Applying Research-Based Training Principles:

Towards Crew-Centered, Mission-Oriented Space Flight Training

Donna L. Dempsey

NASA Johnson Space Center

Immanuel Barshi

NASA Ames Research Center

Author Note

Donna L. Dempsey, Human System Engineering & Integration Division, NASA Johnson Space Center.

Immanuel Barshi, Human Systems Integration Division, NASA Ames Research Center.

Correspondence concerning this chapter should be addressed to Donna L. Dempsey, NASA Johnson Space Center, 2101 NASA Parkway, Mail Code SF3, Houston, TX, 77058. donna.l.dempsey@nasa.gov

Abstract

This chapter describes a training approach that applies empirically derived principles of training to reimagining the overall design of NASA's space flight training program. The chapter is focused specifically on the design of astronaut training for NASA's future deep space, exploration missions to Mars. We briefly describe NASA's space flight training practices during the Apollo and Space Shuttle eras as well as NASA's current practices for training astronauts for their missions to the International Space Station. We provide an overview of NASA's current concepts for a mission to Mars to scope our training approach. We envision a new space flight training approach which we term "crew-centered, mission oriented" training, inspired by the design approach offered in the context of airline pilot training by Barshi (2015). We apply some of the training principles reviewed by Kole and his colleagues in the companion volume (Kole, Healy, Schneider & Barshi, 2019), as well as by other researchers in training science (e.g., Ericsson, Krampe, & Tesch-Römer, 1993; Healy & Bourne, 2012; Salas, Wilson, Priest and Guthrie, 2006), into real-world, practical guidelines for the particular context of training astronauts for a mission to Mars.

Keywords: principles of training, training design, space flight training

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NASA's future deep space, exploration missions to Mars will be, by definition, space flight missions that require the onboard crew of astronauts to operate semi-autonomously to autonomously from the Mission Control Center (MCC) on the ground during periods of long communication delays and possible communication blackouts. Astronauts on these missions will be required to work together as a team to respond to high-risk, critical situations, to command, operate, and maintain their spacecraft, and to conduct scientific research in support of mission objectives. Such missions will require a small, well-trained crew ready to perform critical tasks across a wide range of disciplines and ready to make challenging decisions necessary to achieve mission success, all without real-time ground support. While NASA has a long history of successfully training astronauts for low-Earth orbit and lunar missions, it has never provided astronauts with the training necessary to operate at the level of autonomy that future deep space, exploration missions will require.

To provide our astronauts with the training they will require for their missions to Mars, we agree with Salas, Tannenbaum, Kraiger, and Smith-Jentsch (2012) that the design of a training program "should be informed by the best information science has to offer" (p. 74). As discussed by Salas, Cannon-Bowers, and Blickensderfer (1999), one of the challenges in designing an effective training program lies in how best to integrate training research into training practice. Based on the work of Salas et al. (1999), Bourne and Healy (2012) offered that training could be "optimized by the implementation of empirically valid training principles" (p. 7) where a training principle is defined as, "an underlying truth or fact about human behavior" (p. 7). Principles are then integrated into a training program via guidelines (i.e., "how to" or "what to do" statements) and training specifications or requirements (i.e., "shall" statements). Applying these concepts to the design of training for pilots at the airline level, Barshi (2015) offered a training design approach, including guidelines and specifications based on training principles offered by Healy and her colleagues (e.g., Healy, Kole, & Bourne, 2014; Healy, Schneider, & Bourne, 2012). His approach structured all airline pilot training as "line-oriented" flight training, where the "line" referred to is the air-line drawn on a map between a departure airport and a destination airport. That approach leads to a training design in which the acquisition of new knowledge and skills and the opportunities to use them are completely embedded within the context of a realistic flight timeline.

