

IMPROVING PROCEDURE EXECUTION FOR THE NEXT ERA OF SPACE FLIGHT



Carnegie
Mellon
University



EXECUTIVE SUMMARY

During regular missions aboard the International Space Station (ISS), NASA astronauts are tasked with conducting scientific experiments and performing a variety of maintenance operations. However, carrying out these operational tasks involves memory recall challenges due to the length of time that elapses between when astronauts receive training and when they execute tasks aboard the ISS.

As NASA undertakes the next leap in a new era of human space exploration that extends beyond low-earth orbit, an intelligent system that provides instructions can empower astronauts to autonomously execute procedures. Our team is seeking to explore and understand the context in which astronauts work and will then develop a forward-facing hardware prototype suitable for executing tasks during future missions aboard the ISS and to Mars.

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ABOUT NASA

The National Aeronautics and Space Administration (NASA) was established in 1958 to further research in aeronautics and space exploration. Since its inception, many landmark missions have been completed beyond the confines of our home planet, including the Apollo missions to land astronauts on the moon, as well as the subsequent Space Shuttle efforts to send a crew into space using a reusable airplane-like vehicle.

The NASA Ames Human-Computer Interaction (HCI) Group aims to facilitate NASA's efforts through an emphasis on user experience. The group applies HCI research and design methods to the development of user-centered software for aerospace planning and collaborative decision making. They actively engage with Carnegie Mellon University in the development of forward-facing solutions for space exploration.

LOOKING TO THE FUTURE

INTERNATIONAL SPACE STATION

The International Space Station (ISS) is a habitable satellite used primarily for conducting scientific experiments under conditions of zero gravity. Crews are stationed there to conduct and oversee these experiments, and repair and maintain internal equipment as well as external infrastructure through Extravehicular Activity (EVAs).

2030 MARS MISSION

NASA has outlined a roadmap to send engineers and scientists into deep space, specifically to Mars. By 2018, they hope to complete the development of the Space Launch System, a highly powerful rocket designed to bring humans beyond Earth's orbit. They plan to utilize this new capability by 2025 to send astronauts to capture and redirect an asteroid to the moon's orbit in order to collect samples. These efforts will eventually lead to the anticipated 2030 effort to land humans onto Mars' surface.

PROBLEM CONTEXT

We are tasked with envisioning how an astronaut might execute a procedure with no prior training or when they had been trained long ago and do not remember every instruction of the procedure.

Aboard the ISS, astronauts may diagnose maintenance issues and perform science experiments, with an operator on ground available for clarification and working around issues. In future missions to Mars, an operator may not be available due to communication delays so an astronaut would have to carry out procedures autonomously.

While we aim to solve the grander problem of astronaut autonomy, our prototype will focus on procedures for scientific experiments for the Rodent Habitat, a living facility for rodents used in science experiments in space.

OUR STRATEGY

Understand the context in which astronauts perform procedures as novice users and develop a forward-facing solution that facilitates performing these tasks on the International Space Station and on future missions to Mars.

RESEARCH OVERVIEW

RESEARCH AT NASA

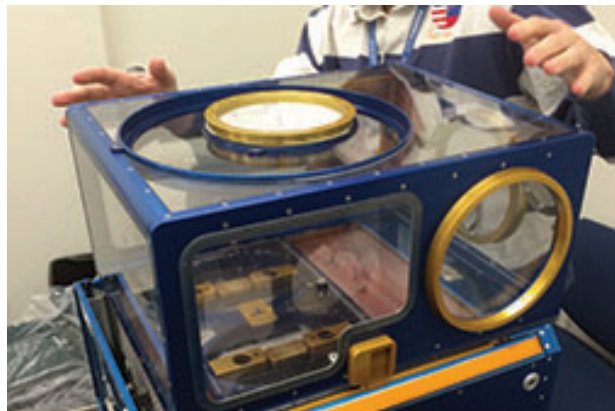
Kennedy Space Center

We conducted research at NASA's Kennedy Space Center (KSC) to better understand procedure execution at NASA. In particular, we conducted a contextual inquiry involving the dimensional verification of billets, which form the base material of thermal protection tiles, at KSC's Thermal Protection System Facility.

Ames Research Center

While at the NASA Ames Research Center, we performed interviews and a contextual inquiry at the Arc Jet Complex while they were conducting a test to simulate the extreme conditions of atmospheric entry. This research allowed us to observe a NASA procedure being executed and how the team dealt with issues during a procedure. Additionally, we were able to view the Rodent Habitat, which houses mice or rats for experiments on space expeditions.

The mice or rats live in the Rodent Habitat (bottom), a research platform for performing long-term animal experiments in space. Astronauts access the rodents through an Animal Access Unit, shown sitting on top of the Rodent Habitat.



