend on operators' individual experience and skills. Therefore, an AR system with an increasing level and richness of information based on user capabilities was proposed. However, these works did not show a valid justification for the choice of visual assets used.

In the literature, there are also hybrid authoring approaches based both on user capabilities and preference. An example is provided by Geng et al (Geng et al., 2020), who developed an adaptive AR system to convey instruction for complex industrial operations. In its design workflow, the choice of visual assets was left to operators instead of developers or engineers, with the possibility of filtering information according to their own skills. A similar study was conducted by Scheffer et al (Scheffer et al., 2021). for maintenance operations in a railway industrial scenario. The goal was to support operators with tailored virtual content based on their competencies and preferences.

Another AR authoring approach relies on choosing visual assets according to task complexity. Stork and Schubö (Stork and Schubö, 2010) developed an assistive AR system analyzing human information processing. Their framework subdivides tasks into elementary operations associated with a pre-established visual asset. The choice depended on the type of information required to perform an elementary operation and on the task complexity. Even Yang et al (Yang et al., 2019). adopted this model, including commissioning and joining subtasks. They designed a user study in which results showed that task complexity influenced the choice of visual assets used to convey AR information. For example, joining low-complexity subtasks may require AR instructions that provide limited information not to increase operators' cognitive load. The effect of task complexity is also taken up by Radkowski (Radkowski et al., 2015), who stated that the virtual elements used to explain a particular assembly operation must correspond to its relative degree of difficulty.

As it is possible to understand from the literature, there are various approaches for the choice of visual assets in the AR instruction authoring. Many works propose virtual content based on technical or empirical considerations but then leave the selection up to user preference: those of a technical writer (Li et al., 2019; Lavric et al., 2022) or an operator (Tainaka et al., 2020; Chu et al., 2020; Alves et al., 2021). Other studies recommend visual assets based only on users' capabilities (Wolfartsberger et al., 2019; Syberfeldt et al., 2016; Holm et al., 2017) or even their preferences in a hybrid authoring approach (Geng et al., 2020; Scheffer et al., 2021). Another way to choose virtual content is to analyze the information required to perform a task (Stork and Schubö, 2010), for which the complexity should also be considered (Radkowski et al., 2015; Yang et al., 2019). All the previous approaches were considered in the development of the minimal AR authoring approach. In addition to these prior works, in fact, our approach takes into account the combined effects of real objects involved, end-user, and task complexity to propose the AR visual assets.

3. Design of "minimal AR" signifiers

We propose guidelines to apply the minimal AR authoring approach in different existing assembly procedures. They guide the choice of the minimal AR signifier and are fundamental for technical documentation designers without previous experience in AR. They were obtained through a focus group of ten people (4 females, 25–50 years old, mean=32.2, SD=9.13), selecting them among experts in the design of AR technical documentation. Their expertise field covers a wide range of production machinery, including Computer Numerical Control (CNC) machines, injection molding machines, and robotic assembly systems. They were instructed on the "minimal AR" authoring approach as well as other fundamentals of our research, such as the "information type" technique (Gattullo et al., 2022b) and the taxonomy of visual assets (Gattullo et al., 2022a). Users in the focus group were provided with five assembly manuals concerning the assembly of a compressor, a pump, a car model, an airplane model, and a piece of furniture. In this way, they could refer to examples of existing instructions for their discussions. Based on their experience and the knowledge acquired on the minimal AR approach, they converted instruction samples from the manuals into AR instructions using the minimal AR approach. Based on the lessons learned from this activity, we proposed a workflow to design minimal AR instructions. In the following paragraphs, we reported the main steps of the workflow, schematized in Fig. 1, for the 3 main phases of the minimal AR authoring approach: decomposition of work instructions into information types (phase A), identification of the information that can be conveyed exploiting object properties (phase B); design of the minimal AR signifier (phase C).

3.1. Phase A: decomposition of work instructions into information types

A preliminary phase is to decompose assembly work instructions into single atomic tasks as described in (Gattullo et al., 2019). For each elemental task, it is possible to determine the set of information needed. The information in work instructions can be of different types, and there is no standard classification. In our previous work (Gattullo et al., 2022b), the "information type" technique was proposed to determine this set of required information. This technique allows to decompose technical instructions into elemental information associated with one or more visual assets. As a result, six mutually exclusive and jointly exhaustive classes called "Information types" were obtained: identity, location, way to, notification, order, and orientation.

The information types were presented to the focus group, which conducted a brainstorming to establish a generic ordered sequence of information types for typical assembly instructions. This sequence follows the logical order in which generic operators request information to fully understand an assembly task, independent of their mental abilities:

1. LOCATION: the operator first needs to know the area of an equipment where the component/s need to be assembled.
2. IDENTITY: the operator needs to know which the component/s is/are to assemble among all the possible components available in the working area.
3. ORDER: in the case of multiple parts that need to be assembled without releasing the hands, the operator may need to figure out the sequence in which the identified components should be mounted.
4. ORIENTATION: the operator needs to understand the correct orientation of the component/s to assemble.
5. WAY TO: the operator has to figure out how the component/s is/are assembled.
6. NOTIFICATION: the operator needs to receive the notification that the component/s has/have been mounted correctly.

For the information about NOTIFICATION, the machine to be assembled must be equipped with sensors to recognize if the assembly was successful. Only in this case, this information could be provided