Our goal in this chapter is to take an approach similar to Barshi (2015) and offer a design approach for space flight training, including training guidelines and specifications, based on empirically valid principles of training reviewed in the companion volume by Kole, Healy, Schneider and Barshi (2019), as well as by other training science researchers (e.g., Ericsson et al., 1993; Healy et al., 2012; Salas et al., 2006), thereby providing NASA with a design for training astronauts for deep space, exploration missions to Mars based on the best information that science has to offer.

A Brief History of Space Flight Training

As the design of NASA's human space flight missions has changed over the decades, NASA's space flight training design has also changed. For Apollo-era and Space Shuttle missions, astronauts were provided extensive practice for mission operations as an intact team training to detailed flight plans with a well-defined set of duties or tasks for their assigned mission roles (Weaver, Weaver, & Weaver, 2015; Woodling et al. 1973). For current International Space Station (ISS) Expeditions, astronauts are provided generic-task training to support the flexibility to perform across a wide range of tasks that may occur throughout a long ISS Expedition (National Research Council, 2011). What has not changed since the beginning of space flight is that each of NASA's space flight training programs has been primarily designed based on what we term a "system-siloed" training approach. That is, an approach in which training begins with vehicle system flows (e.g., an electrical power system training flow, a thermal control system training flow) and discipline flows (e.g., a robotics training flow, an inventory and stowage training flow), with training for mission operations being provided only after extensive training on vehicle systems and disciplines is completed. Additionally, the operational concepts for each of these programs has assumed that the real-time expertise needed to respond to unplanned, complex technical problems or unforeseen medical issues would be provided by the flight control personnel in MCC, and a return to Earth within hours, or at most days, is always an option.

In the early days of space flight, during the Mercury, Gemini, and Apollo programs, astronauts spent years learning the vehicle systems as they worked collaboratively with systems' engineers on the vehicle designs. In fact, the selection criteria for the Mercury Seven included requiring candidates for NASA's first group of astronauts to have an engineering background along with test pilot experience (Weaver et al., 2015). Mission objectives for these early space flights were clearly defined (e.g., placing a manned spacecraft into orbit around the Earth, demonstrating the rendezvous and docking capability needed for lunar missions, landing men on the moon and returning them safely back to Earth). According to Woodling et al. (1973), the mission-specific training requirements were that the astronauts could practice and demonstrate proficiency in the critical aspects of their mission. To support this training, NASA made tremendous engineering advancements in designing simulators that could mimic the various space flight environments the crew would encounter (e.g., neutral buoyancy simulators for extravehicular activities (EVAs, aka spacewalks), motion-based simulators for ascent and entry, and reduced gravity simulators for lunar surface operations) allowing the astronauts to practice critical tasks planned for their missions (Weaver, et al., 2015; Woodling, et al., 1973). Astronauts were assigned specific roles (e.g., commander, command module pilot) with unique job duties, and were provided numerous hours of individual and team training. Training took place in part-task trainers as well as in high-fidelity, full-task, fixed- and motion-based simulators. Astronauts practiced well-defined tasks based on detailed flight plans with MCC, averaging almost 1,000 hour of simulator time per crewman per mission during the Apollo program (Woodling, et al., 1973). Skylab missions flown at the end of this era were longer in duration, but the pre-flight training remained the same in that the crew were provided extensive training for planned tasks (Schneider, 1976).

Much like astronauts in NASA's earlier programs, the first Space Shuttle astronauts learned the vehicle systems as they were being built. As the Space Shuttle program progressed, space flight training was formalized into lessons, where sets of lessons were designed into training flows, and training culminated in a series of simulations that provided crew members practice or rehearsal of critical tasks in their mission timelines. While lessons and flows were sequenced to ensure prerequisites from one flow were trained prior to being needed in a different flow, the fundamental design approach was based on distinct vehicle system and discipline flows. The most influential factor in NASA's design was simple logistics – the instructors were grouped by system or discipline.