ANALOGOUS DOMAIN RESEARCH

We conducted field research to better understand the constraints under which astronauts work. Our research centered around analogous domains whose conditions map very closely to that of astronauts because access to current astronauts is extremely limited. Our team was also able to interview two former astronauts.

LITERATURE REVIEW

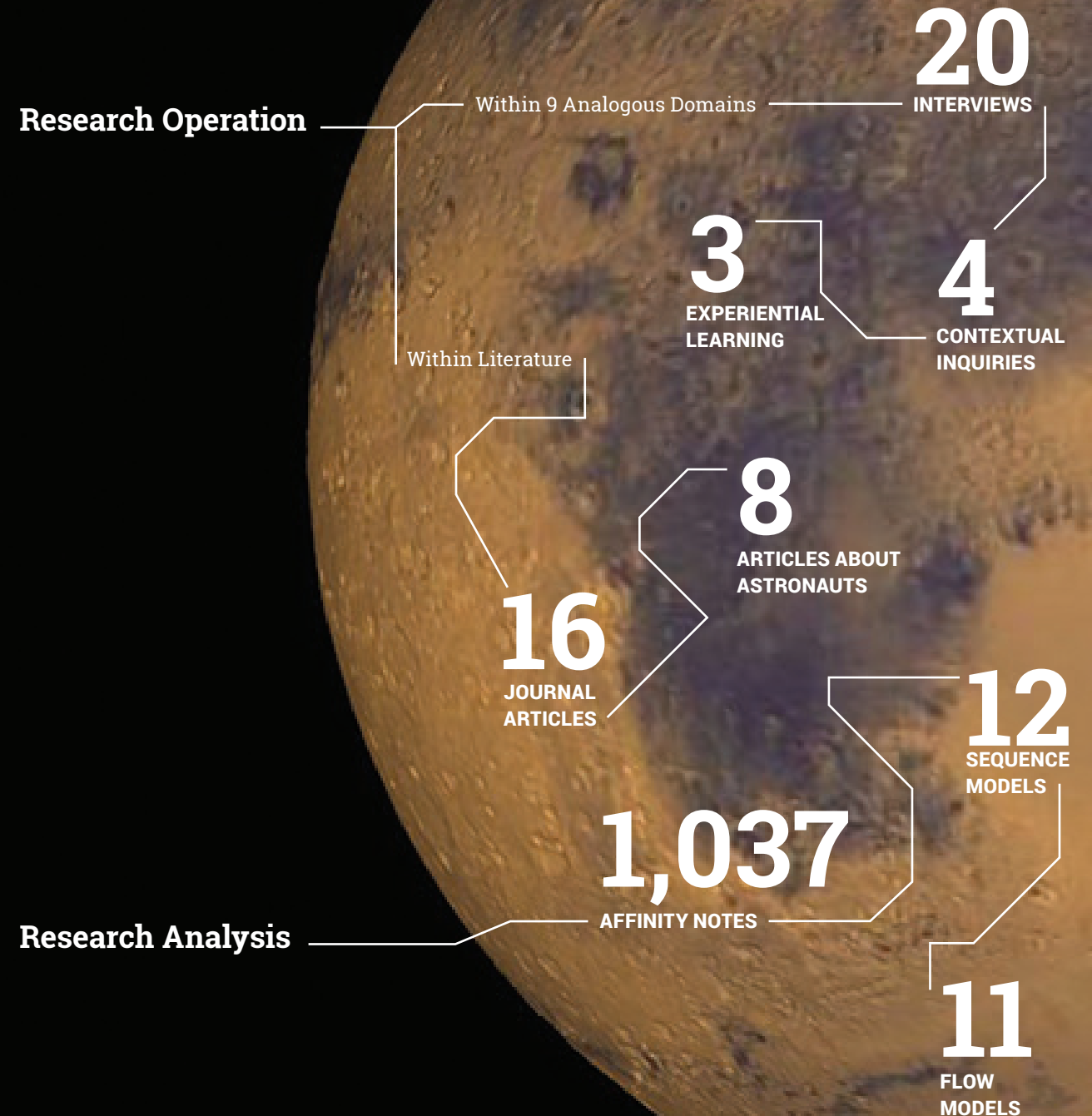
The team considered current literature for domain knowledge to answer the following questions.

- What level of detail in instruction is required to complete a task?
- How can sensors help the ability to complete a task?
- How can augmented reality help the ability to complete a task?

LOW-FIDELITY EXPERIMENT

Another component of our research included conducting an experiment where we observed participants following a set of procedures on a tablet device to construct an origami object. Through this think-aloud exercise, we sought to understand what aspects of procedures influence successful task execution.

RESEARCH METHODS



FINDING ANALOGOUS DOMAINS

We considered the context of an astronaut's working conditions and evaluated other domains for similarity since direct access to current astronauts was limited.