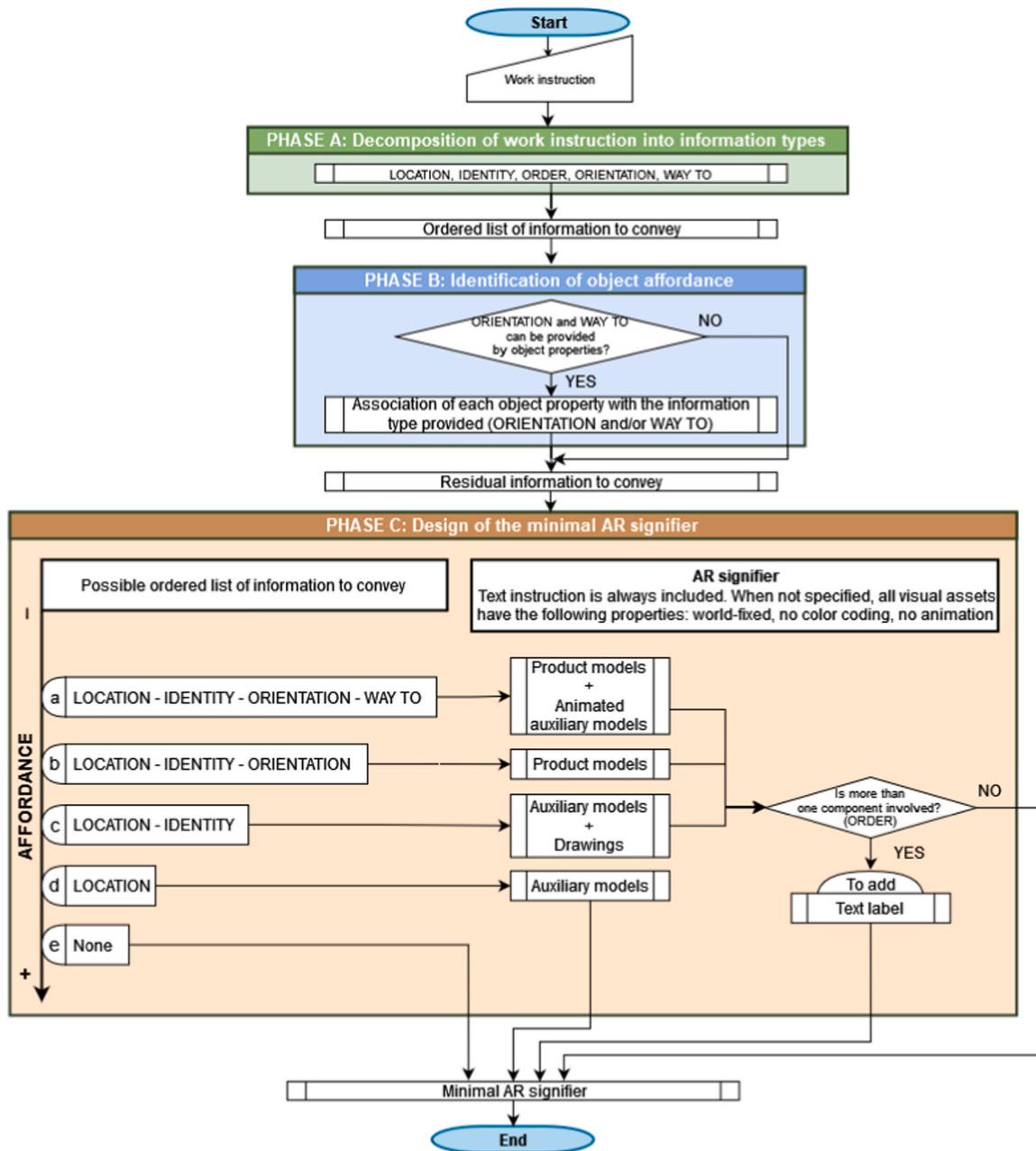


Fig. 1. Workflow of the minimal AR authoring approach to design the minimal AR signifier for an assembly task.

through AR signifiers, otherwise it is left to operators' capabilities.

3.2. Phase B: Identification of the information that can be conveyed by exploiting object properties

As stated by Normann (Norman, 1988), object affordance depends on the relationship between object and users, making it difficult to predetermine. In fact, modeling how users interact with objects to acquire information is not simple because many mental abilities are involved (e.g., prior experience, technical skills, concentration level during the task). However, some object properties (e.g., shape, color) provide affordance independent of user abilities. Then, for phase B, we asked the focus group to identify the information types in assembly procedures that can be conveyed by exploiting object properties.

The focus group concluded that WAY TO and ORIENTATION are the information types that object properties can provide. For example, a high affordance could be attributed to a component that can naturally

communicate how it is intended to be mounted. For example, the WAY TO of a screw can be provided by a threaded insertion, while the ORIENTATION of an asymmetrical component can be given by a designated location, such as a battery that ends with different polarities to be inserted in its proper slot. However, in many cases, object properties can produce a variable affordance. In these cases, although object properties can be identified, they are difficult to detect for some users, thus not providing them with useful information.

3.3. Phase C: Design of the minimal AR signifier

For defining the visual assets that constitute AR signifiers, we used the categorization proposed in (Gattullo et al., 2022a): texts, signs, photographs, drawings, videos, product models, and auxiliary models. Based on the type of visual asset chosen and its properties (e.g., color coding, frame of reference, and animations), an AR signifier can convey a set of information types based on a specific task. The focus group was

instructed with this list of visual assets through some examples and with the design implications described in (Laviola et al., 2022).

The design of the minimal AR signifier is strictly related to the amount of object affordance. There could be some cases for very simple tasks where object properties are enough to understand what to do for every people. In this case, no AR signifiers are needed. However, objects generally can convey a variable amount of affordance based on user cognitive abilities. Then, the focus group identified the following scenarios, listed in terms of increasing affordance. For each scenario, they proposed an AR signifier. In addition, they supposed a text instruction, that shortly describes what to do, will always be present in an AR technical documentation, as proposed by (Marner et al., 2013; Mourtzis et al., 2017). Depending on the target AR device, it could be screen-fixed or world-fixed.

The perceived object affordance is very low when operators have no previous knowledge about the target equipment and generally have no or limited experience in assembly tasks, e.g., novices (Fig. 1, Phase C - a). In this case, this kind of operator finds the text instruction very hard to understand. Then, the whole set of information needs to be conveyed through AR signifiers. The focus group proposed static product models to convey simultaneously the LOCATION, the IDENTITY, and the ORIENTATION, while the WAY TO can be provided further adding auxiliary models with prefabricated animations (e.g., a rotating arrow to indicate the tightening direction of a screw). For multiple components that need to be assembled without releasing the operator's hands, the ORDER can be provided through a text label with the sequence number near the corresponding product model. The whole AR signifier is world-fixed, i.e., spatially registered to the part of the machine where the component must be assembled, thus resembling a virtual preview of the assembly result. A typical scenario may be the case of a bolted flange assembly, where the task involves connecting two flanges using bolts and nuts while maintaining continuous contact with the components. This is commonly encountered in piping systems. Another scenario is a snap-fit enclosure assembly, in which at least two enclosure halves need to be joined in a certain order using snap-fit mechanism, where the parts snap or click together, requiring both hands to apply pressure and keep the components engaged. As to the NOTIFICATION, it cannot be considered as the other information types because it does not provide the user further details on the task to accomplish but only about its success and is presented to operators only after the accomplishment of the task. Therefore, we did not provide an AR signifier for the NOTIFICATION in the proposed workflow.

A higher level of perceived object affordance than the previous one is when operators can exploit the component physical properties and their cognitive abilities to understand the WAY TO mount it (Fig. 1, Phase C - b). In this case, the minimal information comprehends the LOCATION, the IDENTITY (together with the ORDER in case of multiple components), and the ORIENTATION. The focus group proposed static world-fixed product models to convey it. In the case of multiple components, the ORDER is provided as in the previous case.