Newly hired Space Shuttle astronaut candidates (ASCANs) were provided two years of initial training, focused extensively on the vehicle's systems, prior to being designated as "astronauts" qualified for flight assignment and ready for flight-specific training. Between the end of ASCAN training and being flight-assigned, astronauts had additional training opportunities. Space Shuttle mission objectives were clearly defined (e.g., servicing the Hubble Space Telescope, installing the Joint Airlock to the ISS) and detailed flight plans were built for missions lasting up to 17 days. Flight-specific training for Shuttle missions was typically one year long, although flight delays often extended this training time. Crew members were assigned roles (e.g., commander, pilot, mission specialist) with unique job duties, and provided intensive training focused on ensuring they could perform their assigned duties and tasks per their mission timeline. The commander and pilot were required to demonstrate proficiency in piloting the vehicle for ascent, entry, and rendezvous, as well as in docking and vehicle operations. They were provided training on these tasks in training facilities ranging from part-task trainers to high-fidelity, full-task, motion-based simulators, as well as training in the Shuttle Training Aircraft, an aircraft modified to duplicate the handling of a Space Shuttle during approach and landing. Mission specialists were required to demonstrate proficiency in performing EVAs, robotics operations, and scientific operations and were provided training on these tasks in mock-ups and simulators of varying fidelity, including EVA training in a neutral buoyancy simulator. Although much of this flight-assigned training was provided to individual or pairs of crew members within system or discipline training flows, flight-specific simulations allowed the entire crew to practice ascent and entry, as well as practice challenging longer mission flight plan sequences such as satellite deployments or EVA tasks, integrated as a team with MCC. Space Shuttle astronauts averaged about 120-160 hours of flight-specific integrated simulation time with MCC per crew member in fixed- and motion-based simulators.

Unlike Space Shuttle missions, ISS missions differ significantly from NASA's previous missions in several important ways that impact the design of training. The ISS is a large, permanently-orbiting laboratory consisting of modules and elements provided by five international partners (NASA, Russia, the European Space Agency (ESA), the Japanese Aerospace Exploration Agency (JAXA), and the Canadian Space Agency (CSA)). The ISS was designed and built with the objective of supporting ongoing scientific research across a range of disciplines. Currently, astronauts travel to and from the ISS on the Russian three-person Soyuz spacecraft, and six crew members (two three-person Soyuz crews) are in space together for six months as an ISS Expedition crew. ISS operations are ongoing, and detailed flight plans, or timelines, are developed real-time based on long-range plans. Although astronauts are assigned roles (e.g., commander, flight engineer), because of the nature of ISS missions and the need for flexibility in assigning tasks throughout the mission, they are all required to have the skills necessary to perform tasks across a wide range of job duties including EVA, robotics, scientific research, repair and maintenance, and responding to potential malfunctions and emergency situations (National Research Council, 2011). During training, each NASA astronaut is required to demonstrate these skills for tasks conducted in NASA modules, as well as demonstrate the skills needed to perform in each international partner module. They must also meet Russian language proficiency requirements, and Russian Soyuz training requirements. (International partner astronauts and cosmonauts have similar training requirements, including training on tasks in their modules.)

ISS training for NASA astronauts again begins with two years of ASCAN training, including extensive systems training on NASA modules, as well as initial discipline training for EVAs, robotics operations, medical operations, and science operations. While flight assignments can occur immediately after ASCAN training is completed, typically an astronaut is assigned office or mission support duties while waiting for a flight assignment. Pre-assignment training opportunities during this period may include some refresher training on ASCAN skills (e.g., ASCANs assigned as capsule communicators (CAPCOMs) receive refresher training on ISS emergency response), additional training on robotics operations in Canada, and training on new skills as part of assignments (including CAPCOM certification). There are also opportunities for team training in analog missions such as the NASA Extreme Environment Mission Operations project (NEEMO) conducted in the underwater Aquarius habitat operated by Florida International University (Landon, Slack, & Barrett, 2018), and such as the European Space Agency's (ESA) Cooperative Adventure for Valuing and Exercising (CAVES) human behavior and performance skills course conducted in deep underground caves.