WIDE TASK VARIETY

Astronauts perform maintenance, repairs, and experiments on the ISS, which involve different types of tasks.

EXTENSIVE TRAINING

Astronauts spend years training on procedures before they go into space.

TASK UNFAMILIARITY

There may be long periods of time between when astronauts train and when they perform tasks. Unforeseen issues can also arise in which an astronaut may not be able to train. Thus, astronauts might perform tasks that are unfamiliar to them.

ONGOING MAINTENANCE

Astronauts maintain and repair equipment onboard the ISS.

TOOL FINDING

For experiments, maintenance, and repair operations, the astronauts locate the tools they use to perform tasks.

DOCUMENTED INSTRUCTIONS

Astronauts have documents that describe a procedure for completing a task.

PROCEDURAL INSTRUCTIONS

Astronauts follow linear, step-by-step instructions for operations.

LIMITED PROCEDURE FLEXIBILITY

For many procedures, it is critical that astronauts follow steps without deviating much from the original procedure to ensure operational success.

COLLABORATION WITH OTHERS

Astronauts collaborate with each other and mission control on the ground to make sure everything goes as smoothly as possible.

HIGH STAKES TASKS

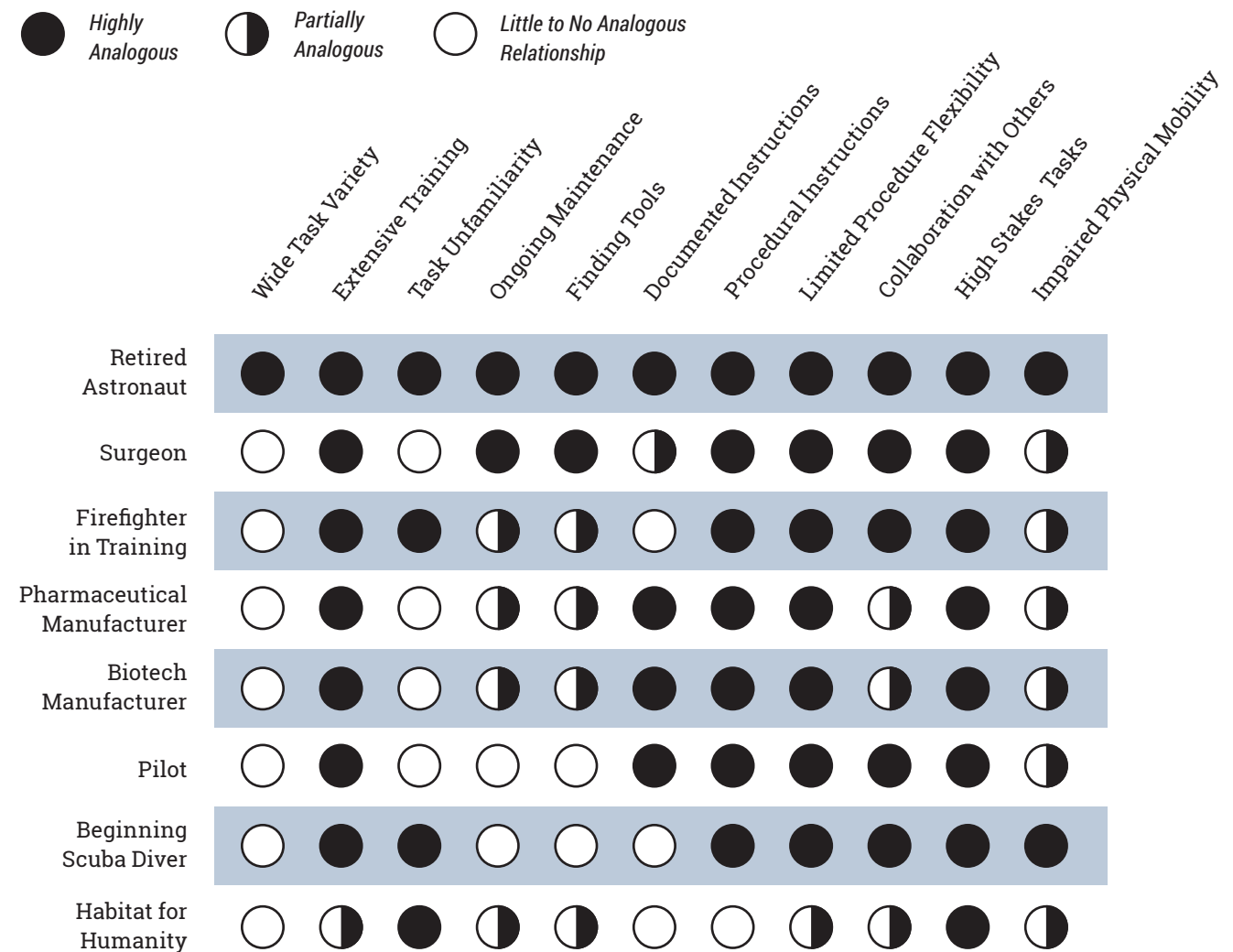
There are high stakes with astronauts' own lives and the high cost equipment they use.

