



## 奈良先端科学技術大学院大学 学術リポジトリ

Nara Institute of Science and Technology Academic Repository: naistar

<b>Title</b>	Guideline and Tool for Designing an Assembly Task Support System Using Augmented Reality
<b>Author (s)</b>	Tainaka, Keishi; Fujimoto, Yuichiro; Kanbara, Masayuki; Kato, Hirokazu; Moteki, Atsunori; Kuraki, Kensuke; Osamura, Kazuki; Yoshitake, Toshiyuki; Fukuoka, Toshiyuki
<b>Citation</b>	2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 14 December 2020, Recife/Porto de Galinhas, Brazil
<b>Issue Date</b>	2020-11-13
<b>Resource Version</b>	Author
<b>Rights</b>	© 2020IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.
<b>DOI</b>	10.1109/ISMAR50242.2020.00077
<b>URL</b>	<a href="http://hdl.handle.net/10061/14208">http://hdl.handle.net/10061/14208</a>

# Guideline and Tool for Designing an Assembly Task Support System Using Augmented Reality

Keishi Tainaka\*  
Nara Institute of Science and Technology  
Hirokazu Kato§  
Nara Institute of Science and Technology  
Toshiyuki Yoshitake††  
Fujitsu Laboratories Ltd.

Yuichiro Fujimoto†  
Nara Institute of Science and Technology  
Atsunori Moteki¶  
Fujitsu Laboratories Ltd.  
Toshiyuki Fukuoka‡‡  
Fujitsu Laboratories Ltd.

Masayuki Kanbara‡  
Nara Institute of Science and Technology  
Kensuke Kuraki¶  
Fujitsu Laboratories Ltd.  
Kazuki Osamura\*\*  
Fujitsu Laboratories Ltd.

## ABSTRACT

Augmented reality (AR) systems support complex tasks like assembly by overlaying task-related content onto the real world. In recent years, the effort of designing and developing assembly task support systems in AR decreased with the availability of high potential head-mounted displays and provision of integrated development environments. Nevertheless, problems still arise when companies craft an effective AR task support system, particularly in the difficulty of selecting appropriate techniques and information-presentation methods, and the requirements that vary with each use case. In this study, we formulated a corresponding guideline, developed a selection aid tool that incorporates filtering based on the categorization of subtasks and the degree of freedom of available tracking, and evaluated their effectiveness in two experiments. First, to confirm effects on system design, we asked 18 participants to perform the design action of the AR system with the guideline for two tasks (PC assembly and rope work). Consequently, to verify the quality of the designed AR systems from Experiment 1, we asked another set of 20 participants to perform the same tasks with those systems. The results confirm that using the guideline can considerably lower efforts creating media and alleviate the error for a specific process. We envision our guideline and tool to be accessible as an online web page, assisting AR assembly task support system designer/developers worldwide.

**Index Terms:** Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed/augmented reality; Human-centered computing—Visualization—Visualization techniques;

## 1 INTRODUCTION

Recently, augmented reality (AR) technology received worldwide popularity and recognition from entertainment and games. Many of its early uses were industry-related, particularly in supporting workers' tasks in the real world. However, to achieve more widespread use, AR systems in industry need to overcome some challenges, like: (1) technical limitation of the AR system making it unsuitable in the target environment. (2) lack of truly functional, practical, long-lasting, and inexpensive information presentation devices. (3)

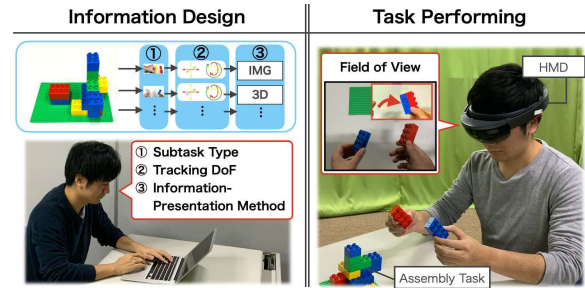


Figure 1: Information design and task performing using our guideline.

cost-effective is unclear. (4) lack of immediately available human expertise for creating high-quality AR systems. In particular, manufacturing support has been important as AR application for the past decade [16] [10]. The use of AR in this way is expected to improve work efficiency, accuracy, ease of understanding, time required, and cognitive load in the assembly tasks [7] [24].

In recent years, head-mounted displays (HMDs) such as HoloLens [4] and MagicLeap [3], can already deliver a high-quality AR experience. Furthermore, integrated development environments (IDEs) for software (e.g., Unity [6]) providing support to these HMDs, enabled an easier development of AR systems. However, AR systems cannot achieve a sufficient effect on the task support unless the AR software of the system is carefully designed and developed. We refer to this practice of careful consideration and selection of content as AR system “information design”. For example, the field of view (FoV) size can limit the display of 3D animations, movies, or images as rendered AR content. Work efficiency is lower when AR content cannot fit within the FoV of the HMD than otherwise [17]. The tasks at which these information-presentation methods excel differ. Using such technologies requires knowledge and experience to understand these differences in the way information is presented. Moreover, if available tracking technologies for estimating object positions and rotations are limited, then advanced information-presentation methods cannot be employed. This decision also requires a deep knowledge of AR and experience of system development.

Big companies, such as Microsoft [5], Google [2], and Apple [1], have released software libraries to realize the tracking, rendering, and user interface (UI) of AR. They have also provided guidelines that summarize how to create user-friendly systems and employ libraries as websites for those who are novices at system development using AR. However, the knowledge provided in these guidelines is intended for general AR systems, including games and information browsers. There has scarcely been discussion on information design including the variety of information-presentation methods, characteristics and selection for each assembly task.

\*e-mail: tainaka.keishi.ta1@is.naist.jp

†e-mail: yfujimoto@is.naist.jp

‡e-mail: kanbara@is.naist.jp

§e-mail: kato@is.naist.jp

¶e-mail: moteki.atsunori@fujitsu.com

¶e-mail: kuraki.kensuke@fujitsu.com

\*\*e-mail: osamura.kazuki@jp.fujitsu.com

††e-mail: yoshitake.toshi@jp.fujitsu.com

‡‡e-mail: t.f@jp.fujitsu.com

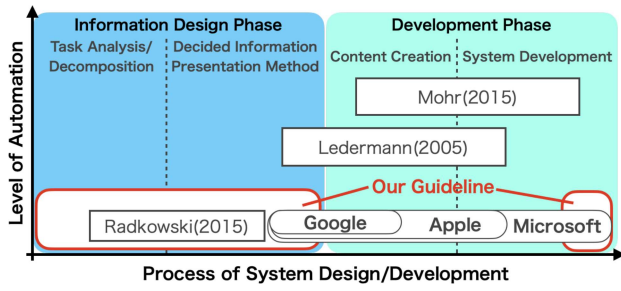


Figure 2: Positioning of this research.

In this paper, as shown in Figure 1, we propose a guideline that enables users with a knowledge regarding assembly operation, who may be not familiar with AR, to perform an appropriate information design for assembly task support with HMD-based AR. It is applied in accordance with the task property and the degree of freedom (DOF) of available tracking technology which we believe that affect AR technologies the most, based on existing studies of AR information-presentation methods. Following the guideline, users first divide the whole work (hereafter referred to as “task”) into smaller parts (the “subtasks”) and decide an available tracking DOF in the system. The guideline provides candidates with available information-presentation methods and a tool for choosing the most appropriate one among the candidates. Through these processes, users can easily perform AR system information design before developing it.

We conducted two experiments to confirm the effectiveness of this guideline. First, 18 participants, assigned to two groups of nine, were asked to use this guideline or an existing guideline to design an AR support system for two kinds of tasks: PC assembly and rope work. The aim is to determine what effect our guideline had on their design. Secondly, based on the design in each of the above groups, we conducted an experiment in which another 20 participants actually performed the two types of tasks using the implemented AR system to confirm how these systems affected user task performances.

Our guideline is published at <https://ar-guideline.naist.jp>. Although the guideline is still incomplete, we will collect user feedback to periodically refine. We envision that the guideline will be used as a form of collective intelligence for various users who intend to develop their own AR task support system, including developers, and researchers. The contributions of this research are as follows:

Proposal of a new information design method by filtering of information-presentation methods in the categorization of sub-tasks and the DOF of available tracking for AR assembly task support systems.