Flight-assigned training for ISS missions is approximately two years, and astronauts are provided portions of their training by each of the ISS international partners, requiring extensive international travel. NASA astronauts spend about one-third of their assigned training at NASA's Johnson Space Center (JSC), about one-third at Roscosmos in Russia, much of which is training for ascent and entry on the three-person Russian Soyuz vehicle, and the remaining one-third either at ESA, JAXA, on holiday and vacation, and traveling between the international partners centers. Flight-assigned training at JSC builds on ASCAN training and covers a wide range of vehicle system's training, medical operations, robotics, EVA, in-flight maintenance and scientific research training, and also includes ongoing spaceflight readiness training in T-38N aircraft, Russian language training, team skills training, and physical training. Much of this flight-assigned training is provided to individual or pairs of crew members within vehicle system or discipline training flows, including generic 2-person EVA training (mission-specific EVAs are not usually known prior to launch). Astronauts are also provided training as an intact three-person crew by Russia during Soyuz training, and by NASA during several operations simulations. Crews then practice typical tasks in a mission setting, as well as vehicle malfunction scenarios in which they practice responding to off-nominal conditions per published procedures. The only training astronauts are provided as a six-person ISS Expedition crew is for integrated emergency response. Because ISS timelines are developed real-time, very little training is to an actual timeline - the notable exception is Soyuz ascent and entry training.

Decades of successes in human space flight in low-Earth orbit and lunar missions have shown the effectiveness of NASA's space flight training programs for these missions. However, to date, the flight control team in MCC has always been able to provide real-time expertise to the onboard crew as needed, and a return to Earth has always been an option in response to any unforeseen event. Now there is Mars. Earth's closest planetary neighbor, but still up to 24 light-minutes away, and at times completely blocked by the Sun. A quick return to Earth will not be possible, and real-time expertise from MCC will no longer be available. The current "system-siloed" approach to the design of space flight training may not be able to adequately prepare future astronauts for their missions to Mars.

Crew-Centered, Mission-Oriented Space Flight Training

While the detailed parameters for NASA's future deep space missions are not yet fully known, in NASA's design reference architecture for missions to Mars, Drake and Watts (2014) stated that flights will be either two- or three-year long missions to the Martian surface, with a surface stay of either 30 days for a conjunction-class mission, or almost 500 days for an opposition-class mission. Conjunction and opposition refer to the planetary alignments of Earth and Mars. The crew will consist of four to six astronauts, each of whom will be trained for multiple primary roles as well as trained as backup for critical mission operations and major mission objectives. Stuster, Adolf, Byrne, and Greene (2019) identified eight primary crew roles that must be divided among the crew members: leader, biologist, geologist, physician, mechanic, electrician, pilot/navigator, and computer specialist, as well as four additional ancillary roles: crew medical officer, botanist, astrophysicist, and equipment officer. Within these roles, the pilot/navigator is trained for robotics and surface rover operations, and all crew members are trained for EVAs. MCC is expected to provide the crew with a timeline of daily activities, and to provide command and control of the vehicle for normal operations (e.g., course corrections, antenna pointing, software upgrades). However, given the communication delays, astronauts on a mission to Mars will be required to execute complex semi-autonomous and autonomous mission operations, such as responding to unanticipated medical and vehicle emergencies or major system malfunctions, including working outside the scope of published procedures, without real-time support from MCC. They will, therefore, require training to a level of autonomy that has never been needed before.

