A Comparison of 3D Models and Photographs in Augmented Reality for Assembly Procedures in Space

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ABSTRACT

a. **Objective**: In future space exploration missions, where communication delays and blackouts will impact communication with NASA's Mission Control Center (MCC), astronauts will need to perform tasks autonomously. The Virtual Intelligent Task Assistant (VITA) is intended to stand-in for MCC and help crew perform procedural tasks.

b. **Background**: The VITA project investigates the effects on human task performance of a virtual task assistant, combining procedure automation with augmented reality (AR). The VITA task assistant is designed to help the user perform maintenance and assembly tasks. A study at Johnson Space Center (JSC) investigated the use of VITA's 3D models in AR for assembly procedures.

c. **Method**: A study conducted at the NASA Johnson Space Center compares small rover model assembly using a static 3D model to assembly using photographs to illustrate procedure steps. This study was part of the Human Exploration Research Analog (HERA) Campaign 7.

d. **Results**: Findings from the HERA study indicate the use of 3D models for assembly tasks reduces user workload significantly over the use of photographs for the first task repetition.

e. **Conclusion**: The significant improvement in workload and overall acceptable performance with 3D models suggests that AR designs with a 3D model may be easier to learn than designs using photographs, when the task is unfamiliar to the user.

Keywords: Wearable devices; Multimedia; Virtual environments; Flight displays; Mental workload; Situation awareness; Long-term missions

Précis: The Virtual Intelligent Task Assistant (VITA) is intended to help astronauts perform procedural tasks. A study using VITA compared human performance using 3D models to performance using photographs in augmented reality for assembly procedures. Study findings show significant reduction in workload with 3D models for the first task repetition.

A Comparison of 3D Models and Photographs in Augmented Reality for Assembly Procedures in Space

In future space exploration missions, astronauts must be more autonomous and perform tasks with limited help from NASA's Mission Control Center (MCC), due to longer communication delays as missions go further from the Earth. The Virtual Intelligent Task Assistant (VITA) is intended to stand-in for MCC and help crew perform procedural tasks.

The VITA project investigates the effects on human task performance of a virtual task assistant, combining procedure automation with augmented reality user interfaces. The VITA task assistant was designed to help a user perform maintenance and assembly tasks. Task instructions are captured in procedures. In this study, the participant performed assembly or disassembly tasks using procedures listing sequential task instructions. When using the virtual task assistant, the user is guided through the procedure one instruction at a time, supporting hands-free performance of these assembly tasks. Visual aids available in VITA include textual task cues, photographs of partially assembled devices, and 3D models of these devices. The VITA task assistant runs as an augmented reality (AR) application on the Microsoft HoloLens 2 headset.

The VITA project performed a study investigating the use of 3D models in augmented reality for assembly procedures. This study was part of the NASA Human Exploration Research Analog (HERA) Campaign 7 (C7) at Johnson Space Center (JSC). The HERA C7 study compared user performance with a static 3D Computer-Aided Design (CAD) model to performance when using photographs to illustrate procedures actions for the assembly. Photographs are a common way to illustrate such actions in NASA procedures.

Related Work

Recent surveys of augmented reality for industrial application identify assembly and maintenance tasks as the most common application (Botanni and Vignali, 2019). Souza et al. (2025) surveyed nineteen applications of AR for industrial assembly tasks. Guidelines and techniques for AR displays to support manual assembly have been collected and proposed (Jeffri and Ramblin, 2020; Agati et al., 2020; Renner and Pfeiffer, 2017). Studies have been performed comparing AR for assembly on a variety of platforms, including tablets, desktop computers, and AR headsets (Blattgerste, et al., 2017; Alves et al., 2022; Belsito et al., 2023; Marino et al., 2024).

NASA space operations also require periodic assembly and maintenance tasks. As the International Space Station (ISS) ages, astronauts on ISS spend more of their time on assembly and maintenance tasks. NASA expects this trend to continue as exploration missions move beyond low Earth orbit and increasing distance from Earth makes it impossible for Earth-based crew like Mission Control to provide real-time procedural support. In consequence, AR task assistants, such as VITA, will become increasingly important for NASA crewed missions.