A further higher level of perceived object affordance than the previous ones is reached when operators can also understand the ORIENTATION information from the component physical properties and their cognitive abilities (Fig. 1, Phase C - c). In this case, the minimal information comprehends only the LOCATION and the IDENTITY (together with the ORDER in case of multiple components). The minimal AR signifier proposed by the focus group for this information consists of a drawing of the component for the IDENTITY, in addition to an auxiliary model (e.g., arrow, sphere, plane) placed in correspondence with the LOCATION where it has to be mounted. Since it may not always be possible to know in advance the initial location of the components to be assembled, the drawing can be placed in whatever position of the interface, ensuring it does not visually interfere with the assembly task. In the case of multiple components, the ORDER is provided through a label with the sequence number near the corresponding auxiliary model, and the same number is reported in the drawing of the corresponding

component.

Another scenario is that of operators who can also recognize the component to be assembled (IDENTITY) based on their cognitive abilities by only reading its name (Fig. 1, Phase C - d). In this case, the minimal information corresponds to only the LOCATION. The focus group proposed to provide it through static and world-fixed auxiliary models, i.e., registered on the part of the equipment where the component must be assembled. In the case of multiple components, the ORDER information is derived from the text information (e.g., "mount first the component A and following the component B").

Finally, the highest level of perceived object affordance is reached when operators have all the prior knowledge available to perform the task, as in the case of a highly trained operator, and/or the object properties are such that they provide all the required information (Fig. 1, Phase C - e). In this case, only text instruction is enough to perform the task, and no AR signifier is needed.

4. User study in a real industrial assembly scenario

We applied the workflow provided by the focus group (Fig. 1) to design an AR interface for a generic assembly procedure that contained all the information types. As a case study, we selected the assembly instruction of the flow regulator (Fig. 2) of a gas-fired radiant heating system. This machine controls the heat flow generated by the gas burner. The device chosen for the AR interface is an Optical See-Through (OST) Head-Mounted Display (HMD), the Microsoft HoloLens 2. However, the application of the workflow is independent of the target device. For the same case study, we also designed a user study to validate the proposed recommendations. We evaluated if the minimal AR signifier designed using the workflow corresponded to the actual minimal AR signifier established by users, as defined in Section 1: the virtual content, which allows to minimize the gap between the information provided and that needed to understand the task.

4.1. Design of the AR signifiers for the proposed scenario

The flow regulator is made up of four main components. Therefore, we could extract, from the maintenance manual, four elemental tasks for its assembly instruction:

- Connect the fitting to the burner with the four ISO 7048 M4×10 screws (Task 1).
- Connect the flow regulator to the fitting with the four ISO 7048 M4×10 screws (Task 2).
- Insert the connectors EV1 and EV2 into the flow regulator with two ISO 7045 M2×22 screws, first EV1 and then EV2 (Task 3).
- Tighten the 3-piece joint to the flow regulator (Task 4).

Then, we identified the ordered sequence of atomic information

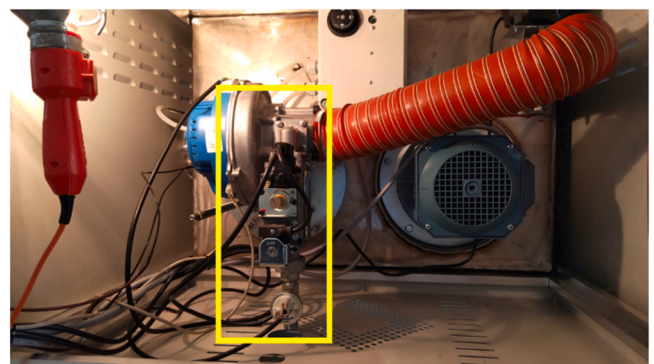


Fig. 2. Gas-fired radiant heating system used for the experiment, the flow regulator for the assembly task is highlighted.

needed to understand each instruction (Phase A of the workflow). As we can see from Table 1, the only task for which is required the ORDER information is Task 3. In the experiment, the experimenter notified users if the task had been accomplished correctly or if an error occurred.

We then applied the Phase B of the workflow (see Table 2). We evaluated if the WAY TO and ORIENTATION information could be conveyed by exploiting the properties of the components involved in the tasks. For Task 1, 2, and 3, the main component must be assembled to the rest of the machine through screws. We considered that the screw insertions with their threads provide a hint regarding the assembly procedure for every user. For Task 4, there is also a high affordance provided by the thread of the 3-piece joint, which suggests being coupled to the ring nut on the flow regulator. As to the orientation, we considered a very low affordance provided by the components in each task, except for Task 3. In fact, in Task 1 and Task 2, the symmetrical disposition of the four holes for the screws would allow various possible orientations of respectively the fitting and the flow regulator (see Fig. 3). In Task 3, instead, the connectors can be placed uniquely in their housings thanks to the pins (highlighted in green in Fig. 4). In Task 4, the 3-piece joint can be screwed in various orientations around its axis, and the correct orientation cannot be derived from object properties (see Fig. 5).

Finally, following the Phase C of the workflow, we designed the minimal AR signifier for each elemental task. In Task 1, 2, and 4, the information types that need to be provided are LOCATION, IDENTITY, and ORIENTATION, therefore a static world-fixed product model was chosen as minimal AR signifier. In Task 3, the ORIENTATION is provided through the object affordance; thus, the minimal AR signifier was the drawing of the component coupled with a world-fixed static auxiliary model. The drawing was world-fixed and registered to an area of the machine, which did not interfere with the main task. We chose as auxiliary model a sphere whose diameter approximated the greater dimension of the component to be assembled. Other shapes of auxiliary models could also be chosen because there are no clear guidelines in the literature about this choice. For all the AR signifiers, color coding is not used. Therefore, we used colors that produced a high contrast with the colors of the real components, such as green (HSV:120°, 1, 1, alpha 1) and blue (HSV:240°, 1, 1, alpha 1), as done in (Ping et al., 2020; Laviola et al., 2023). The text which described the instruction for each task was displayed in a textbox that was always available to the user. For this AR interface, the textbox is placed inside a holographic window which users could move where they desired.

Table 1
Identified order sequence of atomic information needed to understand the instruction for each task (Phase A).

Information type	Task 1	Task 2	Task 3	Task 4
LOCATION	The area of the burner where placing the fitting	The area of the fitting where placing the flow regulator	The area of the flow regulator where placing the connectors	The area of the flow regulator where placing the 3-piece joint
IDENTITY	The fitting	The flow regulator	The connectors	The 3-piece joint
ORDER	-	-	First EV1, then EV2	-
ORIENTATION	Of the fitting respect to the burner	Of the flow regulator respect to the burner	Of the connectors respect to the flow regulator	Of the 3-piece joint respect to the flow regulator
WAY TO	Using four ISO7048 M4×10 screws	Using four ISO7048 M4×10 screws	Using two ISO7045 M2×22 screws	Tightening the ring nut on the flow regulator on the thread of the 3-piece joint

4.2. Design of experiment

To validate the proposed workflow, we designed an experiment to verify if the candidate AR signifiers, i.e., those designed using the workflow, corresponded to the minimal AR signifiers established by users while doing the task. To mark an AR signifier as minimal, it must respect the following requirements (Laviola et al., 2022): AR signifiers with redundant information compared to the minimal one, are not useful to understand the task (R1); AR signifiers with less information leads to a performance reduction (R2).