Training for Mars will be hard. Space flight incidents provide evidence that the current training design of system and discipline flows coupled with rehearsal or practice (though rarely any other training methodology) does not produce the level of autonomy astronauts will require for the challenges of future deep space, exploration missions (Barshi and Dempsey, 2016). While ISS astronauts demonstrate proficiency in pre-mission training (that is, acquisition does not seem to be an issue), Barshi and Dempsey (2016) documented that real-time ground support for ISS Expedition crew members is used to mitigate training retention and transfer issues. Additionally, crew members are not trained to the level of expertise needed for autonomous missions; such expertise is provided real-time by MCC (for challenges in providing this level of training, see e.g., Strauch, 2017). Because of the short duration of the early Mercury, Gemini, Apollo, and Space Shuttle missions, in-flight training retention was rarely an issue. Instructors from this era describe "hammering in" the training content. However, even on such short duration missions, astronauts acknowledged challenges in recalling details of complex technical tasks. Even if we shifted back to Space Shuttle-style task-based training to attempt to address retention issues, the length of the training would be impractical. If a six-month ISS mission timeline could be developed and trained to, the ratio of Space Shuttle training duration to mission duration (one year of training to a twelve-day mission) would imply a 180-month (15 year) training flow for ISS missions. Missions to Mars may be up to six times longer than ISS missions. That won't work. NASA needs a training design that produces the needed skill durability and transferability within a reasonable pre-mission training template.

We propose that the level of autonomy needed for future missions could be achieved by relying on research results from the past two decades that support a training design in which systems knowledge is introduced in the operational context (Barshi, 2015), in which specific training methodologies that support skill acquisition and retention are implemented (Healy et al., 2012), and in which the intact team training that is critical to developing skills necessary for mission success is integrated throughout the entire training program (Landon et al., 2018). In this chapter, we offer a new design approach for space flight training based on empirically derived principles of training, inspired by the approach offered by Barshi (2015) for training airline pilots. This approach is very different from the "system-siloed" approach that has dominated space flight training for decades. "Crew-centered, mission-oriented" design is a training approach in which operational content is introduced to a crew in the context of use. Astronauts learn vehicle systems and procedures in an integrated fashion, as they would interact with them during a mission, rather than abstractly and independently learning this content from a system design or engineering perspective. The entire flow is structured based on the mission timeline, and team skills are learned and practiced in the operational context, rather than in some abstract or generic setting (Barshi, 2015). For example, in current ISS training, the communication and tracking system training flow begins with an introduction to the entire system and then progresses to detailed training on each component in each subsystem, one of which is the audio terminal unit, a component of the audio subsystem used for space-to-ground communications. In contrast, in a space flight training program based on the mission context, an astronaut might be introduced to the audio terminal unit in a training simulation early in their training program while practicing an Earth ascent timeline, but he or she would not be trained on the details of the audio subsystem, nor on other components of the communication and tracking system, until later in training when learning to respond to a loss of communication with the ground.

If the goal of NASA's space flight training program is to train astronauts to work together as a team to meet NASA's mission goals for space flight exploration, to respond to high-risk, critical situations, to command, operate, and maintain the spacecraft, and to conduct scientific research, shouldn't all astronaut training be designed to focus on these mission goals rather than on vehicle systems and engineering disciplines? A "crew-centered, mission-oriented" training design provides such a focus.

Training for Mars

In this section, we imagine how such a "crew-centered, mission-oriented" training program might be designed. It is not our intention to provide a complete training syllabus but rather to demonstrate the application in developing such a training program for a mission to Mars of some of the training principles reviewed by Kole et al. (2019) in the companion volume, as well as by other researchers in training science. We provide three vignettes of training for Mars: Earth ascent, Saturday operations, and critical operations, and we follow each with the principles of training that support such a training design.

Vignette 1: Earth Ascent: Monitoring Orion

With such a training design in mind, instead of starting Day 1 with detailed training on one of the many vehicle's systems, a crew of newly hired ASCANs begins its training with an overview of a Mars mission and overall training objectives. The first mission phase trained is the Earth ascent, and the instructors provide a detailed review of the launch day timeline and nominal trajectory of the Orion spacecraft from the launch pad to rendezvous and docking with their on-orbit Mars Transfer vehicle (MTV), followed immediately by the ASCAN's first training simulation, their launch into space in their Orion vehicle.