IMPAIRED PHYSICAL MOBILITY

Unlike Earth conditions, the environment in space impairs an astronaut's physical mobility.

RELEVANT DOMAINS EXPLORED

Our team evaluated a number of potential domains to find the ones that were most analogous to what astronauts experience. We set up interviews, contextual inquiries, and experiential learning in these analogous domains to better understand qualitative aspects of the experience. This research helped us to understand the context of how astronauts work when we couldn't directly observe them working.



RESEARCH CONDUCTED

Contextual Inquiries

We observed these people while they worked and asked questions along the way to better understand why they were doing things in a certain way and to verify our interpretations of what we observed.



NASA AMES ARC JET

We observed the team running a test at the Arc Jet complex.



NASA KSC BILLET MANUFACTURING

We observed a QA Engineer and a Technician test Thermal Protection Tiles.



HABITAT FOR HUMANITY

We helped with the construction of a Habitat for Humanity home in Pittsburgh.



VOLUNTEER FIREFIGHTER TRAINING

We went through the maze used to train volunteer firefighters.



VOLUNTEER FIREFIGHTER TRAINING

We observed students training to be volunteer firefighters.



BEGINNER SCUBA DIVING

We observed beginner scuba diving classes from both above and below the water.



BEGINNER SCUBA DIVING

We participated in an introductory scuba diving course.

Experiential Learning

We participated in these activities ourselves, so we had the experience of learning to do unfamiliar tasks.

Interviews

Using a loosely structured script, we asked these participants to recount experiences doing their work.



2 RETIRED ASTRONAUTS

We interviewed two retired astronauts about their experiences going into space on Shuttle missions.



8 NASA KSC EMPLOYEES

We interviewed people at KSC to better understand NASA procedure execution.



4 NASA AMES EMPLOYEES

We interviewed people at AMES to better understand NASA, the Rodent Habitat, and Arc Jet.



1 PILOT

We interviewed a pilot about flight procedure, while he was a passenger on a commercial plane.



3 SURGEONS

We interviewed a neurosurgeon, a trauma surgeon, and medical student.



1 BIOTECH MANUFACTURER

We interviewed someone in the biotech industry to learn about their manufacturing processes.



1 PHARMACEUTICAL MANUFACTURER

We interviewed someone in the pharmaceutical industry to learn about their manufacturing processes.

LITERATURE REVIEW

VALIDATED PRIOR FINDINGS

What level of detail in instructions is required to complete a task?

It depends on the user.

Optimal instruction detail and segmenting depends on the user's personal prior knowledge and skills. Users with more familiarity and practice with tasks will work better with higher level instructions while others with less familiarity need a greater level of detail and guidance through the individual steps of procedures.^{1,2}

How can sensors help the ability to complete a task?

By predicting good times for interruption.

Research has found that simple sensors can estimate human interruptibility as well as actual humans do.³ Therefore, it is possible to create an attention-aware system that can optimize the timing of interruptions during procedure execution, thus reducing the negative impact of interruption on performance.⁴

How can augmented reality help the ability to complete a task?

By providing annotations, simulations, and directional assistance.

Augmented reality is uniquely suited to annotated instructions, tool use simulations, and directional assistance which significantly improves the speed of finding specific locations during procedure execution compared to other display solutions.⁵

Our research validated these design considerations that had already been discovered by NASA and past NASA MHCI project teams. Some of these will be used as guiding principles for our solution.

AUTOMATION

Automatically tracking job completion improves efficiency.

COORDINATION

Working in confined spaces often requires assistance to provide necessary tools and support.

HOLISTIC SITUATIONAL AWARENESS

Complications can be minimized by establishing a comprehensive picture of a particular situation.

Knowing "why" promotes work understanding.

Lack of context awareness can lead to complications and unexpected issues.

Lack of holistic context awareness between procedure authors and executors can often lead to disconnects.

FINDING TOOLS

Tools are sometimes difficult to locate without external assistance.

Tools are returned to places other than their expected storage location, leading to frustration when attempting to subsequently locate them.

Systems that can locate tools would very helpful.

LOW RISK EXPOSURE TO TASK

Physically observing others perform tasks aids my learning.

Simulating scenarios comprehensively can drastically reduce failure probability.

REDUNDANCY REASSURANCE

Having available back-up resources when needed provides confidence during task execution.

MULTIPLE RESOURCES

Task completion often requires a back-and-forth process of referring to multiple resources.