Verification of the characteristics of information design with the guideline and the tool and the effect of the designed system through two user studies.

## 2 RELATED WORK

To support the development of AR systems and decrease required human effort, studies have explored information technology in several ways (e.g., convenient authoring content tools and automatic AR content creation).

### 2.1 Authoring Tool for the AR System

Authoring tools employ familiar interactions and higher abstraction to decrease developers’ effort, in the form of *content templates* (e.g., for supporting automobile maintenance procedures [18]) or a *comprehensive system framework* (e.g., for furniture assembly that even non-software engineers can easily use [13, 38, 39]).

Haringer et al. [14] leveraged Microsoft PowerPoint users’ familiarity with editing slides to explore its authoring tool potential for AR annotation (e.g., in a car assembly). Ledermann et al. [19], proposed a general unified modeling language state transition diagram for system scenario design, via ARPIL (AR presentation and interaction language), intended for a complex and non-linear AR on the Studierstube system [32]. In addition, OpenTracker [30] was employed to provide arbitrary interaction and hardware abstraction.

We position our research among previous work in system design and development (see Figure 2). Even though they do not mainly target information design, we still see the importance of these authoring tools as effective in creating unified systems for task support.

### 2.2 Automatic Creation of a Task Support System with AR

Another way to minimize developers’ efforts is through (semi-) automatically creating task support systems with AR through computer vision techniques. Petersen et al. developed an automatic workflow creation method based on video sequences [27, 28], with automatic extraction of workers’ actions from an input video, and a homography-based first-person-view support. Makris et al. proposed an assembly sequence generation algorithm with the CAD data of parts in addition to developers’ minimum inputs [22]. Mohr et al.’s algorithm semi-automatically extracts target parts, text, and arrows for indicating the target location from a printed manual with minimum user input. Afterwards, the algorithm calculates position and rotation of the parts by matching the projected 3D CAD model with the image on the manual to construct the AR content [23].

Although the automatic creations of task support systems may be promising in the near future, current techniques still have limitations in terms of the robustness of the algorithms and the flexibility of designing actual systems in the companies. The actual task types are tremendous, and developers should also meet various requirements including implementation cost, available technology, devices, and environment. Furthermore, in this study, we aim to mainly assist the human designer/developer’s information design before the development (see Figure 2).

### 2.3 Guideline of AR System Development

As of March 2020, some popular companies have provided their own guidelines for developing AR systems (e.g., Google [2], Apple [1], Microsoft [5]). In particular, while the guideline by Google addresses ARCore, it is mostly generalizable to smartphones. In the case of Microsoft, not only does the guideline outline specialized techniques such as a spatial mapping function and a hand gesture interaction for their optical see-through (OST) HMD HoloLens, but it also includes a variety of basic ergonomic knowledge on AR.

Aside from companies, several researchers have proposed their own guidelines for designing and developing AR systems for task support. Rolim et al. [31] surveyed various instructions that use AR. Then, they provided a general guideline, showing the direction of the AR system design. While the motivation is similar to our work, it did not mention how the information-presentation method should be chosen according to the property of each task. Palmarini et al. [25] proposed a design space to decide the necessity of AR, appropriate hardware, development platform, and visualization method for the task support by answering a questionnaire on the tasks and workers. This method can cover various tasks by considering users’ requirements, available tracking technology and characteristics of the task, but the information-presentation method is determined for the entirety of the task only once. As Radkowski et al. pointed out [29], we also think that an actual assembly task performed in a company contains various steps with different properties, and the optimal information-presentation method should differ depending on each task. Therefore, we decided to utilize an approach, which divides one task into smaller tasks in a similar way in [8] and examined

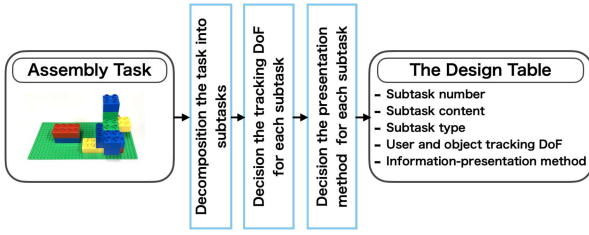


Figure 3: The Flow of our idea.

an appropriate information-presentation methods for each task with consideration of its property (i.e., task analysis). Figure 2 illustrates our guidelines and other similar guidelines/methods presented in this section.

### 3 METHOD

#### 3.1 Main Idea and Overview

Most assembly tasks consist of smaller tasks. We presumed that these decomposed subtasks can be categorized into a unified subtask type set. Furthermore, such a decomposition and categorization makes the selection for the appropriate information-presentation method much clearer and easier. For an easier selection of an appropriate method, we present two main filters.

- 1. Filtering by the six types of subtasks.** In the first step, the user divides the target task into multiple subtasks and categorizes each to one of the six subtask types predefined by its purpose (Section 3.3). Each subtask has different properties of information to be presented to the user. Hence, the appropriate information presentation subset is different for each subtask.
- 2. Filtering by the DOF of tracking used for each subtask.** An additional step considers the strong limitation of the DOF of tracking for each subtask to realize the AR system (Section 3.4).

For each subtask, the available information-presentation methods are narrowed down based on the type of subtask and the DOF of tracking. In the final step, the user chooses one method among the remaining candidates with the guideline policy (Section 3.5) and the supporting tool (Section 4.3). Finally, these are outputted as an “information design table”, which includes sequential subtasks and the corresponding information-presentation methods for the system development. This filtering makes the user follow our information design process easier, as seen on Figure 3.

#### 3.2 Target User and Task

A previous study [25] has been for non AR technical person with a knowledge regarding maintenance. Similarly, we envision that our target users are expert technicians who craft work procedure manuals for novice company workers (e.g., group leaders who coordinates tasks in the factory). These experts have sufficient knowledge on the target task, and present information as technical assistance to novice workers in different media (e.g., paper, video). However, they may also not have enough fundamental knowledge on information-presentation methods with AR. Furthermore, we do not place assumptions on their ability to implement AR systems because this ability can be learned with the existing guidelines for AR system development kit or other learning materials. We also include experts with AR knowledge. We believe that choosing the right methods for each subtask, even if one is familiar with the use of AR, will be a bit of a challenge and that the guideline will enable easier choices.

For the target task, we focused on the assembly task, which is one of the most important processes in the industrial work. To narrow our scope, we assumed only one worker (non-collaborative work) working in a desk space.

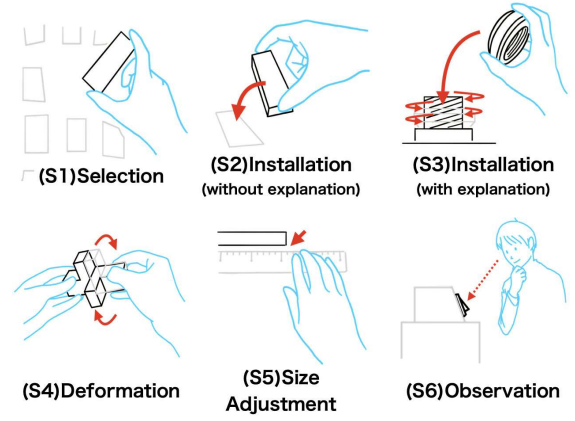


Figure 4: The images of the 6 subtask-types.

#### 3.3 Decomposition into Subtasks and Categorization

The first step is the decomposition of task into subtasks. Here the volume of each subtask is assumed to be small, such as “find part A and pick it up” or “assemble part B to part C.” In the subtask set, we empirically defined the following six types of subtasks through a pre-study where we decomposed 10 tasks including rope work (4 types), origami (2 types), block assembly (2 types), and PC assembly (2 types).

- S1 Selection** Find and pick up the object in the environment.
- S2 Installation (without explanation)** Fix the object to the target location (when the installation method is clear).
- S3 Installation (with explanation)** Fix the object to the target location (when the installation method is unclear and additional explanation is needed).
- S4 Deformation** Change the shape of the object to the target shape.
- S5 Size adjustment** Measure and adjust the target size, length, or volume of object to be used.
- S6 Observation** View the object from a target location and direction and check the state of the object.