A common design approach for AR task assistance during assembly is placing virtual task cues near the real-world objects referenced in the cue (Tobiskova et al., 2024; Murauer et al., 2018; Jeffri and Ramblin, 2020). The VITA AR display, however, does not automatically position virtual cues near real-world objects during the assembly. Instead, virtual cues are placed near the relevant components in the 3D model. This design choice was made in response to characteristics of the assembly task that affected the reliability of image recognition (Schreckenghost, et al., 2024). Image recognition software like Vuforia (developer.vuforia.com/home) did not work well to distinguish the changing partial rover assemblies as the task proceeded. Additionally, the rover used many small parts that are similar in appearance. These components were difficult to identify and could be occluded by the user's hands during assembly. Botto et al. (2020) report similar difficulties with poor image recognition using VisionLib (visionlib.com/) in their Unity-based unity.com/solutions/xr/ar) AR app, "especially when the component is small and rich of details". They also found that occluding parts of a partial assembly could result in wrong object recognition. Finally, the field of view for the small rover assembly was limited when assembling these small parts and could become cluttered by adding virtual overlays near them. The VITA studies evaluate the use of 3D models to improve user performance for assembly tasks with these characteristics.

The use of 3D models for AR displays typically refers to the use of CAD assemblies that illustrate how parts fit together. The assembly process can be illustrated statically using an exploded model with action overlays (as done for VITA), or dynamically by animating the assembly sequence. Virtual objects, like arrows pointing at a real-world component to highlight it, are sometimes referred to as 3D symbolic cues as well. Radowski et al., (2015) found that the use of 3D models and animations to illustrate the assembly process improved task performance over the use of 2D images and 3D arrows to identify parts.

The HERA C7 study evaluated a 3D CAD model of the assembled rover, exploded to show the relative position of each component. This 3D model (called the base 3D model) does not change as the user moves through the assembly procedure. Components are highlighted in a companion 2D figure of the CAD model, with annotations that identify and label components used at each procedure step, and arrows that illustrate how these components fit together.

This base 3D model with figure is displayed in an AR headset. Performance using the base 3D model is compared to an AR display with task cues overlaid on photographs of rover parts and partial assembles that are specific to each procedure step. Both displays also provide textual instruction with the models and figures.

Dan and Reiner (2017) found that users reported significantly higher cognitive workload when processing 2D images than when processing 3D models. They also found the cognitive workload difference was higher for more complex tasks, such as the rover assembly task evaluated in VITA. Consistent with their findings, workload was reduced significantly for VITA when using a 3D model instead of photographs to learn small rover assembly tasks

Method

This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at NASA Johnson Space Center. Informed consent was obtained from each participant.

The VITA task assistant combines software for procedure automation with augmented reality displays. Procedure automation is provided by the Procedure Integrated Development Environment (PRIDE) electronic procedure software developed for NASA (Schreckenghost, et al., 2008) and used commercially for assembly and maintenance tasks in the energy and chemical industries. The PRIDE software encodes procedures using an XML-based procedure representation language (PRL) (Kortenkamp, et al., 2008). The PRIDE View server loads PRL procedures, displays them, and provides automation functions for their execution. Automation functions used for VITA include tracking the completion of a procedure task, cueing of the next task in a task sequence, and recording data related to tasks.

The PRIDE View server runs remotely as a cloud service. Client displays communicate with this server using a Representational State Transfer (REST) interface. Data from procedure execution are stored in a MySQL database. To improve system responsiveness, the 3D models were stored locally on the Microsoft HoloLens 2 headset.

Natively, PRL procedures are displayed in a browser using a web application. For VITA, new augmented reality displays were developed to investigate the performance effects of using 3D CAD models with assembly procedures. These AR displays were implemented as an application using Unity (unity.com/solutions/xr/ar) and Microsoft Mixed Reality Tool Kit (MRTK3) (learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk3-overview). The VITA app ran on a Microsoft HoloLens 2 headset (learn.microsoft.com/en-us/hololens/). The CAD 3D models in digital asset exchange (DAE) format were converted to an internal “prefab” format in Unity to improve loading efficiency.