In this first simulation, the instructor is assigned the role of commander, and the ASCANs are assigned the simplest of duties, monitoring the Orion vehicle displays during a nominal Earth ascent. As the instructor and ASCANs are strapped into their seats, the instructor begins familiarizing the ASCANs with the interior layout of Orion, such as showing the ASCAN where to stow equipment before launch. Rather than requiring the ASCANs to spend hours of classroom training on display navigation before using these skills in a mission context, the instructor shows the ASCANs how to access the mission timeline on their tablets or displays. As the instructor explains the features of and information contained in the timeline interface, such as the ability to view each scheduled activity in the launch sequence, the ASCANs practice navigating the timeline interface. The instructor shows the ASCANs how to access procedures for executing activities and how to navigate the vehicle system displays that the ASCANs must monitor during this first simulation.

Throughout the simulation, the instructor explains the roles and responsibilities of each of the teams involved in the launch (Launch Control Center, MCC, Crew, etc.) and demonstrates how to work and communicate with each, integrating teamwork and system training within the overall training flow. For example, as the instructor and ASCANs review the launch day timeline and execute the pre-flight checklist with the Launch Control Center (LCC), the instructor discusses the role of LCC with the ASCANs. The instructor demonstrates, and the ASCANs practice performing, the various call outs between the crew and LCC as they confirm readiness for launch. Just after Orion leaves the launch pad, the instructor explains that clearing the launch tower is the indication that communication switches from LCC to the Mission Control Center (MCC), and the instructor discusses the role of MCC with the ASCANs.

Launch is followed by a nominal rendezvous and docking. The ASCANs learn how to confirm docking on their displays, while the instructor confirms the data with a space-to-ground call with MCC. The instructor shows, and the ASCANs practice, how to confirm equalized pressure between the Orion spacecraft and the MTV, and how to open the Orion and MTV hatches to ingress the MTV, all within the context of the launch day timeline. After confirming MTV ingress with MCC, their first simulation ends with a facilitated debrief that includes a discussion of the purpose of and protocols used for crew-led debriefing.

Once a first Earth-ascent simulation is completed, training on subsequent simulations allow the instructors to review and reinforce all that the ASCANs learned in the first simulations, building on that knowledge, and, at the same time, starting to add complexity. For example, in their second simulation, as the they continue to learn the procedures to monitor vehicle data on their Orion displays, the ASCANs practice using the audio equipment to make their space-to-ground calls. In so doing, they continue their training on communication equipment and protocols. In their third simulation, MCC directs the ASCANs to execute a procedure to configure to the backup communication system. The instructor uses the ASCAN's knowledge of the audio system gained in earlier simulations along with this direction from MCC to start teaching the ASCANs the information that is relevant to their job on the design of the communication system, including the system's redundancies.

Subsequent simulations add yet more complexity. They provide the ASCANs with additional training on Orion's vehicle systems, command and control interfaces, as well as procedures and protocols for executing a nominal launch, rendezvous, and docking. (Note, ASCANs will learn skills for piloting the Orion spacecraft and responding to vehicle emergencies and malfunctions later in the training flow.) It may take several weeks to train the entire timeline from launch to rendezvous to docking, with the knowledge required to understand all of the relevant procedures and protocols that come into play in the course of a nominal ascent. Each simulation allows the ASCANs to acquire and practice new skills in the operational context, while also reviewing and reinforcing previously acquired skills.

In the training guidelines described above, the entire focus of the training is centered on the ASCAN's operational, or mission, perspective, and all of the training is presented within the context of the mission. There are three principles of training that motivate the overall design of such a "crew-centered, mission-oriented" space flight training program:

Applied Training Principle: Contextual Reinstatement.

Kole et al. (2019) state that, "both retention and transfer are enhanced when context is reinstated" (p. X). Specifically, training new information in the context in which it will be used supports retrieval of both declarative and procedural knowledge. Context primarily refers to the physical environment, but also includes “emotional factors” and “non-essential perceptual features of the task” (p. X). The entire structure of the program of training described in this chapter is designed to provide training in the context in which the trained knowledge and skills will be used. This context includes the order and sequence of tasks as they will be performed in a mission (e.g., executing a launch day timeline), training as a team (e.g., flying the mission as an intact team, interacting with LCC and MCC), and training in the physical environment in which tasks will be performed (in mockups and simulators, noting the limitations of providing 1-g training for a reduced-g and μ-g missions).