For example, the task of attaching a hard disk drive (HDD) to the PC chassis is decomposed into the following tasks: 1) Find the HDD in the environment and pick it up (S1). 2) Attach the HDD into the target location inside the PC with the appropriate posture (until you hear a click sound). (S1), 3) Find the power cable for HDD and pick it up (S1). 4) Insert the cable into the HDD plug (S2). The available information-presentation methods for each type are described in Section 4.2 and Table 5 of Appendix.

#### 3.4 Tracking DOF for Each Subtask

In this second step, the tracking DOF for each target object and the user’s view is important, as they limit the applicable information-presentation methods. For example, if the object position cannot be tracked, only head-registered information-presentation methods can be used. On the other hand, the object tracking with 6DOF enables overlaying of the 3D model onto the target object. Therefore, in the second step, the user decides the available tracking technologies for each subtask to limit candidates of the information-presentation methods. Specifically, the user first considers the available tracking DOF for the user’s view toward the world coordinate system (hereinafter, user-tracking). This process is basically performed only once because we basically assume the same display device is consistently used and the tracking DOF for the display device will be also the same in a task. Then, the user also considers how the camera (whether attached onto the HMD or placed in the environment) can track each object in each subtask (hereinafter, object-tracking). The



guideline features four commonly-used DOF states: 6DOF (representing both position and rotation), 3DOF (position only), 3DOF (rotation only), and N/A (cannot be tracked). For instance, Microsoft HoloLens has 6DOF as its camera can track the position and rotation toward the environment.

### 3.5 Basic Rule for the Selection from Candidate Methods

The group of available information-presentation methods is limited based on the subtask decomposition/categorization, and the consideration of the tracking DOF. In the final selection, the user finally should choose one among the remaining candidates provided in the guideline. The basic requirements for the optimal method are ease of worker's understanding for the task and ease of implementation for the developer. In most of the methods, if the amount of assistance provided for the worker (hereinafter, the assistance level) is large, the high implementation cost is required. Specifically, displaying an image or a video onto the static location on the user's view is an example of the low assistance level with the low implementation cost. Conversely, an example of the high assistance level with the high implementation cost includes overlaying rich 3D models through an animation connected with a specific location in the real world. Here, we empirically observed that the method with the low assistance level is understandable enough for most subtasks and the method with the high assistance occasionally disturbs workers' task performance due to its excessiveness. Therefore, our guideline presents candidates of information-presentation methods in ascending order of the assistance level, as it basically recommends methods with a low assistance level. Moreover, we recommend to select a method with a higher assistance level only for a complicated subtask. This method is discussed in Section 4.3.

## 4 GUIDELINE DEVELOPMENT

In this section, the tool on web page that implements the idea in section 3 is described. We refer it as the "Guideline on Design Refinement of AR System (Dr. AR)" hereinafter. Dr. AR is available at <https://ar-guideline.naist.jp>.

### 4.1 Procedure of Information Design with Guideline

According to Section 3, first, the user detects the degree of freedom in the user-tracking decision, that is, the tracking DOF of the HMD to be used. Next, as shown in Figure 5, for each subtask, the user inputs the type of the subtask, the DOF in the object-tracking, the object name, and the content of the supporting information. Then, based on the input information, the guideline presents available information-presentation methods, and a video of an example of use cases in order of the lowest development cost. The user selects a method among the candidates with the checkbox. At this time, the user also can utilize the aid tool in Section 4.3 for easier selection. Those procedures are repeated for all subtasks. Finally, the website outputs the information design table including all information as a CSV file. The file is assumed to be referred while developing each step of the system by the developer. In the future, we aim to provide a support tool that facilitates the development of the AR system based on the information contained in the CSV file.

### 4.2 AR Information-presentation Method for Assembly Task Support

We divided these candidate information-presentation methods into the following elements (a summary is also in Appendix Table 5).

**Registration type** There are three main types of information registration methods for OST-HMD: the head registration that the information is displayed onto the static position of the user's FoV (e.g., [15] [20]), the object registration that the information is overlaid onto the target object or displayed next to the

object (e.g., [34] [11] [36]), and the environment registration that the information is overlaid at a specific position in the environment (e.g., [15], [34], [9]). The tracking DOF constrains this.

**Media type (availability of 3D models)** The media that conveys necessary information to the user include images, videos, and 3D models. 3D models are very different from other medias in terms of its capability to convey the spatial structure of an object in three dimensions [15] [37]. Thus, we defined the element to represent whether or not 3D models are used. The text can be displayed as additional information in all methods.

**Use of the current state of the object** In subtasks requiring a complex control of position-rotation on an object, the real-time overlay of the difference between the current and target state of an object may enable the worker's easier understanding [39].

**Use of the semi-transparent effect** The methods were classified according to whether or not the images and videos were transparent. When a transparent effect is used, the displayed information and the real object (environment) can be observed simultaneously, so the difference can be easily noticed [27] [11].

**Use of 2D rotation** When the direction of the worker's observation is different from the direction of the image or video capture, the user adjusts mentally. This mental rotation takes approximately 1 second to rotate 60 degrees, which increases cognitive load [35]. To cope with this, a method of displaying images/videos after rotating them in 2D to match those direction with the user's current direction has been proposed [26].

### 4.3 Aid for Decision of Information-presentation Method

The guideline presents the candidates of available information-presentation methods were presented to facilitate the selection. However, the user's knowledge and experience on the AR system are still required in this choice. Therefore, based on the findings of existing studies, we assumed various situations in which the specific methods can improve the work efficiency. Then, that information is provided via the checkbox function related to the characteristics of the subtask, and the working environment. When the user selects a checkbox corresponding to his or her subtask, a recommendation mark is displayed to the candidates that are appropriate for that situation.

### 4.4 Tips for Development

The guideline comes with various AR task support systems in its creation, and the know-hows obtained from their system development. An example is shown below.

"In the selection subtask, if images or movies are displayed with head-registration, the guideline recommends that they are displayed in full scale." In finding a specific part among various ones, its size can be also a clue. The worker can find it by comparing the size of the image with the size of physical part.

## 5 EXPERIMENT 1: GUIDELINE USE EVALUATION

### 5.1 Evaluation Method and Overview

We conducted two experiments for the purpose of answering the corresponding research questions: (1) How does the use of the proposed guideline, which is based on filtering information-presentation methods by six subtask classifications and investigating the tracking DOF, affect the AR system information design? (2) What are the effects on task support of the system implemented based on the information design using the proposed guideline? For this purpose, the following two experiments were conducted.

In Experiment 1, we asked participants to perform the AR system information design for predetermined tasks using the guidelines. We then compared the resulting information design with one using the existing guidelines to determine what kind of design was undertaken.

Figure 5: The flow of use of the website.

We also evaluated the usability of the guidelines, including the validity of the current subtask types. In Experiment 2, the experimenter actually implemented the system based on the information design table created in Experiment 1. The participants were asked to perform the tasks using it. The effects of the system on task support were assessed by comparing the work efficiency and usability of the system with those in one based on the existing guidelines.

## 5.2 Participants

As described in Section 3.2, one of our target users was a creator of work procedure manuals for novice workers in a company. However, because of the difficulty of utilizing such a user, we employed an alternative participant in this study after the following considerations. The above users are considered to have 1) a good understanding of the work, 2) the ability to express information in a way that is easy for people to understand on paper, and 3) a minimum amount of knowledge about AR (required for guideline use) but no actual development experience in some cases. We compensated for (1) and (2) by providing training before the experiment, as described in Section 5.5. We confirmed (3) by conducting a simple test on the web that asked the basic knowledge of AR upon recruitment. For those who scored less than 60%, we provided a textbook [33] and had them study parts of it in advance to confirm that they had acquired a minimum level of knowledge.