The VITA task assistant was used to investigate the use of 3D models in augmented reality procedures for assembly tasks. A study was conducted during the NASA exploration analog HERA C7. Figure 1 shows crew member using VITA during a HERA C7 mission.

Figure 1. *HERA C7 crew member performing rover assembly with VITA*

HERA is a NASA analog facility that conducts simulated exploration missions for the purpose of human performance research (www.nasa.gov/mission/hera/). A HERA campaign consists of four missions. Each mission lasts for 45 days and has 4 crew members. During the mission, crew members work and reside inside the HERA habitat located at JSC; see Figure 2. They conduct tasks similar to those performed by astronauts in space. HERA C7 simulated a mission to Mars, including time-delayed communication. The VITA study provided a small rover assembly task performed as part of the crew's work to prepare for Mars exploration.

Figure 2. Human Exploration Research Analog (HERA) habitat used for NASA study

For this study, procedures are investigated that vary the visual aid used to illustrate an instruction. Specifically, user performance when using a static 3D model for assembly is compared to performance when using photographs annotated with assembly actions. When using the 3D model, a 2D image of the model annotated with assembly actions is also provided.

Figure 3 illustrates the two visual aids investigated by VITA in HERA C7. On the left of this figure, the visual aid using a 3D model with diagram is shown (the 3D Model condition). The 3D model is shown at the top of the screen. It can be moved where the user wants, and can be rotated by grabbing and moving the model. The 2D figure below the 3D model shows the labeled components for each step, followed by the actions indicated as arrows on the diagram. A caption with figure number is shown to the right of the 2D figure, and a textual instruction is shown below the 2D figure. On the right of this figure, the visual aid using 2D photos with annotations is shown (the Photograph condition). Similar to the diagrams of 3D models, photographs show labeled components for each step, followed by the actions as arrows on the photograph. As with the 3D model, a caption with figure number is shown to the right of the 2D figure and a textual instruction is shown below the 2D figure.

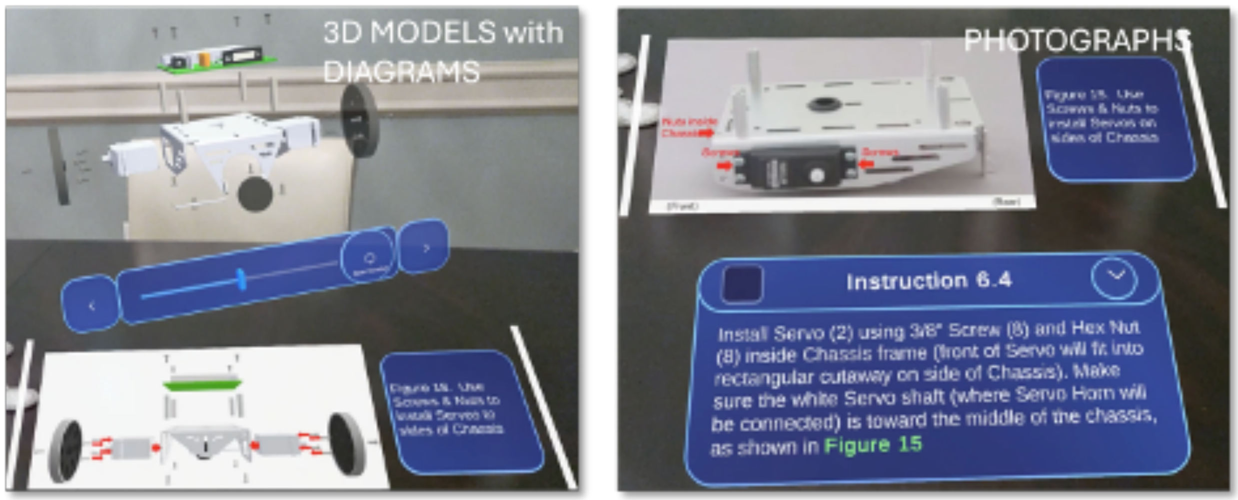

Figure 3. The two visual aids studied in HERA C7

To reduce practice effects on user performance, the two visual aids were evaluated using different but comparable procedures. The Photograph condition was evaluated using a procedure to assemble the rover with legs (Crawler), while the 3D model condition was evaluated using a procedure to assemble the rover with Gripper attached (Gripper). Figure 4 illustrates both rover configurations.