ADMITTING MISTAKES

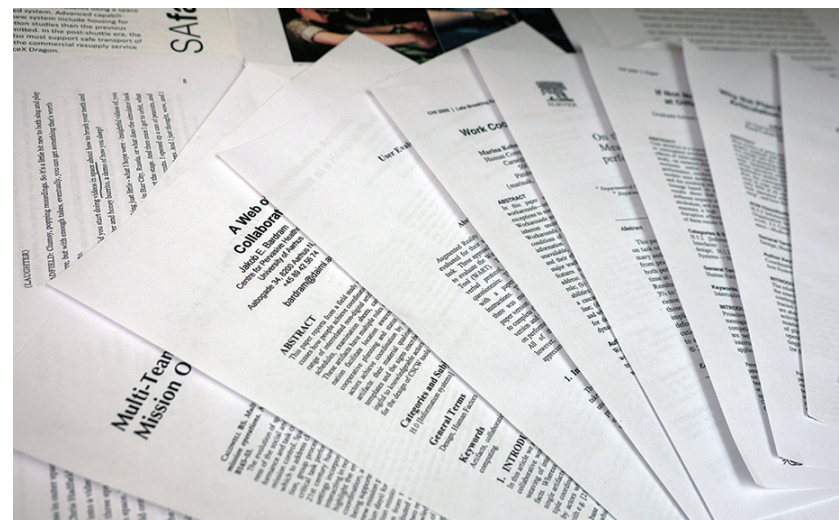
Fear sometimes deters the admission of mistakes.

COMMUNICATION

Building relationships foster improved communication and work efficiency.

In addition to knowledge and skills, quality training also covers effective communication.

The need to share resources demands proper coordination to ensure their efficient usage.



Our literature review covered topics including studies on different types of technology, interruptions, e-learning design principles, collaboration, the daily lives of astronauts, and more.

ASTRONAUT PERSONA



DEMOGRAPHICS

Name Donald Ridgell
Age 49
Gender Male
Vision 20/20 (deteriorating)
Interests Mountain climbing, skiing
Family Wife (48), Son (21)

BACKGROUND

B.S. in Biology, Ph.D. in Biomedical Engineering
 1,400 hours of flight training in jet aircraft
 Proficient in Russian and Japanese

PERSONALITY

Intelligent, logical, adaptable, works well with others, continual learner, explorer, and laid back or intense as required.

GOALS

Motivations Learn new things, be on the edge of scientific discovery and exploration
Short Term Goals To be effective and efficient, smooth operation of tasks
Life Goals Wants to be a role model for his son and for other children interested in space and science, greater good of humanity

ROLES

Occupation NASA Mission Specialist on the ISS for 1 year.
Required Knowledge Detailed knowledge of computer systems, payload equipment, mission requirements, and objectives.

TASKS

Typical Activities Performing maintenance and experiments within the ISS.
Atypical Activities Performing EVA repair operations on the outside of the ISS.



FINDINGS

We looked at our affinity diagram consisting of 1,037 notes, consolidated flow models, and sequence models for findings in behavior that surprised us, were related to procedure execution, and that could lead to feasible solutions in the context of NASA. We then rolled up these findings into general insights that would guide our visioning and subsequent implementation.

INSIGHTS

How might a procedure anticipate a worker's momentary needs?

WORKER-SUGGESTED IMPROVEMENTS CAN MITIGATE DISCONNECTS BETWEEN PLANNING AND EXECUTION.

We found domains where there were disconnects between the work planner and the person executing the work. Some domains have a feedback loop built into the process where a worker who notices issues can suggest improvements that will be evaluated and the best ones implemented. This has the dual benefit of improving processes while also allowing the workers to feel empowered that they are able to positively impact change.

DISCONNECTS BETWEEN THE PERSON WHO PLANS THE WORK AND THE PERSON WHO DOES THE WORK LEAD TO INEFFECTIVE PROCEDURES.

Surgery Interview

One surgeon examined a patient and scheduled that patient for surgery. When another surgeon went to perform the surgery, he was not able to perform the surgery and said that he would not have scheduled this patient for this particular surgery.

Retired Astronaut Interview

One former astronaut referenced a time when his team received a procedure from the ground to address an unexpected event. The astronauts were not physically able to get into the positions required to execute the procedure as it was written.

SOME DOMAINS HAVE A FEEDBACK LOOP FOR WORKERS TO SUGGEST IMPROVEMENTS TO PROCEDURES.

Biotech Manufacturing Interview

At a biotech manufacturing company, there is a process where a worker can suggest a procedure improvement that will be escalated to management and tested in manufacturing to determine if it is effective. If the suggestion is found to be an improvement, the procedure will be updated.

NASA Arc Jet Contextual Inquiry

At the NASA Arc Jet facility, anyone can suggest a process improvement and it is evaluated by the team to determine if it should be implemented.