We recruited 18 students (all graduate students, 16 males, two females, ages 23 to 27 years) by e-mail at a local university. Among them, three participants did not pass the test, so they learned with the aforementioned method in advance. At the same time, when we checked the number of times they had developed a system using AR, ten of them had no experience, seven had developed a system one to three times, and one had developed a system more than three times. We divided the participants into two groups, as described in Section 5.4 ensuring an equal distribution of these development experiences. We paid each participant an honorarium of 3,000 JPY after approximately 3 hours of the experiment.

## 5.3 Experimental Task

Users performed two types of tasks, PC assembly and rope work, to consider the information design with reference to the guideline. The former required a variety of rigid components, whereas the latter required only a pole and a deformable rope. We chose these tasks to assess if the guidelines can accommodate with the relative characteristics. Table 1 and 2 show the entire process of each task.

## 5.4 Experimental Condition

To compare the information design using our proposed guideline with the one using existing guidelines, we established the used guideline as an experimental factor and conducted a between-subject

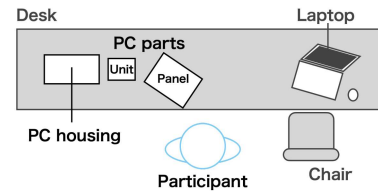


Figure 6: Experiment 1 environment setup for PC assembly

experiment. We refer to the condition with the proposed guideline as Con.P and the condition with the existing guidelines as Con.E. In Con.E, we referred to three guidelines: “Augmented Reality Design Guidelines” by Google Inc. [2], and “AR in Human Interface Guidelines” provided by Apple Inc. [1], and “Mixed Reality Guideline” by Microsoft Corporation [5]. In the experimental environment (Figure 6), participants checked the work contents on a laptop, checked the real tasks while standing, and then created the design table again on the laptop. Microsoft HoloLens was assumed to be the display device for the system to be designed. In addition, the tracking DOFs for each component were predetermined and the participants could refer to those at any time.

## 5.5 Procedure

We divided the participants into two groups in advance to balance participant experience of AR system development in both groups. One group created an information design table of the AR system in Con.P and the other group created it in Con.E. Firstly, the experimenter provided an explanation on the experiment overview to a participant and obtained the informed consent from him/her. Next, each participant sufficiently learned how to create an information design table for the AR system using the guideline(s) for 50 min as a tutorial task (block assembly). In the existing guidelines, the experimenter introduced the participants to each site in separate tabs, and since especially Microsoft site has a lot of text, mainly introduced them to parts with photos about information-presentation methods. All sites were in English, and if participants were not good at English, they were presented in Japanese using the translation function of Google Chrome. Then the participants could refer to these at any time during the experiment. On the other hand, in proposed guideline, the experimenter introduced the participants to our tool, “Dr. AR”. After the training on the guideline use, the participants first watched a video of experimental task 1 and then experienced it for 15 min to fully understand it. Then, in 45 min, the participant in Con.P developed an information design table for the target task on a laptop, following the procedure in Section 4.1. Meanwhile, the participant in Con.E created an information design table by directly entering each subtask and determining how the information is presented on an Excel sheet on a laptop. Finally, the

experimenter administered questionnaires and interviews on the design table and guideline to the participants for 5 min. After a 10 min break, the same procedure was repeated with the same guideline(s) for task 2. The order of experimental tasks 1 and 2 was balanced among participants to avoid learning effects.

After completion of the two tasks, each information-presentation methods selected or described by each participant in the information design tables was classified into nine types based on the classification in section 4.2. In both conditions, the experimenter interactively asked the participants about the described contents to eliminate inaccurate classifications due to open-ended statements.

## 5.6 Outcome Measurements

We categorized the evaluation indicators into two: (1) evaluations of each participants' information design table (IDT) and (2) the usability of the guideline (GU). We analyzed the results with the indicators listed below.

**IDT1 Information-presentation method** We confirmed what method was used for each subtask by each participant.

**IDT2 Pseudo-implementation cost** We confirmed the implementation cost inferred from the design table. Depending on the materials used in each information presentation method, the cost is clearly different. Creating a 3D model requires time and money. The additional animation using the 3D model is also expensive even if it can be prepared in advance (e.g., from 3D CAD). Furthermore, the cost of making 3D models differs depending on whether it could be substituted by a combination of general primitives, such as rectangles, spheres, or arrows prepared in advance, or if it needed to be made by oneself. In this study, the number of times of selecting each presentation method was used as a substitute index of the implementation cost of creating the 3D model (if not, i.e., an image or video was used instead), the necessity of making one's own 3D models (hereinafter, primitive or original), and the necessity of creating the animation.

### GU1 Task decomposition/categorization: intersubject variability

We assessed the inter-subject variability in the results of decomposing each task into subtasks and categorized them. If the difference among participants was small, then no one was lost in the categorization, i.e., the six subtask types in this study were considered reasonable. For this metric, we employed the Levenshtein distance [12], which is often used to represent the similarity of two strings in the field of natural language processing and life information science. It was applied to represent the similarity of two information design tables by regarding the type assigned to each subtask as a character. This distance was defined as the minimum number of operations in the procedure of converting one string to another using the three editing operations: replacing, adding and deleting characters. We evaluated the inter-subject variability of each group by calculating the brute force mean of the distances between participants within the same group.

## 5.7 Result

The summary shown in Table 1 (PC assembly) and Table 2 (rope work) indicate the information design generated by the participants. The object Tracking row shows the tracking DoF predefined for each objects in each process.

Then, a series of horizontal bars represent participants' selections, with each color indicating the type of information-presentation method. In addition, the bars are arranged based on the participants' experience of the AR system development in each group (less in upper cluster, more in lower cluster). The blue color denotes a simpler approach of presenting information, whereas the red color is a higher-assistance-level approach requiring a 3D model. Horizontal

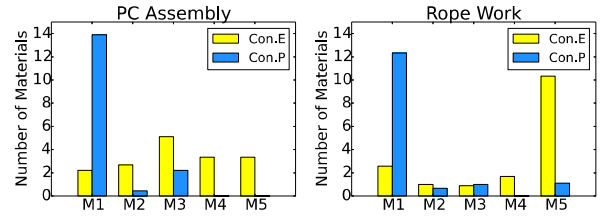


Figure 7: The average number of materials used in information-presentation methods for each participant. The method on the right is assumed to incur a higher implementation cost. Material used in information-presentation method M1: image or movie, M2: primitive 3D model, M3: primitive 3D model with animation, M4: original 3D model, M5: original 3D model with animation. Note that Material M1: used in A-F, M2-5: used in G-I (in Table 5).

subdivisions of the bar indicate subtasks in the process, while vertical subdivisions indicate simultaneous use of two information presentation methods. The star on the left of each information-presentation method in Table 1 and 2 indicates that each participant judged the method to be difficult after the experiment. Each participant was asked, "Which subtask was difficult for you in actually performing the work?" As clearly shown in the tables, participants generally employed high-assistance-level information-presentation methods in Con.E, and simple low-assistance-level methods in Con.P, with exceptions discussed in the next subsection.














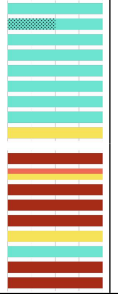

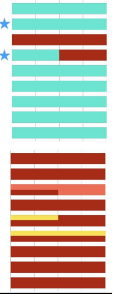
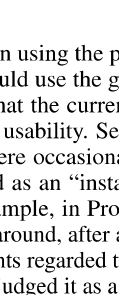
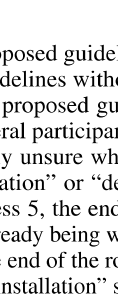
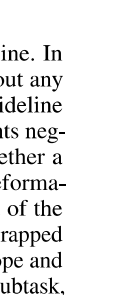
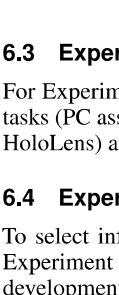
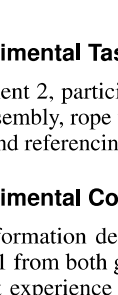
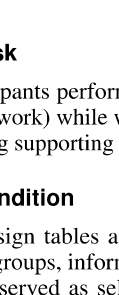
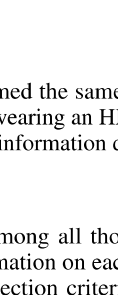
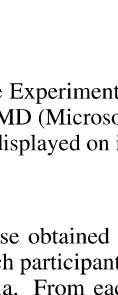
Figure 7 illustrates the participant mean values of the selected numbers of materials in each method sorted in terms of the pseudo-implementation cost (Section 5.6). We performed a non-parametric Mann-Whitney test between each condition. We regarded each method as an ordinal measure whose implementation cost is higher toward the right. For both tasks, the implementation costs of Con.P were significantly lower than of Con.E (PC assembly:  $p < 0.01$ , rope work:  $p < 0.01$ ).