During the experiment, each participant proposed a minimal AR signifier by choosing the AR signifier, which they considered the one needed to understand the task. Therefore, we implemented all the possible AR signifiers for each affordance scenario presented in phase C of the workflow. No AR signifiers are presented for the highest level of affordance, and users could rely only on the text instruction. We called it BASELINE because the text instruction should always be present in an AR technical documentation regardless of the level of affordance, as proposed by (Marner et al., 2013; Mourtzis et al., 2017). It is the same information content contained in the original manual, here presented inside a holographic window. For each task, a total of four AR signifiers were then implemented, including the candidate minimal one (Table 3 shows the AR signifiers for Task 1). To test R1, we also designed an additional AR signifier (ID 5) which conveyed the same information needed for the lowest level of affordance but used animations for product models rather than auxiliary models to convey the WAY TO information. We decided to include also animated product models because they are the most common (Gattullo et al., 2022a) and captivating (Gattullo et al., 2020) visual assets in the AR interface development, even if they require a high authoring effort (Lavric et al., 2022; Gattullo et al., 2020). In fact, creating product models demands expertise in 3D modeling, and the amount of work involved in creating them is directly linked to how complex their shapes, materials, and animations are. Additionally, product models are greatly affected by the precision of their 3D alignment. If there is a mismatch between the virtual model and the actual object during assembly, it can result in visual inconsistencies and reduce user satisfaction. Given their large use in the literature, we called them STAR (State of The ART).





The evaluation process to determine the minimal AR signifier, repeated for each task, can be summarized as follows:

- Users read the textual instruction proposed through the BASELINE.
- If users believed they did not have enough information, they could press a button to gradually add information in the AR signifiers displayed, from level 1 to STAR. Users could not go back to a lower level of AR signifier.
- Only when users believed they had enough information with a specific AR signifier, they could perform the assembly task manually. If users did not make a mistake, they could proceed to the next task, and the AR signifier was marked as minimal. Otherwise, the experimenter informed users that an error was made. In that case, the same experimenter performed the manual task and asked the users to proceed to the next task.

4.3. Experimental set-up

The AR interface was developed for the Microsoft HoloLens 2. Unity 3D Engine (Unity Real-Time Development Platform, 2023) was used to implement the application using Vuforia Engine (Vuforia engine developer portal, 2023) and the Mixed Reality Toolkit (Releases-microsoft/MixedRealityToolkit-Unity, 2023). The natural feature image used for the tracking was placed in the right panel of the gas-fire radiant heating system. We obtained the 3D model of the entire equipment from the company in STEP format, which was later converted to OBJ. HoloLens 2 eye tracking input has been implemented to interact with a red cursor to press buttons on the interface. In this way, it was

Table 2
Object properties and information types provided by them for each component involved in the experiment (Phase B).

Task	Component to be assembled	Image	Phase A	Phase B		Information types provided by minimal AR signifier
			Information types needed	Object properties	Information types provided by object properties	
1	Fitting		LOCATION IDENTITY ORIENTATION WAY TO	Insertions screws	WAY TO	LOCATION IDENTITY ORIENTATION
2	Flow regulator		LOCATION IDENTITY ORIENTATION WAY TO	Insertion screws	WAY TO	LOCATION IDENTITY ORIENTATION
3	Connectors		LOCATION IDENTITY ORDER ORIENTATION WAY TO	Inserts attachment Insertions screws	ORIENTATION WAY TO	LOCATION IDENTITY ORDER
4	3-piece joint		LOCATION IDENTITY ORIENTATION WAY TO	Threaded ends	WAY TO	LOCATION IDENTITY ORIENTATION

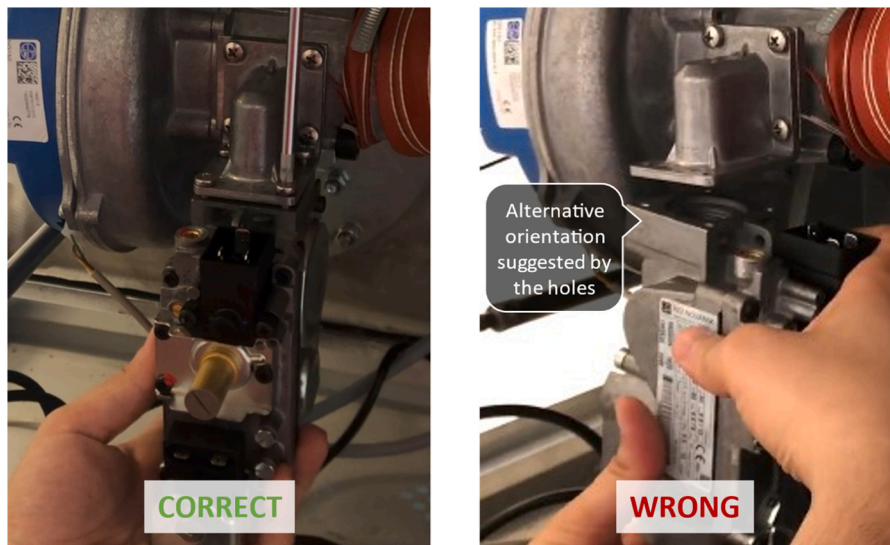


Fig. 3. The correct orientation of the flow regulator with respect to the fitting (on the left) and a wrong alternative orientation due to the symmetrical disposition of the screw holes (on the right).

possible to avoid spending time on gesture-based interaction training for each user. Voice command was not considered as it is not always reliable.

The company provided the gas-fired radiant heating system to conduct the experiment in our laboratory. It was positioned considering the average height at which operators perform maintenance tasks on the installed machine. We placed an incandescent lamp inside the machine to ensure an adequate and constant light condition for all participants. We checked that the lamp was the same one used by the operators during their work. A tool table was placed near the equipment with all the components to be assembled and the necessary tools, such as screwdrivers. To avoid bias in component selection, especially for the last step, we also included other components not required by the instructions.