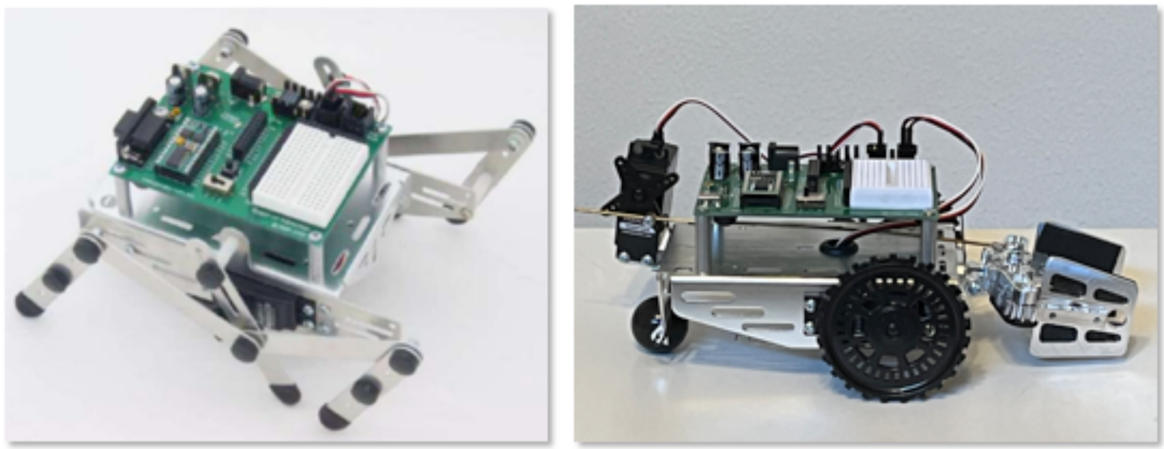

Figure 4. Rover Crawler configuration (left) and rover Gripper configuration (right)

The assembly procedures for these rovers have the same number of assembly actions, and the average assembly time for both procedures is within 10% of each other. Additionally, both assembly tasks are reported by users to be complex tasks. The sessions for the Photograph and 3D Model conditions are counterbalanced.

Each crew member used the VITA task assistant with two training procedures during pre-mission training. Then, each crew member used the VITA task assistant for 6 over the course of a month during the mission. All rover assembly procedures were performed twice. This permitted investigating the effect of practice on performance. The same assembly task was repeated from 1 to 3 weeks after the initial performance of the task. This study uses a within-subject design, counterbalanced for the 3D Model and Photograph conditions.

The VITA study in HERA Campaign 7 had a total of 16 participants (four crew for each of four HERA missions). Participants were selected by HERA to be of similar age and background as NASA astronauts. A survey was administered at the end of each session (end of condition survey) and after the final VITA session (end of mission survey). Data included measures for situation awareness, workload, usability, and task timing.

Results

In this section, human performance using 3D models is compared to performance using photographs in assembly procedures.

Workload

The Bedford workload scale (Roscoe, 1984) was administered at the end of each rover assembly session. The Bedford scale ranges from 1 (lowest workload) to 10 (highest workload). Table 1 compares workload when using photographs with workload when using the 3D model. The first row of this table shows the workload for the first repetition of the procedure, while the second row shows workload for the second repetition of the procedure. For the first repetition, the Photograph condition has a median workload of 6, while the 3D model condition has a much lower median workload of 3.5. When the procedure is repeated, however, the median workload is the same at 3.0 for both visual aids. Some workload differences may be due to task differences discussed earlier.

Table 1. Bedford workload for the VITA study in HERA C7

	Photograph		3D Model	
Session	*n*	*Median*	*n*	*Median*
First	16	6.0	16	3.5
Second	15	3.0	16	3.0

The large difference in median workload between the Photograph and the 3D Model conditions for the first assembly prompted an additional analysis of workload.