The "Subtask-Variability (LD)" shows the Levenshtein distance for the inter-subject variability of the subtask decomposition/categorization results. In the PC assembly, the values were smaller in Con.P than in Con.E, except in process 6. Most of the values were less than 0.3, indicating a constantly uniform selection among participants. Conversely, for rope work, values were larger in Con.P than in Con.E in all processes except Process 1.

## 5.8 Discussion

The experiment confirmed that our proposed guidelines produced the information design tables with significantly lower pseudo-implementation costs than the existing guidelines. This result was obtained by the user following the guideline selection criteria for the information presentation, as described in Section 3.5, compared to the existing guidelines that recommend 3D models. Here, the exceptions are discussed, i.e., the certain subtasks for which a method with a higher assistance level was selected. In PC assembly, such exceptions were found in steps 3, 4, and 5. Those were the processes of finding a target connector in a PC chassis with many cables, and inserting it into the correct connector port among the multiple ports nearby. Some participants judged this to be difficult and thought that the method of directly pointing to the port in real space with the object-registered 3D model would be effective at avoiding an incorrect installation. In steps 2 and 9 of the rope work, which were deemed difficult, the images and movies with head-registration were employed instead of a 3D model. According to the interview results, participants noticed that displaying the 3D model on the target object reduced the visibility of the work space in processes with complex deformations. This is because the proposed guideline featured a video for illustrating each candidate information-presentation method. Therefore, it can be inferred that the participants chose information-presentation methods by account-

Table 1: Results of the information design for the PC assembly task. Subtask-Variability (LD): the inter-subject variability of the subtask results. Information-presentation method A: display images/videos with head-registration, B: A + the semi-transparent effect, C: A + 2D rotation in relation to the HMD, D: display the arrow to guide user with head-registration, E: display images/videos with world-registration, F: display images/videos with object-registration, G: display 3D model with world-registration, H: display 3D model with object-registration, I: display 3D model of the current object-state with object-registration. Blue (red) means lower(higher)-assistance-approach.

Process		1	2	3	4	5	6	7	8
Description		Mount the power supply unit.	Install the four short screws.	Plug the ATX connector.	Plug the CPU connector.	Plug the SATA connector.	Put all cables inside the PC housing.	Install the panel on the side of the PC housing	Install the four long screws.
									
Object Tracking		PC-housing: 6DoF, Unit: 6DoF	Screws: N/A	Connector: N/A	Connector: N/A	Connector: N/A	Cables: N/A	Panel: 6DoF	Screw: N/A
Subtask-Variability(LD)	Con.P Con.E	0.11 0.36	0.27 0.87	0.27 0.77	0.27 0.71	0.27 0.54	0.56 0.00	0.27 0.77	0.36 0.74
Information Presentation Method	Con.P								
	Con.E								

ing for the work properties when using the proposed guideline. In this study, as all participants could use the guidelines without any serious problems, confirming that the current proposed guideline possesses the minimum level of usability. Several participants negatively commented that they were occasionally unsure whether a certain subtask was categorized as an “installation” or “deformation” in the rope work. For example, in Process 5, the end of the rope should be further wrapped around, after already being wrapped around the pole. Some participants regarded the end of the rope and the pole as separate objects and judged it as a “installation” subtask, whereas others regarded the pole and the wrapped rope as a single object and considered it as a “deformation” subtask. The ambiguity of the definition of each subtask may have caused such difficulties.

## 6 EXPERIMENT 2: EVALUATION OF SYSTEM QUALITY ON INFORMATION DESIGN WITH THE PROPOSED GUIDELINE

### 6.1 Overview

We evaluated the quality of the system developed based on the information design that used the proposed guideline in experiment 1. We compared the result with the one based on the system developed using an existing guideline by asking the participants to perform the tasks using these systems. Thus, for Experiment 2, the same experimenter actually implemented the system based on the information design table created in Experiment 1. Participants used this system to perform the tasks. We evaluated the comprehensibility of the information-presentation method with the working time, number of errors, and system usability.

### 6.2 Participants

We recruited 20 participants (all graduate students, 15 males, 5 females, ages 22 to 34 years) via email from a local university, excluding those who previously participated. After finishing the experiment, each participant received a 1,000 JPY voucher.

### 6.3 Experimental Task

For Experiment 2, participants performed the same Experiment 1 tasks (PC assembly, rope work) while wearing an HMD (Microsoft HoloLens) and referencing supporting information displayed on it.










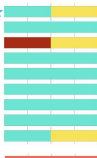


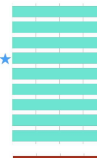
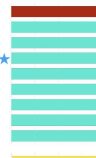
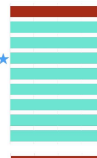

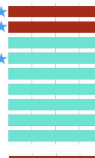

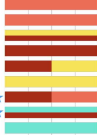








### 6.4 Experimental Condition

To select information design tables among all those obtained in Experiment 1 from both groups, information on each participant’s development experience served as selection criteria. From each group, we selected two information design tables for each task: one created by a participant who developed the most AR systems and scored highest on the test (denoted by E), and another created by a participant who had no development experience and garnered the lowest score (denoted by IE). Based on selected tables, the experimenter implemented four systems in advance for one task, crossing two factors: *used guideline* (Proposed and Existing, denoted by P and E), and *development experience* of the Experiment 1 participant (denoted by E and IE). simplicity, we label each system condition as follows: Con.P-E, Con.P-IE, Con.E-E, and Con.E-IE.

Among these system conditions, some elements vary, like information-presentation methods (as shown in Table 3), and existence of supplementary information. Taking rope work for example, an overview of the four systems are as follows (illustrated in Figure 8): In the Con.P-E system, many cases adopted the information-presentation method of images or movies with head-registration. In the Con.P-IE system, some cases also adopted the 3D animation with object-registration, while mainly using the same head-registration method. In the Con.E-E system, many cases adopted the method of the 3D animation with object-registration. Additionally, head-registration came with supplementary information, such as the required number of rolls, and “pull strongly”. Finally, in the Con.E-IE system, all cases adopted the method of displaying the 3D animation with object-registration, along with the changing of the color of noteworthy places in the 3D animation to red.



Table 2: Results of the information design for the rope work task. Subtask-Variability (LD): the inter-subject variability of the subtask results. Information-presentation method A: display images/videos with head-registration, B: A + the semi-transparent effect, C: A + 2D rotation in relation to the HMD, D: display the arrow to guide user with head-registration, E: display images/videos with world-registration, F: display images/videos with object-registration, G: display 3D model with world-registration, H: display 3D model with object-registration, I: display 3D model of the current object-state with object-registration. Blue (red) means lower (higher)-assistance-approach.

Process		1	2	3	4	5	6	7	8	9
Description		Measure a rope. 	Wrap and tie the rope around poles. 	Loop the rope horizontally. 	Wrap the rope around the front pole. 	Loop the rope vertically. 	Pull the rope behind the front pole. 	Loop the rope diagonally. 	Insert the rope under the last loop. 	Tie the rope around the front pole. 
Object Tracking		Rope: N/A, Ruler: 3DPos	Poles: 6DoF							
Subtask-Variability(LD)	Con.P Con.E	0.22 0.63	0.74 0.41	0.67 0.27	0.67 0.00	0.67 0.00	0.67 0.00	0.70 0.00	0.67 0.00	0.82 0.34
Information Presentation Method	Con.P									
	Con.E									

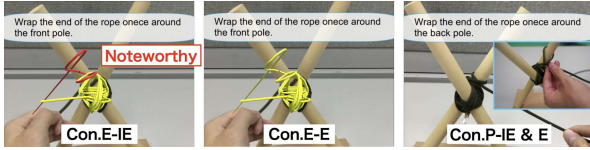


Figure 8: Presentation methods of four systems of the four conditions in a subtask of Process 9 of rope work

We adopted a between-subjects design in which each participant performed the PC assembly and rope work tasks with one system respectively chosen for each task.