4.4. Procedure

At first, the experimenter collected general information about each participant in each session. Afterwards, details were provided regarding the procedure of the experiment and how the AR application worked. Then, an eye calibration procedure was conducted to ensure accuracy before each user's use of the eye tracking. Afterwards, a one-step training was performed to familiarize with the eye tracking interaction and the modality of choosing the AR signifiers. This trial refers to a different instruction, i.e., the regulation of the machine thermostat. After participants declared they understood how to use the AR application, the experimenter instructed the users to start the assembly from Task 1. They proposed a minimal AR signifier for each task, as described in Section 4.2. The experimenter observed users while performing the

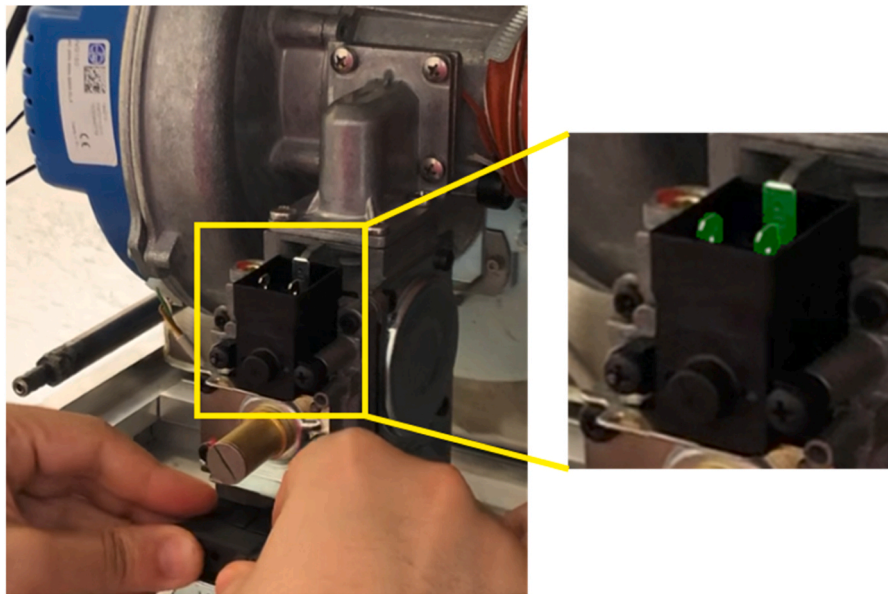


Fig. 4. Example of a connector housing (on the left) suggesting the right orientation of the connector thanks to the pins highlighted in green (on the right).



Fig. 5. Example of a possible orientation to assemble the 3-piece joint. The yellow arrow suggest that the component can assume every orientation around its axis and the correct one cannot be derived from object properties.

assembly procedure and took notes useful to verify the two requirements of this study. At the end of the four tasks, users pressed a button to finish the experiment.

4.5. Participants

34 participants (6 females, 18–61 years old, mean=31.2, SD=12.07) were recruited from our university and the local company that provided us with the equipment. We ensured an equal distribution of participants in terms of user capabilities by distinguishing them between experts and novices. However, no user had prior knowledge of the machine that was the subject of the assembly task. It was ensured that all the participants were not color-blind. Users were allowed to wear the eyeglasses along with the HoloLens. They stand up in front of the machine while performing the assembly tasks. For each participant, the experiment lasted on average 40 min. The data collected for each participant during the experiment are as follows: set of information types required to comprehend the instruction and errors manually checked by the

experimenters. We also collected participants' feedback through the think-aloud method as done in (Satkowski et al., 2022). To prevent users from losing focus on the tasks during their performance, users were not forced to talk all the time and the experimenter guided their thoughts by providing questions targeted to the specific task when necessary. Each participant's answers were recorded with their consent.

5. Results

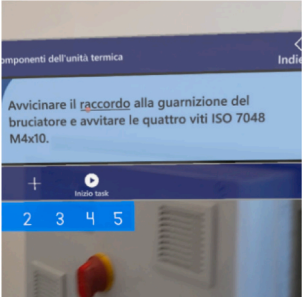
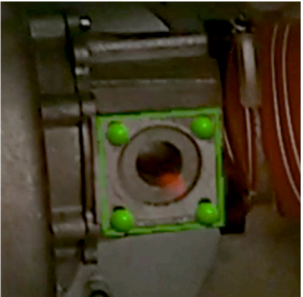


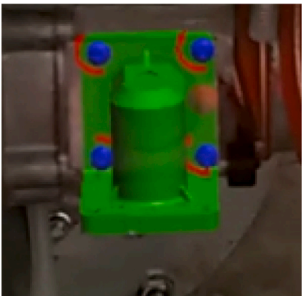
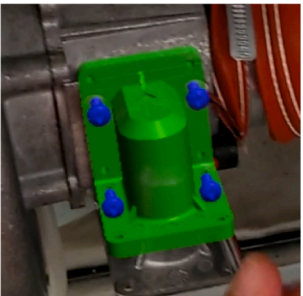
5.1. Minimal AR signifiers established by users

In Task 1, AR signifier 3 that conveys LOCATION, IDENTITY, and ORIENTATION is the candidate minimal AR signifier. As shown in Table 4, most users (13, 43% of users who successfully comprehended the instruction) confirmed this choice, considering this AR signifier as the minimal one. Only 2 users (6%) requested a minimal AR signifier that conveys WAY TO as an additional information type (AR signifier 4 and STAR). On the other hand, 15 users (50%) requested AR signifiers that provide fewer information types than AR signifier 3. Among these, 2 users were able to successfully accomplish the task by only reading the textual information, 9 users only asked for an AR signifier to understand where to place the fitting, and 4 users were able to understand the information about the ORIENTATION and WAY TO based on their capabilities.

Also for Task 2, the candidate minimal AR signifier is signifier 3. As shown in Table 4, most of the users (12, 41% of users who successfully comprehended the instruction) considered this as the minimal AR signifier, too. 5 users (17%) requested a minimal AR signifier that conveys WAY TO as additional information type (AR signifiers 4 and 5). On the other hand, 12 users (41%) requested an AR signifier that provides fewer information types than AR signifier 3. Among these, 6 users were able to successfully accomplish the task by only reading the textual information, and 6 users only asked for an AR signifier to understand which is the flow regulator among the components on the tool table and where to place it, whereas they understood the information about the ORIENTATION and WAY TO based on their capabilities.

In Task 3, AR signifier 2 that conveys LOCATION, IDENTITY, and ORDER is the candidate minimal AR signifier. As shown in Table 4, most of the users (13, 50% of users who successfully comprehended the instruction) considered this as the minimal AR signifier. 8 users (31%) requested an AR signifier that conveys more information: 1 user

Table 3
AR signifiers designed for the experiment in Task 1 as an example.