Applied Training Principle: Procedural Reinstatement.

Kole et al. (2019) state that, “To maximize performance at test, the procedures required during training should be reinstated at test” (p. X). For space flight training, the application of this principle goes the other way around; that is, the procedures required at “test”, during the mission, are the procedures that should be used during training. The procedural reinstatement principle is similar to the contextual reinstatement principle; however, as Kole et al. (2019) explain, while the context relates to factors that are external to the task, the procedural reinstatement principle relates to procedural knowledge within a task. Applying the procedural reinstatement principle means basing the content of the training not on an engineering perspective, not on how a system or vehicle is designed or built, but rather -- on what the ASCANs need to know and what they must be able to do to execute nominal and off-nominal procedures during their mission (e.g., making space-to-ground calls to MCC using correct communication protocols, opening hatches between vehicles, configuring to the backup communication system). The design approach of "crew-centered, mission-oriented" training is an application of the procedural reinstatement principle.

Applied Training Principle: Easy to Difficult Ordering.

In discussing the different views on the easy to difficult ordering principle, Healy and Bourne (2012) suggested, "Whether or not training should begin with the easiest or most difficult components of a fractionated task depends on task characteristics" (p. 20). They continued to recommend, "trainers need to be sensitive to these characteristics before deciding on the order of the subtasks" (p. 20). While the easy to difficult ordering principle informs the design of task training, Barshi (2015) suggested that this principle can motivate the design of the entire training flow, supporting a training design approach that structures the entire flow starting from the simplest of activities and gradually building to more challenging tasks. The easy to difficult ordering can be seen here in the progression from a nominal Orion flight in which the ASCANs simply monitor vehicle data to more demanding flights in which they execute procedures to configure vehicle systems. Further complexity is added later in the training flow when the ASCANs learn to pilot the Orion vehicle and respond to vehicle malfunctions and emergencies.

Vignette 2: Cruise to Mars: Saturday Operations

As ASCANs continue to train on the skills necessary to monitor and operate the Orion vehicle during an Earth ascent, instructors start training ASCANs in the MTV for the cruise-to-Mars phase of their mission. Training continues to be provided within the context of the mission rather than structured by vehicle system or engineering discipline. Given the long duration of the cruise-to-Mars, instructors provide ASCAN training on several cruise-to-Mars timelines each covering a segment of this mission phase. On the first day of their cruise-to-Mars training, instructors begin training a crew of ASCANs with the simplest of these timelines -- “Saturday operations.”

The ASCANs’ first MTV mission simulation begins with the instructors training the ASCANs how to prepare breakfast, and the ASCANs practice rehydrating and heating dehydrated meal and drink packets using the galley’s potable water dispenser and food warmer. Training includes resupplying the food packets stowed near the galley, and as the ASCANs restock the food pantry, the instructors explains how the MTV inventory system automatically records food usage via the radio-frequency identification (RFID)-based inventory and management system. As the ASCANs continue learning their Saturday timeline, the instructors train them how to conduct their scheduled housekeeping activities. The ASCANs locate and use the vacuum cleaner to clean air vents, bacteria filters, and smoke detectors, and they properly dispose of wet cleaning wipes after cleaning the galley, table, and toilet. Instructors build on the ASCANs’ knowledge of their timeline interface learned in their initial Orion training. The instructors describe the details in the stowage notes accessed via the timeline interface, as the ASCANs use the stowage notes to determine where needed equipment is stowed. The instructors train the ASCANs how to self-schedule “to-do list” activities in their timeline. As the ASCANs rearrange their daily schedule, instructors discuss the operational guidelines and constraints for doing so. Instructors continue to train activities typically scheduled on Saturdays, having the ASCANs practice making video calls to their family for private family conferences, logging their exercise bicycle workout data, and using the still and video cameras for Earth observations and public affairs events.