A Wilcoxon signed-rank test was done for median workload in the first session with both visual aids. The Wilcoxon signed-rank test is a non-parametric statistical test that can be used as an alternative to the paired samples T-test when data may not be normally distributed.

Figure 5 shows the respective medians of this test. Workload was higher for participants during the first rover assembly when using photographs for a visual aid than for the 3D model. This workload difference is significant (W = 10, p = .0429, r = 0.54), with a large effect size.

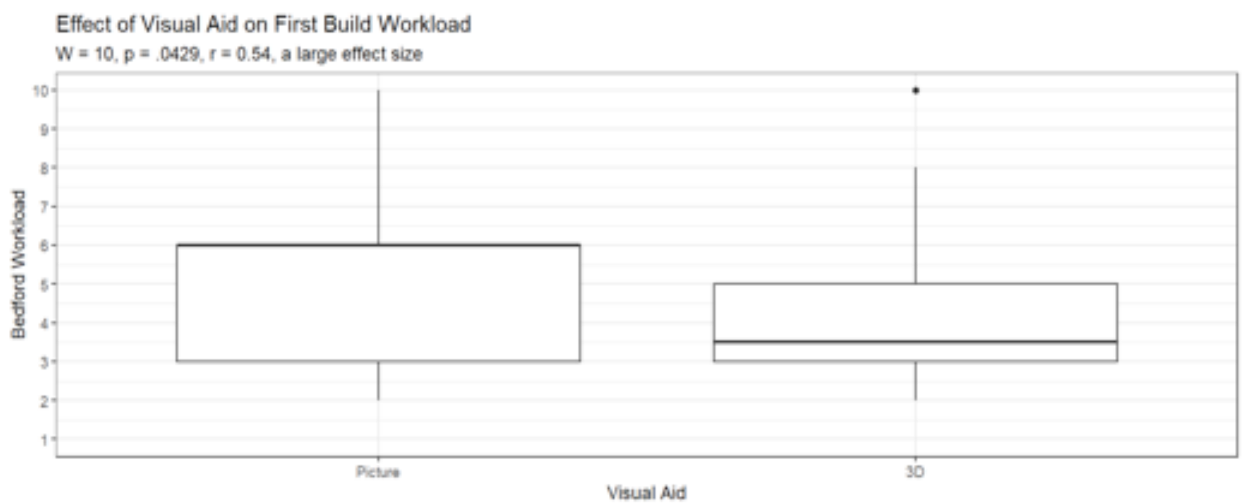

Figure 5. Bedford workload for first assembly compared in Wilcoxon signed-rank test for visual aids in HERA C7

Usability

System usability is measured using the NASA-modified System Usability Scale (NMSUS) (Holden and Robertson, 2022). NMSUS was assessed at the end of each assembly session. The NMSUS scale ranges from 0-100, where higher ratings indicate a more usable system. Table 2 compares usability with photographs to usability with the 3D model. The first row of this table shows usability for the first repetition of the procedure, while the second row shows usability for the second repetition of the procedure. Mean usability ratings for the Photograph and the

3D model conditions shown in Table 2 are comparable for both the first and second repetition of the procedure. Mean usability scores are considered “Acceptable” by the standards set in Bangor et al. (2009).

Table 2. Usability for the VITA study in HERA C7

	Photograph		3D Model	
Session	*n*	*M* (*SD*)	*n*	*M* (*SD*)
First	16	74.02 (20.50)	16	70.90 (21.64)
Second	16	79.69 (12.45)	16	77.54 (17.76)
Overall	32	76.86 (16.93)	32	74.22 (19.76)

Situation Awareness during the Task

Situation Awareness (SA) was measured during the assembly task. Participants were shown the definition of SA with guiding questions, as seen in Figure 6, and then asked to rate SA from a low of 1 to a high of 7. Two ratings were assessed by the participant, one halfway through the task (SA1) and one just after the task was finished (SA2).

Situation awareness (SA) is the perception, understanding, and anticipation of factors impacting the effective complete of the task

- Are you getting the information that you need to do the task?
- Do you understand what you are doing?
- Do you have a good feel for what is coming next?