Signifier ID	0 (BASELINE)			1	
Visual assets	Text			Auxiliary model	
Properties	World-fixed no color coding static			World-fixed no color coding static	
Information provided	Location Identity Orientation Way to			Location	
Signifier ID	2			3	
Visual assets	Auxiliary model	Drawing		Product model	
Properties	World-fixed no color coding static	World-fixed no color coding static		World-fixed no color coding static	
Information provided	Location	Identity		Location Identity Orientation	
Signifier ID	4			5 (STAR)	
Visual assets	Product model	Auxiliary model		Product model	
Properties	World-fixed no color coding static	World-fixed no color coding animated		World-fixed no color coding animated;	
Information provided	Location Identity Orientation	Way to		Location Identity Orientation Way to	

accomplished the task with the additional information about the ORIENTATION, 5 users also needed the WAY TO information with the animated auxiliary model, whereas 2 users requested the animated product model. On the other hand, 5 users (19%) requested an AR signifier that provides fewer information types than AR signifier 2. Among these, 2 users (8%) were able to successfully accomplish the task by only reading the textual information, while 3 users only asked for an AR signifier to understand where to place the connectors.

For Task 4, AR signifier 3 that conveys LOCATION, IDENTITY, and

ORIENTATION is the candidate minimal AR signifier. As shown in Table 4, there is not a clear preference for this AR signifier. In fact, only 7 users (29% of users who successfully comprehended the instruction) considered this as the minimal AR signifier. 9 users (37%) asked for an AR signifier also conveying the WAY TO information. 7 of them could not understand the instruction with AR signifier 4 and thus requested the animated product model. On the other hand, 8 users (34%) requested an AR signifier that provides fewer information types than AR signifier 3. Among these, only 1 user was able to successfully accomplish

Table 4

Users who understood the task with a specific set of information types. The candidate minimal AR signifier is highlighted in red for each task. Percentages refer to the total number of users performing the individual task correctly.

AR signifier	Number of users (%) who successfully comprehended the instruction					
	BASELINE	1	2	3	4	STAR
Task 1	2 (7%)	9 (30%)	4 (13%)	13 (43%)	1 (3%)	1 (3%)
Task 2	6 (21%)	0	6 (21%)	12 (41%)	3 (10%)	2 (7%)
Task 3	2 (8%)	3 (12%)	13 (50%)	1 (4%)	5 (19%)	2 (8%)
Task 4	1 (4%)	3 (13%)	4 (17%)	7 (29%)	2 (8%)	7 (29%)

the task by only reading the textual information, 3 users only asked for an AR signifier to understand where to place the 3-piece joint, and 4 users were able to understand the information about the ORIENTATION and WAY TO based on their capabilities.

Considering all tasks together and neglecting errors made, 20 users (59% of all participants) performed tasks correctly with an AR signifier providing exactly the information conveyed by the candidate AR signifiers or less. Among all the other 14 users, none performed all 4 tasks with an AR signifier that provided more information than the candidate.

5.2. Errors

In Task 1, no users made any errors with the candidate minimal AR signifier whereas, as shown in Table 5, 4 users tried to accomplish the task with signifier 1 (only LOCATION provided), but they failed. Among these, 3 participants had been unable to predict the ORIENTATION and 1 the WAY TO successfully.

In Task 2, a mistake with the candidate minimal AR signifier was made by 1 user who did not successfully predict the ORIENTATION already provided. Whereas, as shown in Table 5, 4 users tried to accomplish the task with signifier 2 (only LOCATION and IDENTITY provided), but they failed. Among these, 1 participant had been unable to successfully predict the IDENTITY (even if already conveyed), and 3 the ORIENTATION.

In Task 3, 3 users made a mistake with the candidate minimal AR signifier. Among these, 1 participant had been unable to predict the ORIENTATION and 2 the WAY TO successfully. Whereas, as shown in Table 5, 2 users tried to accomplish the task with a signifier conveying less information, but they failed. Both did not successfully predict the WAY TO. Finally, 3 users who requested an AR signifier also conveying the ORIENTATION information made an error, failing to predict the WAY TO. In fact, all the users who made errors in this task forgot to fix the connector with the screw.

In Task 4, 10 users (29% of all participants) made a mistake. 2 users made a mistake with the candidate minimal AR signifier whereas, as shown in Table 5, 6 users tried to accomplish the task with signifier conveying less information, but they failed. Finally, 2 users who requested AR signifier 4 which also conveys the WAY TO information, made an error. It is worth noting that all the errors regarded the

Table 5

Users who made a mistake with a specific set of information types. The candidate minimal AR signifier is highlighted in red for each task.

AR signifier	Number of users who unsuccessfully comprehended the instruction					
	BASELINE	1	2	3	4	STAR
Task 1	0	4	0	0	0	0
Task 2	0	0	4	1	0	0
Task 3	1	1	3	3	0	0
Task 4	3	1	2	2	2	0

ORIENTATION. Even when the AR signifier showed a preview of the final orientation of the 3-piece joint through its product model, users could not use this information and assembled it in an arbitrary orientation.

5.3. Overall results

We can consider each task as a replication of the test for each user. Therefore, we can analyze the overall results considering the 136 assembly cases (4 tasks x 34 users). In Fig. 6, we distinguished cases where users accomplished the task with the candidate minimal AR signifier from cases where they exploited an AR signifier providing either more or less information than the candidate one. We also marked cases where users accomplished the task successfully and cases where they made a mistake. In 33% of the analysed cases, we found that users successfully accomplished the task exploiting the candidate minimal AR signifier. We also found that in 29% of the cases, users could successfully accomplish the task with an AR signifier which provided less information than the candidate. However, this choice led people to make more errors (12%). Finally, in 18% of the situations, users asked more information than the minimum needed to accomplish the task correctly. Both with the candidate minimal AR signifier and with those providing more information, some users (4%) could not correctly accomplish the task.

6. Discussion

The application of the minimal AR authoring approach to the case study proposed in this work allowed us to explore the main assembly scenarios in terms of the three design variables of an AR assembly documentation (work instructions, affordance, and AR signifiers) along with the 136 takeovers. Fig. 7 shows a qualitative graph that provides a comprehensive overview of all possible scenarios that can occur in an industrial context regardless of the case study. The first distinction is between cases where people were able to successfully comprehend the instruction from cases where people were not able and then made a mistake (20% of the takeovers, see Fig. 7a). Then, we can make a second distinction between cases where people exploited a minimal AR signifier (62%, see Fig. 7b) and cases where people used an AR signifier that conveys more information than the minimum needed (18%, see Fig. 7c).