The Facility Operator controls the NASA Arc Jet from the Control Room, but anyone on the team can suggest procedure improvements.

DISTINCTIVE SPATIAL REFERENCES PROVIDE GUIDANCE THROUGH A PROCEDURE.

In some domains, artifacts in the environment or within the interface of a tool help workers navigate a physical area during a procedure. In other domains, hand positions and gestures give physical cues for how to perform a task.

REFERENCE POINTS INFORM WORKERS OF ORIENTATION IN AN ENVIRONMENT.

Volunteer Firefighters Training

From our experience watching volunteer firefighters train and from actually trying out the training ourselves, we learned that they maintain a reference point in their surroundings - the location of a particular wall, for example - that could help them find their way back in a situation.



Our team members navigate through a maze during firefighter training. This exercise revealed the importance of maintaining a reference point in the environment.

HAND POSITIONS AND HAND GESTURES CLARIFY AND COMMUNICATE INSTRUCTIONS.

Origami Experiment

Participants in our experiment crafting an origami butterfly from written instructions found that the pictures with hands were most helpful in understanding steps. The presence of hands gave them a sense of scale and rotation, which provided additional context for a step.

Scuba Diving Instruction

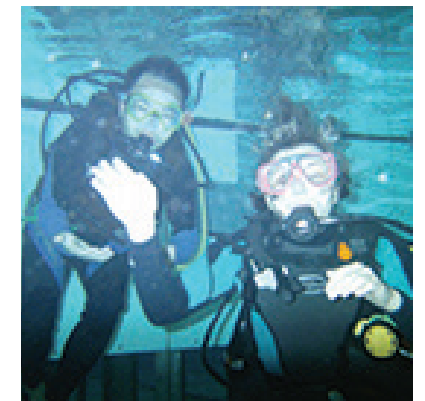
From observing beginner scuba divers and trying out a scuba diving class, we found that hand gestures were used prominently throughout training to supplement a verbal instruction with physical demonstrations before the dive.

Habitat for Humanity

As volunteer workers at Habitat for Humanity, we found it most helpful when our supervisor would motion with his hands exactly how to perform tasks, such as where to cut the drywall. The hands served as a relatable visual guide for tasks we weren't really familiar with.



A finished origami butterfly from our origami experiment. This participant read through all the instruction steps before beginning the origami piece.



Our team members tried out scuba diving in order to understand how divers learned high risk procedures.

WORKERS USE ARTIFACTS TO TRACK STATUS WITHIN A PROCEDURE.

Astronauts will follow long, multi-step procedures that often reference other books. They need to be able to keep track of not only where they are in a procedure, but also the important, actionable parts.



We interviewed experts at the Kennedy Space Center to learn about how NASA procedures are authored and how workers executed them.

WORKERS NEED TO BE ABLE TO TRACK WHERE THEY ARE IN A PROCEDURE.

Kennedy Space Center Interviews

From our interview with a NASA Ground Systems Development and Operations (GSDO) expert involved with recovering the Orion Multi-Purpose Crew Vehicle (MPCV) from its recently-conducted inaugural test flight, we learned that sticky notes would be used to bookmark certain pages in a paper procedure in order to help the overseeing conductor keep track of completed steps across multiple procedures.

Many of our interviews suggested that engineers and technicians working on ground procedures would use a software package called Solumina to record completed steps in a procedure. The software system eliminates post-procedure followups by ensuring that all the steps were completed and by allowing upper-level personnel to track the progress of execution in real-time.

Retired Astronaut Interviews

One of the former astronauts we interviewed remarked that the procedures that they would follow were really long, and they would sometimes have to reference multiple books. In a particular instance, the procedure spanned 700 pages in a book, and often the conductor inside the ISS would carry out multiple procedures from the same book.

WORKERS NEED ARTIFACTS TO GUIDE THEIR ATTENTION THROUGH A PROCEDURE.

Retired Astronaut Interviews

A former astronaut we talked to had stated that some of the procedures he would read were really long and were overcrowded, and so he would highlight the important action steps.

Literature Review

From researching how to design instructional material, we found that the use of sub-goal labels helped learners progress through instructions by guiding them in the formation of mental models.² We also learned that “Guided Attention,” the use of words in instruction to include cues about organization, can assist learners to move through steps.¹

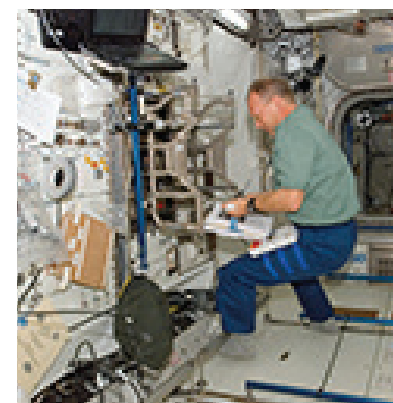
ADJUSTING INSTRUCTIONS TO A USER'S PAST EXPERIENCE CAN IMPROVE UNDERSTANDING OF WORK.