## 6.5 Procedure

First, the experimenter provided an explanation on the overview of the experiment to a participant and obtained informed consent from him/her. He/she wore the HoloLens and performed a 10-min. training phase with a tutorial task (block assembly) for operation familiarity. The training presented how to perform the task while observing the information on the HMD, and how to continue to the next step in sequential tasks. The participant can select any of three available input methods, namely, AirTap (a one-handed gesture), Clicker (a one-button Bluetooth controller), and Voice Input (supported by a one-button Bluetooth controller). After training, they performed a task (i.e., PC assembly or rope work) with a certain system (i.e., Con.P-E, P-IE, E-E, or E-IE). The experimenter ensured participants did not know which system was used. After the first task, they completed several questionnaires on any observed on-task fatigue. Then, after a 5-min. break, they repeated the above procedure for the second task with another different system.

## 6.6 Outcome Measurements

We recorded data from the following as indices for evaluating the ease of understanding the tasks using each information-presentation method:

**Number of errors** In each subtask, the following three cases were

regarded as errors: 1) The cases when the participant performed the same subtask without any progress for more than 30 seconds, 2) when they gave up performing the subtask and asked the experimenter for help, 3) or when they moved to the next subtask although they did not notice that it was not completed yet. When the experimenter identified each error case, he immediately taught the participant the correct working method and asked them to redo the work.

**Working time** We recorded the time required for the actual task, excluding the time taken to provide input through the HMD and attach/detach the HMD from the measurement to focus only on task performance. However, we included the times of instruction by the experimenter and repeating when the errors occurred in the working time owing to the difficulty of removing them. Furthermore, we measured the working time for each process to evaluate the effect of each method for subtasks with different properties.

**Subjective Workload** Finally, we assessed subjective workload with the NASA Task Load Index (TLX).

## 6.7 Hypotheses

Basically, we expected that the system based on the proposed guideline would improve the participant's understanding of the task regardless of the development experience of the person who designed the system. This is because we thought that the candidate filtering and recommendation tool would bridge the gap in tacit knowledge that arises from the development experience of users. We thus set the hypotheses as follows.

**H2-1** The numbers of errors with Con.P-E and Con.P-IE are lower than those with Con.E-E and Con.E-IE.

**H2-2** The working times with Con.P-E and Con.P-IE are shorter than those with Con.E-E and Con.E-IE.

**H2-3** The work loads (score of NASA-TLX) with Con.P-E and Con.P-IE are lower than those with Con.E-E and Con.E-IE.

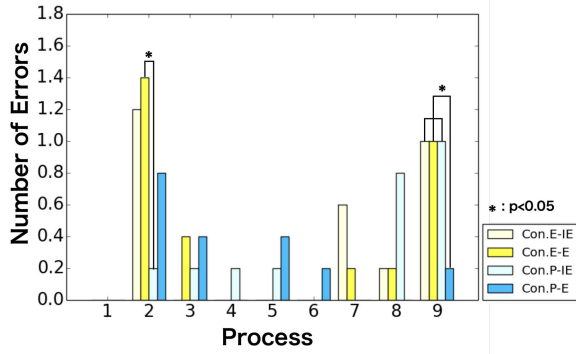


Figure 9: The number of errors for each process in rope work

## 6.8 Results

We used Levene’s test on our data, and confirmed the equivariance of each measure. We also used Shapiro-Wilk normality test and found out that only results of the number of errors did not follow normal distribution. Thus, we applied a Kruskal-Wallis test and Dunn-Bonferroni test for error data and a two-way ANOVA for other outcome measurements ( $\alpha = 0.05$ ). Table 3 shows the average working time and score of NASA-TLX and Table 4 shows the average number of errors. Although the average number of errors in PC assembly and rope work were both  $\text{Con.P-E} < \text{Con.E-E}$  and  $\text{Con.P-IE} < \text{Con.E-IE}$ , the differences were not statistically significant. Similarly, in both average working time and NASA-TLX, both the main effect of the guideline type and development experience were also not significant. Therefore, H2-1, H2-2 and H2-3 could not be supported.

To investigate further, we focused on error results as the most important factor in task completion (see Figure 9). In processes where participants deemed difficult in Experiment 1, the number of errors had statistically significant differences. Specifically, these are in Process 2, where  $\text{Con.P-IE}$  is less than  $\text{Con.E-E}$  ( $p = 0.044$ ) and in Process 9, where  $\text{Con.P-E}$  had the least errors ( $\text{Con.P-E-Con.E-E}$ :  $p = 0.012$ ,  $\text{Con.P-E-Con.E-IE}$ :  $p = 0.012$ ,  $\text{Con.P-E-Con.P-IE}$ :  $p = 0.012$ ).

## 6.9 Discussion

While our guideline may provide positive effects on errors and working time according to the effect size, they were not statistically significant due to the small number of participants. However, we observed a decrease of errors by our guideline for particular processes. Process 2 of rope work consisted of complex processes in which ropes were tied and secured to the pole while intertwining with each other. In this process, while the 3D animation was displayed with object-registration to show how to tie the rope by changing the color of noteworthy places in  $\text{Con.E-IE}$  and by same color in  $\text{Con.E-E}$ , the video was displayed with head-registration in  $\text{Con.P-IE}$  and displayed with head and environment-registration in  $\text{Con.P-E}$ . There were large effects between  $\text{Con.Es}$  using 3D models and  $\text{Con.Ps}$  using videos, particularly, between  $\text{Con.E-E}$  and  $\text{Con.P-IE}$ . After the experiment, we received comments from the participants who used the existing guidelines, such as “It was difficult to check the status of the work because the 3D model was in the way” ( $n = 4$ ) and “I felt uneasy about completing the process” ( $n = 6$ ). Because the ropes themselves were not tracked, there was a discrepancy between the real object and the overlaid 3D model, making it difficult for the participants to understand the process. By contrast, the simple displaying of an image with head-registration may not have produced such problems. From these results, it is inferred that displaying images or movies at a non-target-object location may be more suitable than overlaying 3D models on a real object in the subtask when

complex deformation of the target is needed.

In addition, in process 9 of rope work,  $\text{Con.P-E}$  had the least number of errors. In only  $\text{Con.P-E}$ , the subtask of “observation” to guide a user to the appropriate work position/posture was adopted before the subtask of tying the rope. Therefore, the observation of the object occasionally made it possible for users to grasp the situation from an appropriate viewpoint, which may have reduced the errors.

Regarding the uniformity of information presentation for each subtask, one of the participants commented after the experiment, “The information-presentation method changed depending on the subtask, and the reduced uniformity made it difficult to check it.” In fact, the number of errors was lower in some processes that consistently used the same method than in the processes that included such switching of the registration type. Therefore, the uniformity of the types of the methods should be also considered in selecting methods in the future.

With regard to PC assembly, 16 participants commented that 3D model using animation displayed on the installation site made it easy to understand the process of installing the connector. In the installation subtask, where there were several similar installation sites around the correct one, they considered the information-presentation method using 3D models and animations effective.

After the experiment, many participants negatively commented on the usability of the HMD, such as “it was heavy ( $n = 6$ ),” and “the viewing angle was narrow ( $n = 6$ ).” The participants adjusted the HMD during the work an average of 6.9 times per person (PC: 6.5; rope: 7.5). Accordingly, to compare the experimental systems with a traditional method for task support (video viewing with a tablet), we conducted a small follow-up experiment in which five different participants performed each task. The average working time of PC assembly task was 475 s, with 0.6 occurrences of errors, whereas the time of the rope work was 405 s, with 1.2 occurrences of errors, all of which were significantly better than the four conditions in experiment 2. Therefore, the systems using HoloLens with the proposed guideline may still be inferior to the traditional information-presentation method, at least for the two tasks. However, as mentioned above, the current HMD wearability and the FoV were likely key factors. By performing the same experiment with a more sophisticated device (e.g., HoloLens v2), we believe that systems designed with the proposed guideline can be expected to compete with the traditional method.