6.1. Insights from users who comprehended the instruction

The user study results revealed that some people could perform the task with less information than the candidate minimal AR signifier. This

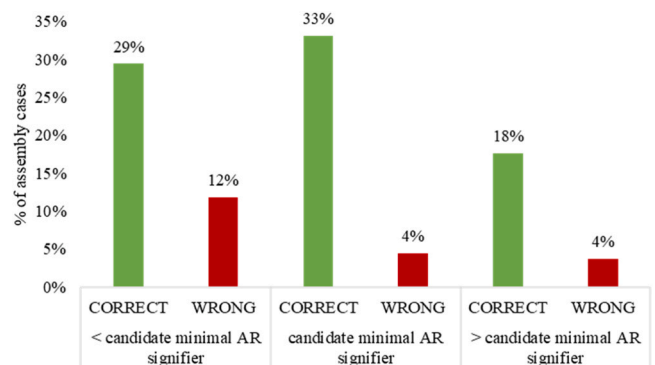


Fig. 6. Overall results considering the 136 assembly cases. There can be 4 different scenarios: (i) users accomplished the task with the candidate minimal AR signifier or exploited an AR signifier providing either (ii) more or (iii) less information than the candidate one. In the last scenario, (iv) users may misinterpret instructions due to an inadequately designed minimal AR signifier or insufficient or redundant conveyed information due to incorrect screening of their user capabilities.

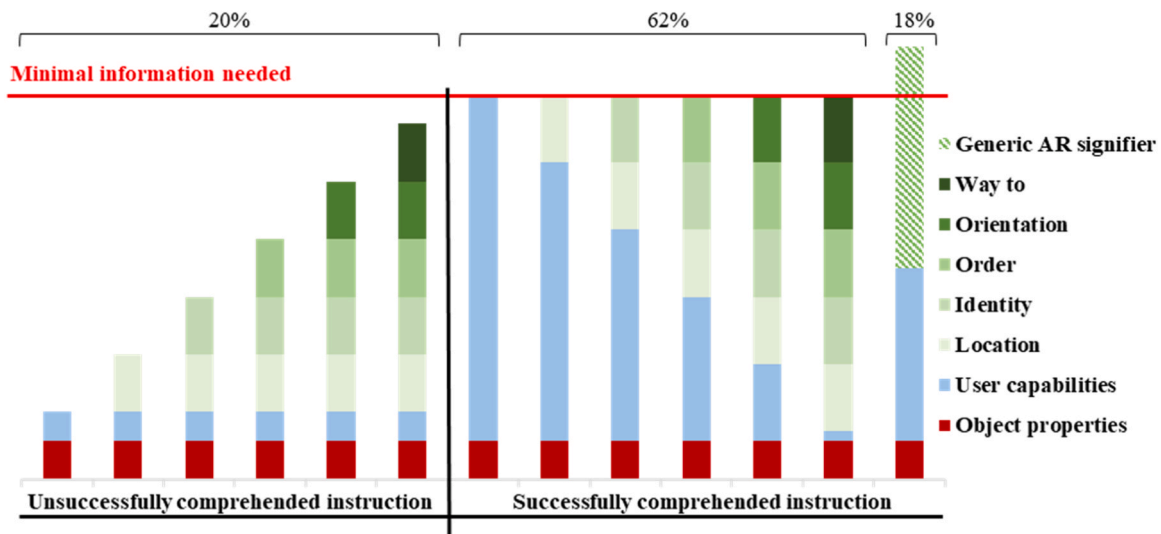


Fig. 7. Qualitative graph showing all the possible scenarios that can occur during an assembly task. Percentages refer to the 136 takeovers. By considering a constant object property, different AR signifiers may be necessary and sufficient to accomplish the task as the user capability differs. However, the case study revealed that, in all these cases (62%), a minimal AR signifier is exploited. The scenarios where the information provided through the minimal AR signifier is not enough to understand the task (20%) or is redundant (18%) are limited.

means that, although the object properties are always the same for a component, users may acquire different information based on their capabilities. Therefore, for each user, a different minimal AR signifier can provide the necessary and enough information to perform a task correctly. Overall, we found that in 62% of the analyzed scenarios, users could successfully accomplish the task either using the candidate minimal AR signifier (33%) or an AR signifier with less information (29%).

A surprising result is that in some cases (18%), users decided to accomplish the tasks with AR signifiers containing more information than the candidate minimal AR signifier. We could understand the reasons behind this result from the users' impressions gathered in the think-aloud process. For Tasks 1 and 2, users stated that they used it only for further confirmation, but it would not have been needed if they had not been given the opportunity. Then, it is reasonable to think that they would be able to accomplish the task even with the candidate minimal AR signifier correctly. As regards Task 3, a great percentage of users requested more information than those provided with the candidate minimal AR signifier, which were LOCATION and IDENTITY. In particular, users revealed that they could not understand how to insert the screw to secure the connectors to the machine due to the small screw insertions. This is a case where an object property (the small hole in the connector), even if present, could produce a low affordance, thus requiring AR signifiers with a greater amount of information than the candidate minimal AR signifier. This outcome confirms the difficulty of predetermining affordance produced by object properties in the design of an AR technical documentation, thus requiring a tuning of the minimal AR signifiers after the development. Task 4 is the most complex task to understand in our case study due to the complexity of the components involved and their spatial arrangement within the machine. For this task, many users could not understand how to assemble the 3-piece joint to the machine with the candidate minimal AR signifier. Even if the properties of the components involved in this task should produce a high affordance, not all the users could perceive it. In particular, they did not understand that the ring nut of the flow regulator had an internal thread and that, rotating it, the 3-piece joint would have assembled. Therefore, they felt that some information was missing and asked for more. It is worth noting that 7 users performed the task with the STAR. However, they confirmed that they could understand how to accomplish the task with AR signifier 4, but they thought that requesting a higher level of information would have solved their doubts. This result allows us to say that using animations of product models, even if it does not provide

additional information and requires a high authoring effort (Lavric et al., 2022; Gattullo et al., 2020), may help to reinforce the understanding of complex tasks, like Task 4.

6.2. Insights from users who did not comprehend the instruction

Considering the nature of the conducted experiment, we intentionally intended for users to self-assess their capabilities. In fact, they had to choose which set of information types was most suitable for their task understanding while being careful not to use an AR signifier that provided redundant information with respect to their effective capabilities. However, not all users were able to self-assess correctly. This led some of them (20%) to make mistakes with an AR signifier that did not effectively turn out to be their minimal. In particular, the scenarios where users could not successfully accomplish the task mainly regard Tasks 3 and 4. As explained before, for these tasks, many users could not perceive the affordance provided by the object. For Task 3, users assembled the connectors forgetting to insert the screws because they could not detect the small screw insertions. For Task 4, all the mistakes were about the ORIENTATION of the 3-piece joint. Even when this information was provided through the product model, which shows a preview of the final assembly, some users missed detecting this information. This is mainly due to the inexperience of the participants with AR manuals. Text information saying that the 3-piece joint must be oriented as shown by the product model would have solved this problem. In the future, it is reasonable to think that operators will be trained with AR manuals, and then they will be able to acquire all the possible information from the AR signifiers provided without using this additional text information which infringes the minimal AR approach. However, at present, these mistakes demonstrate the importance of proposing a system that can adapt to the individual operator's capabilities in a real-world industrial setup.