The amount of detail necessary for a user to follow in a given task varies by a particular person's experience and role. A beginner typically requires detailed information to ensure proper task execution, but with greater experience and increased knowledge, however, the need for fine levels of detail typically decreases. Additionally, for certain roles whose execution of certain tasks is not dependent on their understanding of the details behind them, communicating only the necessary aspects of the procedure is often appropriate.

USERS MODIFIED PROCEDURES BASED ON THEIR PAST EXPERIENCE.

Retired Astronaut Interviews

Through our interviews with former astronauts and various NASA personnel, we learned that astronauts often participate on multiple missions in their career. As astronauts become more familiar with various aspects of the space station and associated procedures, they typically need less guidance for specific tasks. We learned from a former astronaut that he often highlighted steps in a procedure that were most applicable to him so that he wouldn't be distracted by details with which he was already familiar.



Customized procedures can reduce dependence on multiple paper-based guidebooks, which are shown being used here by astronaut Hans Schlegel to install experiment racks aboard the ISS.

ABSTRACTING AWAY UNNECESSARY DETAIL CAN IMPROVE PROCEDURE UNDERSTANDING.

Pharmaceutical Manufacturing

Our study of pharmaceutical manufacturing technicians showed the effective use of procedures simplified enough to execute safely and accurately, abstracting away unnecessary technical detail not important to the task itself.

Habitat for Humanity

Our volunteer experience with a project for Habitat for Humanity revealed differences in procedure explanations between first-time and recurring volunteers. Procedure explanations for first-time volunteers assume no background in construction and generally include more information concerning safety and health than those for recurring volunteers who have more construction expertise. However, supervisors usually omitted technical details of procedures for first-time volunteers as this information was not needed to perform the necessary tasks.



A Habitat for Humanity site supervisor uses simple, high-level instructions with a first-time volunteer in diagnosing a water leak above the ceiling.



During drug production, batch records are referred to by pharmaceutical manufacturing technicians, who need essential steps for safe manufacturing but can do without the low-level background chemistry details.

ASSUMPTION PROTOTYPES

Our team engaged in an exercise we referred to as **assumption prototyping**, a brainstorming method based on a set of assumptions before all research data is available and performed in a rapid fashion. This exercise helped us to quickly visualize possible ideas and assess merits and drawbacks to them.

IDEAS EXPLORED

- Indication of progress in a task
- Feature to direct a worker to a tool
- Tools indicating how they're used for a step
- Animations in glasses to indicate how to use a tool
- Gestures on glass for advancing through instructions
- Animations in glasses to show end state of a step
- An overview showing the different regions that will be touched in the course of a task

We collectively generated many ideas that would assist a user through a procedure. We felt that including various features simultaneously would clutter the interface, so we would need to consider how to design for procedure guidance without overwhelming the user.

LOW-FIDELITY EXPERIMENT

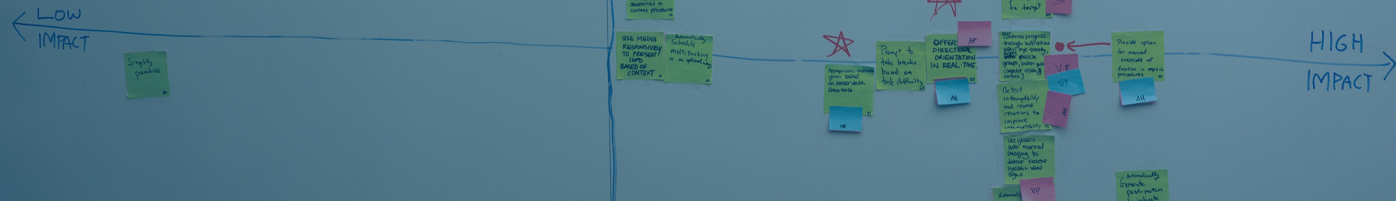
Building off ideas and concepts that we discussed during the assumption prototyping exercise, we later conducted an experiment to observe how people read and follow instructions. We presented to participants on a tablet computing device a set of procedural instructions for building an origami object. We observed four participants, one of whom successfully completed the exercise.

KEY FINDINGS FROM THE EXERCISE

- Users preferred a certain order in the presentation of information: to have written text for a particular step listed first, followed by a descriptive, annotated image.
- Users found images that included human hands working with artefacts very helpful to provide proper physical orientation and sense of scale.
- Users preferred using their hands to complete a particular step, even if the procedure called for a particular tool to be used.
- Users favored having all of the steps displayed on a single page, versus having them paginated. Presenting all of the instructions on a single page allowed users to gain an overview of the process as well as quickly view to expected end result.