## 7 GENERAL DISCUSSION

### 7.1 Findings

Using the experiments’ results, we discuss the research questions in Section 5.1.

(1) *How does the use of the proposed guideline and the tool affect the information design behavior of the AR system?*: First of all, results revealed that all participants could perform the information design of the AR system with no major problems for the two completely different tasks. This suggests that the proposed guidelines could be extended as a framework for information design. In  $\text{Con.P}$  conditions, participants tended to add an “observation” before a main subtask, in which the observation direction of the work object changed significantly, contributing to the error reduction in some processes, as discussed in Section 6.9. Thus, the current six subtask classifications in this study had a locally positive impact on user information design.

In Experiment 1, several participants chose the information-presentation method that could not be used unless the connector of the PC could be tracked in  $\text{Con.E}$ . Nevertheless, there were no such participants in  $\text{Con.P}$ . This finding implies that consideration of the available tracking DOF helped the user’s selection.

When using the proposed guideline, the implementation of information design tended to have a smaller cost than when using

Table 3: The working time and total score of NASA-TLX.

		Con.E-IE	Con.E-E	Con.P-IE	Con.P-E	Guideline		Effect size	Experience		Effect size
		F(1,16)	p						F(1,16)	p	
Working Time	PC	601±92	597±103	538±63	554±79	2.263	.152	d=.71	0.115	.739	d=.15
	Rope	499±95	543±78	578±79	60±60	2.996	.103	d=.80	0.687	.419	d=.36
NASA-TLX	PC	34.8±14.3	43.8±17.7	51.2±12.0	27.2±11.1	0.000	.989	d=.01	1.153	.299	d=.44
	Rope	68.6±20.7	60.0±17.9	71.8±21.7	57.0±11.0	0.000	.991	d=.01	1.635	.219	d=.60

Table 4: The number of errors. (Z: test statistic value, n: the number of data)

	Con.E-IE	Con.E-E	Con.P-IE	Con.P-E	p	Effect size ( $r = \frac{Z}{\sqrt{n}}$ )
PC	1.0±0.6	2.2±1.5	0.8±0.8	1.0±0.6	.265	r=0.89
Rope	3.0±0.6	3.2±1.0	2.8±1.0	2.0±0.6	.198	r=1.04

the general/existing guideline. Furthermore, the subtask properties dictated the assistance level of the information-presentation method to be adopted (i.e., the presence of similar installation holes near the correct positions needed high assistance). The readily available sample video for each method presented in the proposed guideline might have been the reason. This comparison among the videos influenced many participants' decision to choose displaying images and videos with head-registration as more suitable. This seems to be a particularly important characteristic, especially for task support systems with short development cycles or short usage periods.

(2) *What are the effects on task support of the system based on the information design with the proposed guideline?*: While the system created out of the proposed guideline information design did not significantly impact the working time and subjective workload, the significant error reduction in complicated tasks (e.g. hard to track object in rope work Process 2) indicate an advantage. The effect of the proposed guideline may have been more pronounced for a task including more of such subtasks because the guideline will advise against ineffective information-presentation methods and suggest alternative ones.

## 7.2 Limitation and Future Work

The result of Experiment 1 suggested that the ambiguity of the current definition of a subtask (especially deformation) may have caused confusion for some users when categorizing. In the future, this definition should be clarified according to the number of objects used, the means of interacting with them, and the target conditions. Additionally, we should investigate if the subtask decomposition and categorization process can be investigated can accommodate more diverse tasks. Furthermore, we believe that a (step-by-step) selection tree for the subtask categorization may ease confusion.

As mentioned in Section 3, the current guideline basically leaves the final choice for the user among the candidate information-presentation methods after filtering. It presents a recommended method according to a checkbox input of the subtask characteristics as a selection aid (Section 4.3). Inexperienced participants commented that it was difficult for them to judge the subtask characteristics. Therefore, a more systematic manner of determining the information-presentation method will be considered in the future. At this time, the consistency of methods in sequential subtasks should be also taken into account.

In our experiments, the DOF of available tracking in each process were set beforehand, but the user needs to decide on the actual use. In the future, we plan to prepare condition-based questions that can be easily identified by inexperienced users (e.g., available tracking devices, tracking libraries (e.g., Vuforia), availability of a CAD model of the object, and possibility of marker attachment onto the object (Is each side of the object larger than x mm?)).

Although the current guideline focuses on the target task and the available tracking DOF for considering the appropriate information-

presentation method, the individuals who will use the designed system should ideally also be considered. For instance, a novice worker will need a higher-level of assistance, whereas a skilled worker will be able to perform a task with only a lower level of assistance to help him/her recall the task procedure. Such user conditions will be incorporated into the guidelines in the future.

In this experiment, we verified with only with an HMD (i.e., the HoloLens), which may present safety issues in an actual industrial environment [21]. In the future, we should consider extending types of usable devices, as well as recommendation tool for the devices by asking the user to input the assumed working environment.

The results of this experiment may be difficult to generalize because of the very small number of participants, and only two types of tasks were examined. We also did not take into account each subject's familiarity with the experimental task, which may have biased the results. Furthermore, the participants were different from our target users, and the tasks likewise differed from those of an actual assembly factory. In Experiment 1, the participants seemed to occasionally decide information-presentation methods without considering the actual worker's behavior. On the other hand, the target user is well aware of that, so there will be differences in the usage of observation and in the position of the information presentation. One of the most important objectives in future works is to evaluate the guideline with actual users and actual tasks. The present issue is to provide easier user feedback collection functions, as well as a browsing function so that many actual users can use a web page to collect various feedback for further guideline improvements. We envision that this web page will work to provide access to AR system design knowledge from various users and help lower the barriers to task support-system development.

## 8 CONCLUSION

In this paper, we proposed an information-design guideline for an AR system to support assembly work. The main idea of this guideline is to narrow the choices of available information-presentation methods by decomposing the given task into six subtask types and the available tracking DOF for each subtask. The two experiments conducted in this study suggested the possibility for creating a system with low efforts creating media and minimal errors using the proposed guideline compared to the existing ones. The main goal of our future work is to improve these guidelines, now published as a web page, by increasing the number of active users, and by collecting actual data from users worldwide.

## ACKNOWLEDGMENTS

The authors wish to thank Takafumi Taketomi and Alexander Plopski for their help on the construction of the early prototype of the guideline.

## APPENDIX

Table 5: information-presentation method in DR. AR (Mar. 2020). The subtask types are as follows; S1:Selection, S2:Installation w. exp., S3:Installation w/o exp., S4:Deformation, S5:Size adjustment, S6:Observation. The registration types are as follows; H:Head, E:Environment, O:Object. Refer to <https://ar-guideline.naist.jp> for more details.

No.	Subtask type	Registration type	Use 3D model	Use current pos. of obj.	Use semi-transparent eff.	Use 2D rotation	Information Presentation Method ID
1	S1	H	no	no	no	no	A
2	S1	H	no	no	no	no	A
3	S1	E	no	no	no	no	E
4	S1	H	yes	no	no	no	D
5	S1	O	yes	no	no	no	H
6	S2	H	no	no	no	no	A
7	S2	H	no	no	yes	no	B
8	S2	H	no	no	no	yes	C
9	S2	E	no	no	no	no	E
10	S2	O	yes	no	no	no	H
11	S2	O	yes	yes	no	no	I
12	S3	H	no	no	no	no	A
13	S3	H	no	no	yes	no	B
14	S3	H	no	no	no	yes	C
15	S3	E	no	no	no	no	E
16	S3	O	yes	no	no	no	H
17	S3	O	yes	yes	no	no	I
18	S3	O	yes	yes	no	no	I
19	S4	H	no	no	no	no	A
20	S4	H	no	no	yes	no	B
21	S4	H	no	no	no	yes	C
22	S4	E	no	no	no	no	E
23	S4	O	yes	no	no	no	H
24	S5	H	no	no	no	no	A
25	S5	E	no	no	no	no	E
26	S5	O	no	no	no	no	E
27	S6	H	no	no	no	no	A
28	S6	H	no	no	yes	no	B
29	S6	H	no	no	no	no	A
30	S6	O	yes	no	no	no	H