Figure 6. Definition of situation awareness provided to the participant for the VITA study in HERA C7

Table 3 compares SA with photographs to SA with the 3D model. The first row of this table shows SA for the first repetition of the procedure, while the second row shows SA for the second repetition of the procedure. For the interim rating SA1, the median SA for the

Photograph condition is one point lower than the median SA for the 3D model. The final rating SA2, however, is similar for both visual aids. All SA ratings are moderately high.

Table 3. Situation awareness during the task for the VITA study in HERA C7

	Photograph				3D Model			
	SA1		SA2		SA1		SA2	
Session	*n*	*Median*	*n*	*Median*	*n*	*Median*	*n*	*Median*
First	15	5.0	16	5.5	16	6.0	16	5.0
Second	16	5.0	16	6.0	16	6.0	16	6.0

Situation Awareness after the Task

A questionnaire was administered at the end of each assembly session. This questionnaire used the modified Situation Awareness Rating Technique (SART) (Taylor, 1990) to measure SA. Responses were ranked on a scale from "1 - Not at All" up to "7 - Very Much.".

Situation Awareness was rated for both visual aids at the end of the task. Overall, the 3D model had slightly better SA than the Photograph; see Table 4. SART Demand indicates a slightly less demanding task with the 3D model. SART Supply indicates somewhat more crew resource was available with the 3D model. SART Understanding indicates a slightly better task understanding by the participant with the 3D model.

Table 4. Situation awareness after the task for the VITA study in HERA C7

	Photograph		3D Model	
Scale	*M*	*SD*	*M*	*SD*
Demand	3.93	1.32	3.85	1.14
Supply	4.60	0.73	4.83	0.61
Understanding	5.06	0.95	5.19	1.08

Preferred Visual Aid

Participants were asked which visual aid they preferred. Ten of 16 crew participants preferred figures using the 3D model. A key reason given was that the 3D model provides more information more quickly. Some participants also felt the 3D model was easier to use. Additionally, the 3D model shows the relationship between the parts to be assembled, and makes this relationship available at all steps of the assembly. Four of 16 participants preferred photographs. These participants felt photographs were straightforward to use and captured more detail than the 3D model. Finally, two of 16 participants had no preference, but mentioned that they liked having both options for different situations.

Participant comments indicate how the 3D models improved their situation awareness:

- “The 3D model speaks volumes for understanding the system”
- “3D picture is really helpful; really enjoyed 3D model; very effective in determining orientation of parts”
- “The exploded view was key to knowing which holes to put things in”
- “I really liked how the 2D and 3D figures dovetailed so nicely. The red indicators in the 2D figures were fantastic for adding instruction. The exploded 3D models were super helpful”

Manipulating 3D Model in HoloLens 2

Many participants felt that the ability to rotate and relocate the 3D model while assembling the rover was useful e.g., “Being able to rotate and move around the model helped greatly with ensuring I was orienting the physical parts correctly in the assembly”. One participant suggested adding the ability “to zoom in and out of the model” could help focus on the components needed for the current step by removing visual clutter.

Multiple participants observed, however, that the virtual panes, including the 3D model, would move unexpectedly at times, requiring them to re-position the panes to the desired virtual location. This unintended motion was caused by the HoloLens 2 reacting to assembly hand motions near the virtual panes. It also was possible to get unintended motion for more distant virtual panes, if the HoloLens 2 pointer line (used to grab virtual panes at a distance) intersected with the pane. Once an assembly motion was interpreted as intending to move a virtual pane, the pane would follow the assembly hand motions and appear to jump around randomly until released. And once a virtual pane was “attached” to the hand, it could be difficult for the user to release the pane. Slow deliberate motions to release the pane often worked best.

Discussion

Comparing use of 3D Models to Photographs

The study in HERA C7 investigated the performance effects of using a 3D model instead of photographs to illustrate assembly actions. The 3D model shows an exploded view of the assembled device. This model can be moved where the user wants, and can be rotated in virtual space. A 2D diagram below the 3D model shows the labeled components for each step, or the assembly actions as arrows on the diagram. The visual aid using 2D photographs included labeled components for each step, or the actions shown as arrows on the photograph.