The participant's work area for following an origami procedure. We provided redundant tools and hid some required tools in the experiment room to observe how a participant handled finding needed tools.

VISIONING

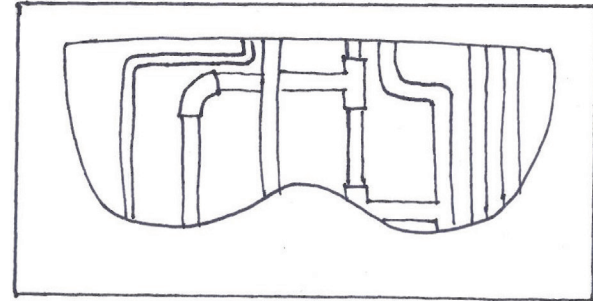


After we extracted insights from our research findings, we began to explore the solution space through a set of brainstorming sessions. We first collectively produced 140+ ideas inspired by our insights and research. We then grouped together similar ideas to produce a set of 40 concrete feature ideas. These 40 ideas were then compared using an impact-feasibility matrix to determine which would have the greatest impact while at the same time be reasonable to implement at NASA. This process ultimately yielded 12 ideas, which led to a set of initial visions.

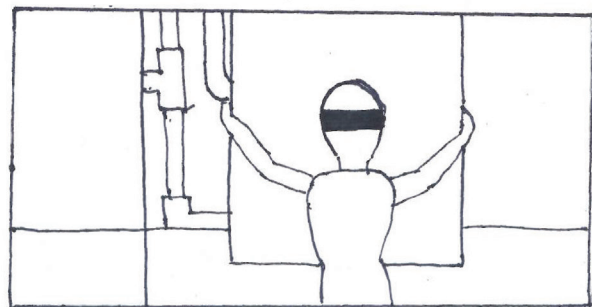
IDEA #1 – X-RAY VISION



1. Don needs to repair a leak inside the wall of the ISS, but he isn't sure which panel the leaky pipe 64 is behind.

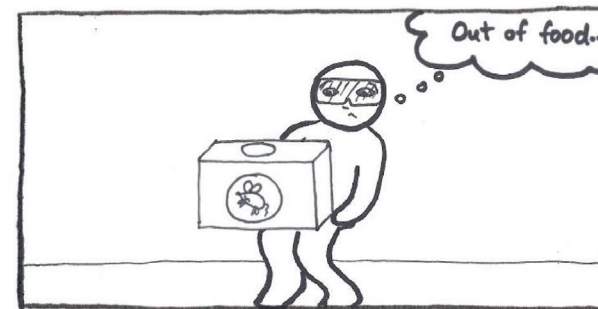


2. Through his augmented reality goggles, Don can see behind the panels to see which one to remove to get to pipe 64.

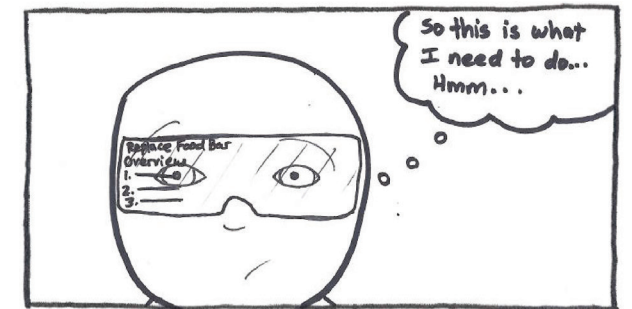


3. Don removes the correct panel and is able to fix the leak.

IDEA #2 – DETAIL OF INSTRUCTION



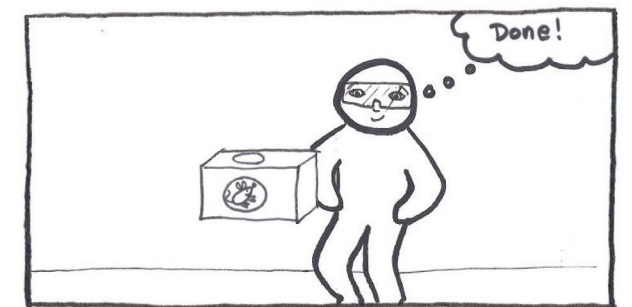
1. Don needs to replace the food in one of the Rodent Habitats on the Mars station.



2. Don glances through the procedure overview and continues to the first instructional step.



3. Don has already replaced the food in the Rodent Habitat ten times, so he just gets the high level detail of each step.



4. Don is able to move quickly through the instructions and finish replacing the food bar.

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TEAM PARALLAX

An interdisciplinary team of five master's students at Carnegie Mellon University's Human-Computer Interaction Institute.



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PHOTO CREDITS

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ADDITIONAL BIBLIOGRAPHY

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