## REFERENCES

- [1] Apple: Human interface guidelines - augmented reality. <https://developer.apple.com/design/human-interface-guidelines/ios/system-capabilities/augmented-reality/>.
- [2] Google: Augmented reality design guidelines. <https://designguidelines.withgoogle.com/ar-design/augmented-reality-design-guidelines/introduction.html>.
- [3] MagicLeap: MagicLeap One. <https://www.magicleap.com/>.
- [4] Microsoft: HoloLens. <https://www.microsoft.com/en-us/hololens>.
- [5] Microsoft: Mixed reality guideline. <https://docs.microsoft.com/en-us/windows/mixed-reality/design>.
- [6] Unity. <https://unity.com/>.
- [7] E. Bottani and G. Vignali. Augmented reality technology in the manufacturing industry: A review of the last decade. *The Institute of Industrial and Systems Engineers Transactions*, 51(3):284–310, 2019.
- [8] V. Chimienti, S. Iliano, M. Dassisti, G. Dini, and F. Failli. Guidelines for implementing augmented reality procedures in assisting assembly operations. In *Proc. International Precision Assembly Seminar*, pp. 174–179, 2010.
- [9] G. Evans, J. Miller, M. I. Pena, A. MacAllister, and E. Winer. Evaluating the microsoft hololens through an augmented reality assembly application. In *Proc. Defense + Security*.
- [10] P. Fraga-Lamas, T. M. Fernandez-Carames, O. Blanco-Novoa, and M. A. Vilar-Montesinos. A review on industrial augmented reality systems for the industry 4.0 shipyard. *IEEE Access*, 6(1):13358–13375, 2018.
- [11] M. Goto, Y. Uematsu, S. S. H. Saito, and A. Iketani. Task support system by displaying instructional video onto ar workspace. In *Proc. IEEE International Symposium on Mixed and Augmented Reality*, 2010.
- [12] D. Gusfield. *Algorithms on strings, trees, and sequences*. Cambridge University Press, 1997.
- [13] M. Haller, E. Stauder, and J. Zauner. Amire-es: Authoring mixed reality once, run it anywhere. In *Proc. International Conference on Human-Computer Interaction*, 2005.
- [14] M. Haringer and H. T. Rogenbrecht. A pragmatic approach to augmented reality authoring. In *Proc. The IEEE and ACM International Symposium on Mixed and Augmented Reality*, pp. 237–245, 2002.
- [15] S. J. Henderson and S. Feiner. Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret. In *Proc. IEEE International Symposium on Mixed and Augmented Reality*, pp. 135–144, 2009.
- [16] K. Kim, M. Billingham, G. Bruder, H. B.-L. Duh, and G. F. Welch. Revisiting trends in augmented reality research: Ar review of the 2nd decade of ismar (2008–2017). *IEEE Transactions on Visualization and Computer Graphics*, 24(11):2947–2962, 2018.
- [17] M. Kim, S. H. Choi, K.-B. Park, and J. Y. Lee. User interactions for augmented reality smart glasses: A comparative evaluation of visual contexts and interaction gestures. *Applied Sciences*, 9(15):3171, 2019.
- [18] C. Knofle, J. Weidenhausen, L. Chauvigne, and I. Stock. Template based authoring for ar based service scenarios. In *Proc. IEEE Virtual Reality*, pp. 249–252, 2005.
- [19] F. Ledermann and D. Schmalstieg. April: A high level framework for creating augmented reality presentations. In *Proc. IEEE Virtual Reality*, pp. 187–194, 2005.
- [20] T. Leelasawassuk, D. Damen, and W. Mayol-Cuevas. Automated capture and delivery of assistive task guidance with an eyewear computer: the glacier system. In *Proc. the Augmented Human International Conference*, pp. 1–9, 2017.
- [21] M. Lorenz, S. Knopp, F. Biocca, and P. Klimant. Industrial augmented reality: Requirements for an augmented reality maintenance worker support system. In *Proc. IEEE International Symposium on Mixed and Augmented Reality Adjunct*, pp. 151–153, 2018.
- [22] S. Makris, G. Pintzos, L. Rentzos, and G. Chrysosolouris. Assembly support using ar technology based on automatic sequence generation. *CIRP Annals*, 62(1):9–12, 2013.
- [23] P. Mohr, B. Kerbl, M. Donoser, D. Schmalstieg, and D. Kalkofen. Retargeting technical documentation to augmented reality. In *Proc. ACM Conference on Human Factors in Computing Systems*, pp. 3337–3346, 2015.
- [24] A. Y. C. Nee, S. K. Ong, G. Chrysosolouris, and D. Mourtzis. Augmented reality applications in design and manufacturing. *The International Academy for Production Engineering Annals - Manufacturing Technology*, 61(1):657–679, 2012.
- [25] R. Palmirani, J. A. Erkoyuncu, and R. Roy. An innovative process to select augmented reality (ar) technology for maintenance. In *Proc. International Conference on Through-life Engineering Services*, pp. 23–28, 2017.
- [26] S. Pathirathna, C. Sandor, T. Taketomi, A. Plopski, and H. Kato. Video guides on head-mounted displays: The effect of misalignments on manual task performance. In *Proc. International Conference on Artificial Reality and Telexistence & Eurographics Symposium on Virtual Environments - Posters and Demos*, 2016.



- [27] N. Petersen, A. Pagani, and D. Stricker. Real-time modeling and tracking manual workflows from first-person vision. In *Proc. IEEE International Symposium on Mixed and Augmented Reality*, pp. 117–124, 2013.
- [28] N. Petersen and D. Stricker. Learning task structure from video examples for workflow tracking and authoring. In *Proc. IEEE International Symposium on Mixed and Augmented Reality*, pp. 237–246, 2012.
- [29] R. Radkowski, J. Herrema, and J. Oliver. Augmented reality-based manual assembly support with visual features for different degrees of difficulty. *Human-Computer Interaction*, 31(1):337–349, 2015.
- [30] G. Reitmayr and D. Schmalstieg. Open tracker - an open software architecture for reconfigurable tracking based on xml. In *Proc. ACM Symposium on Virtual Reality and Software Technology*, pp. 59–66, 2001.
- [31] C. Rolim, D. Schmalstieg, D. Kalkofen, and V. Teichrieb. Design guidelines for generating augmented reality instructions. In *Proc. IEEE International Symposium on Mixed and Augmented Reality - Posters*, pp. 120–123, 2015.
- [32] D. Schmalstieg and G. Hesina. Distributed applications for collaborative augmented reality. In *Proc. IEEE Virtual Reality*, pp. 59–66, 2002.
- [33] D. Schmalstieg and T. Höllerer. *Augmented Reality Principles and Practice*. Addison-Wesley, 2016.
- [34] B. Schwald and B. de Laval. An augmented reality system for training and assistance to maintenance in the industrial context. *International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision*, 11(3):425–432, 2003.
- [35] R. Shepard and J. Metzler. Mental rotation of three-dimensional objects. *Science*, 171(3872), 1971.
- [36] M. Sukan, C. Elvezio, O. Oda, S. Feiner, and B. Tversky. Parafrustum: visualization techniques for guiding a user to a constrained set of viewing positions and orientations. In *Proc. the ACM Symposium on User Interface Software and Technology*, pp. 331–340, 2014.
- [37] A. Tang, C. Owen, F. Biocca, and W. Mou. Comparative effectiveness of augmented reality in object assembly. In *Proc. Conference on Human Factors in Computing Systems*, pp. 73–80, 2003.
- [38] J. Zauner and M. Haller. Authoring of mixed reality applications including multi-marker calibration for mobile devices. In *Proc. Eurographics Symposium on Virtual Environments*, 2004.
- [39] J. Zauner, M. Haller, A. Brandl, and W. Hartman. Authoring of a mixed reality assembly instructor for hierarchical structures. In *Proc. IEEE and ACM International Symposium on Mixed and Augmented Reality*, pp. 237–246, 2003.