The use of a 3D model instead of photographs to illustrate actions in assembly procedures reduced user workload significantly for the first repetition of an assembly procedure. For the first repetition, the Photograph condition had a median workload of 6 (medium on the Bedford scale), while the 3D model condition had a much lower median workload of 3.5 (low on the Bedford scale). When the procedure was repeated, however, the median workload was low and the same at 3 for both visual aids. The workload difference in the first session is statistically significant.

This difference indicates that the assembly task with a 3D model may be easier to learn than the task with photographs, when the task is unfamiliar to the user. Once the user practices the task, these workload differences disappear. In addition to the effects of these visual aids on workload, some workload differences could be due to the task differences discussed earlier.

Measures of usability and situation awareness do not show significant differences between conditions in the HERA C7 study. The NASA-modified usability rating was comparable for both the 3D Model and Photograph conditions, and considered acceptable with values between 70 and 80 (Bangor et al., 2009). Situation awareness is measured both during the task and after the task. Median SA measured during the task is moderately high for both conditions, varying between 5 and 6 on a 7-point Likert scale. SA measured after the task using SART is comparable and acceptable for both conditions.

Customizing 3D Models for Procedure Steps

VITA virtual visual aids in HERA Campaign 7 combined an unchanging 3D model of the gripper in the AR headset with annotated 2D images of the model that are customized for each step. These annotations show parts labels and indicate assembly actions. In a subsequent study the 2D images used in HERA were replaced by overlaying the annotations directly onto the 3D model. This resulted in a custom 3D model for each step of the procedure.

Subjective feedback about the 3D models used in both studies was more favorable for the customized 3D model than for the static 3D model. Additionally, both workload and SART Demand were lower and usability was higher when using the customized 3D models. Task differences between the studies may have influenced these findings, however. While participants of both studies assembled the rover gripper, participants in the HERA C7 study additionally assembled the rover wheeled base and attached the gripper to it. The additional tasks in the HERA C7 study may have impacted performance and the additional 3D models for the rover base may have affected participant feedback about these models.

Locating Virtual Cues

The HoloLens 2 often reacted to assembly hand motions near the virtual panes by moving the pane unexpectedly. Thus, placing virtual cues near real-world assembly components can result in unexpected cue motion during assembly sequences. A common AR design, however, is to locate virtual task cues near real-world objects. Locating assembly cues relative to a 3D model provides an alternative design that can minimize these unintended motions for cues that are movable. Additionally, locating cues relative to a 3D model can address challenges encountered in some assembly tasks, such as tasks with components that are small and difficult to distinguish, and that can be occluded by the user’s hands during assembly (Schreckenghost, et al., 2024; Botto, et al., 2020). The low workload and overall acceptable performance with 3D models indicate that AR designs with such models can provide a performant alternative to designs locating task cues near real-world objects for assembly tasks.

Conclusion

Findings from the VITA study in HERA C7 indicate the use of 3D models to illustrate assembly actions reduces user workload significantly over the use of photographs, for the first repetition of the assembly procedure. These workload differences are eliminated when the assembly procedure is repeated within a few weeks. These findings suggest that assembly instructions with 3D models may be easier to learn than instructions with photographs, which are typically used in NASA procedures. This finding also suggests that 3D models might be better for illustrating operations not performed frequently. 3D models could potentially improve performance for procedures with long delays between training on procedures and their operational use. Such long delays are common for procedures used in space exploration missions.

The 3D models used in the HERA study were accompanied by custom 2D figures for each step that provided component labels and arrows illustrating assembly actions. In a later study, these labels and arrows were moved to overlays on the 3D model, eliminating the need for the 2D figures. Findings from this study indicate that such customization of the 3D models for each procedure step can further improve performance by increasing situation awareness and usability, as well as reducing user workload. The use of 3D models customized to each procedure step merits further study.

Key Points

- The VITA project investigates the effects on human task performance of a virtual task assistant combining procedure automation with augmented reality (AR) for assembly and maintenance tasks.
- The use of a 3D model instead of photographs to illustrate actions in assembly procedures reduced user workload significantly when learning to perform an assembly task.
- Locating task cues near 3D models in AR can provide a performant alternative to designs locating task cues near real-world objects.

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Author Biographies

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