6.3. Overall discussion

Although it is not possible to define a universal minimal AR signifier, the obtained results allow to positively answer our research question "Is it possible to provide guidelines for creating AR signifiers even if dealing with a variable affordance to accomplish an assembly task?" In fact, we can make some considerations useful to create standards for the authoring of an AR technical documentation. Fig. 8 shows a qualitative

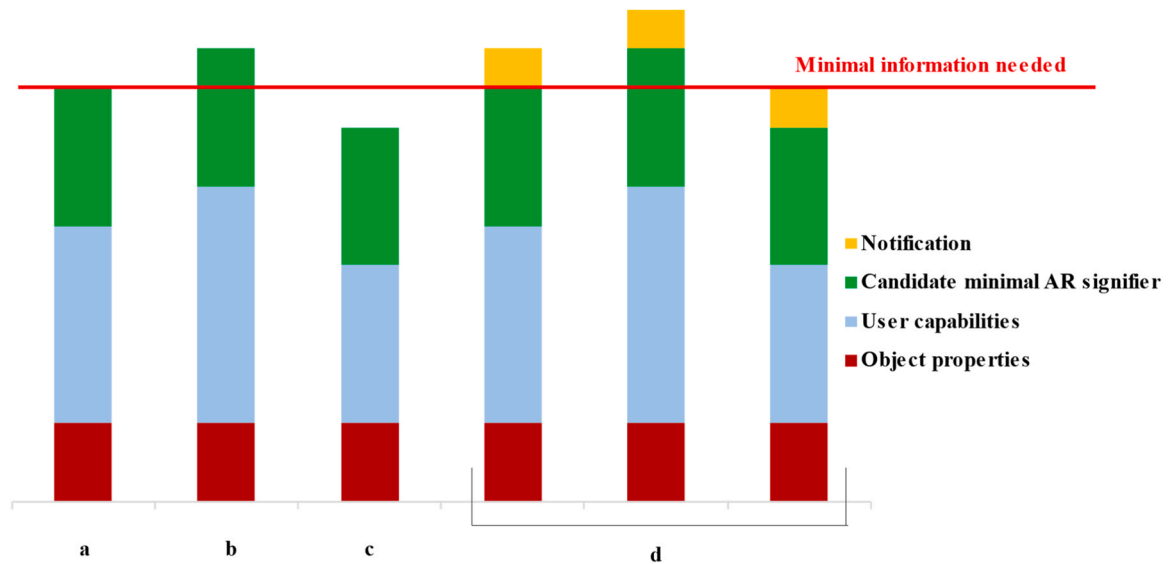


Fig. 8. Qualitative graph showing all the possible scenarios that can occur during an assembly task: the candidate minimal AR signifier (a) is sufficient to comprehend the instruction correctly, (b) provides more information than necessary, (c) is not sufficient, (d) is sufficient thanks to the NOTIFICATION even in case users become aware of the error they made.

graph based on possible generalized scenarios that can occur in an industrial context regardless of the case study. The information provided through this AR signifier could be exactly those requested by the operator (Fig. 8a) or slightly more in the case of operators with greater capabilities than the average (Fig. 8b). In both scenarios, nevertheless there is an advantage in choosing this AR signifier because it requires less authoring effort than the STAR. To ensure that every operator is provided with exactly the minimal AR signifiers, future developments of AR manuals should be integrated with a system that profiles operators before the assembly procedure. The initial profiling could be conducted in a controlled environment on a testing procedure. In case of mistakes, the system would propose an AR signifier with more information, otherwise it would propose an AR signifier with less. After this initial procedure, it would be possible to determine his/her capabilities and propose the AR signifier with exactly a minimal information needed. A critical issue arises when operators have lower capabilities than the average (Fig. 8c) and they are neither able to understand they made a mistake. In this case, a signifier should also be needed for the information about the NOTIFICATION (Fig. 8d). This signifier could prompt operators to reanalyze the provided AR signifier or object properties more carefully and then accomplish the task again. To provide the information about NOTIFICATION, the equipment must be implemented with a system that could sense if the assembly task was successful or not. A possible AR signifier for NOTIFICATION is a sign (Scurati et al., 2018) which depicts the information about success (e.g., a green check mark) or failure (e.g., a red wrong check mark).

In conclusion, considering the results obtained, we can validate and generalize our workflow (Fig. 1) to design minimal AR signifiers in a complex industrial assembly scenario involving different variables (real objects involved, end-user, and task complexity). The main steps of the minimal AR authoring approach are summarized below:

- **Phase A.** Analysis of the work instruction to understand the information types involved (LOCATION, IDENTITY, ORDER, ORIENTATION, WAY TO).
- **Phase B.** Identification of the information types (ORIENTATION and/or WAY TO) that can be conveyed by exploiting object properties.
- **Phase C.** Design of the minimal AR signifier according to the residual information to be conveyed together with those provided by object properties.

7. Conclusion and future work

The user study results confirmed that, in future developments of AR assembly manuals, the minimal AR signifier derived from the proposed guidelines would help operators to successfully comprehend the task with a reduced authoring effort for the developers. We found a good match between the candidate minimal AR signifier and the one proposed by the users for all four tasks, demonstrating that the candidate minimal AR signifier could be used as default AR signifier in AR technical documentation. In fact, thanks to the operator profiling, it would be possible to adjust the AR signifier based on their actual capabilities. We confirmed that AR signifiers with redundant information or attractive appearance, like animated product models, are unnecessary to understand the task. However, animations could be useful to reinforce the understanding when the object properties are hard to detect. The results also confirmed that it is not possible to define a universal minimal AR signifier, i.e., providing the necessary and sufficient information for all the operators. In fact, based on their different capabilities (e.g., technical skills, overall experience, previous knowledge), operators could acquire a variable amount of information from object properties and, thus, require AR signifiers with a variable amount of information provided. This result confirms the difficulty of predetermining minimal AR signifiers in real assembly scenarios due to the variable contribution of affordance. Other industrial case studies will be useful in understanding the effect of affordance better. In future work, we plan to apply the minimal AR authoring approach for further industrial case studies, also involving disassembly tasks. In fact, for these, different AR signifiers could be needed, for example, to identify components already mounted on the machine. In addition, it will be necessary to carry out an in-depth study of how to optimize the design of visual assets that provide the same set of information types.

CRedit authorship contribution statement

Enricoandrea Laviola: Methodology, Software, Visualization, Investigation, Writing – original draft
Antonio Emmanuele Uva: Supervision, Resources, Funding acquisition, Writing – review & editing
Michele Gattullo: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Enricoandrea Laviola reports financial support was provided by Politecnico University of Bari.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.compind.2023.104026](https://doi.org/10.1016/j.compind.2023.104026).

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