Again, it may take several weeks to train the entire “Saturday operations” timeline from breakfast, through morning housekeeping, to afternoon exercise and personal activities, including all of the procedures and protocols associated with a typical Saturday. Each simulation concludes with a facilitated debrief of team and technical skills to ensure ASCANs stay focused on the training objectives (see more on feedback below).

As they gain competency in their trained skills, ASCANs practice the skills and tasks they have learned in a full-day training simulation independently from instructors. In their first instructor-independent “Saturday operations” simulation, the ASCANs might decide to work their housekeeping activities together, and then they might practice their newly learned galley skills by dividing the meal preparation duties for lunch. They might decide to rearrange their afternoon schedule by switching exercise and private family conference times with each other to accommodate a spouse’s availability for the family conference. In the late afternoon, they might decide to conduct a team-building exercise such as the NASA-developed Moon Base simulation, a low-fidelity paper and pencil simulation designed to exercise important team skills such as leadership and communication.

In addition to the contextual reinstatement and procedural reinstatement principles that are carried throughout the flow, the easy to difficult ordering principle can be seen in the training specifications above that suggest beginning the cruise-to-Mars phase of training with the simplest of timelines and tasks (e.g., Saturday operations of housekeeping, food preparation, exercising on a bicycle) building to more complex operations that will be trained in subsequent cruise-to-Mars timelines later in the training flow (e.g., vehicle commanding, payloads operations, malfunction response). The easy to difficult ordering principle also enables the strategic use of knowledge, described next.

Applied Training Principle: Strategic Use of Knowledge.

Kole et al. (2019) state that, "When acquiring new information, learners should attempt to relate that information to prior knowledge, regardless of whether or not that prior knowledge is related or conceptually similar to the new information" (p. X). They go on to explain how to best support retention of new knowledge, "When committing new information to long-term memory, that information becomes associated with retrieval cues. … By increasing the number of retrieval cues, the chance of successful retrieval [of new information] in the future increases" (p. X). By starting cruise-to-Mars phase training with the simplest of tasks for which ASCANs should already have some familiarity (e.g., protocols for trash, constraints associated with galley operations, procedures for logging exercise data), ASCANs can begin to relate the new information to preexisting knowledge, that in this case is conceptually similar, and also related to their mission. As ASCANs build their knowledge of the vehicle layout, equipment, and interfaces, and as training explicitly expands into new areas (e.g., conducting research, piloting spacecraft, diagnosing and troubleshooting health and vehicle issues), training on subsequent mission timelines is designed to include a review of previous material learned, using the prior knowledge to build retrieval cues for more challenging information, iterating this process throughout the entire training flow.

Applied Training Principle: Spacing.

Like each of the training principles discussed above, the spacing principle is also integrated throughout this "crew-centered, mission-oriented" training approach. Healy and Bourne (2012) described several studies supporting the advantage of spaced, or distributed, practice over massed practice for skills training and recommended that "for optimal benefits from training, repeated practice on particular items or responses should be spaced in time" (p. 21). Spacing can be seen throughout this training design in the way in which previously trained tasks and skills are reintroduced in different contexts during subsequent learning opportunities. For example, from the beginning of their Orion training, astronauts practice all aspects involved in their launch and ascent from Earth. They learn their pre-flight checklist along with the various call outs and other nominal procedures that they will execute during the flight and then a few days later practice executing these procedures in their first Earth ascent simulation. Each subsequent simulation involves practicing some aspect of the checklist and other nominal ascent procedures. Later training in MTV and Mars Surface Habitat simulations follow the same pattern of providing the astronauts with training on frequently used procedures such as galley operations, exercise protocols, and nominal maintenance tasks followed later still with practice of the same, or similar, MTV or Mars Surface Habitat procedures in subsequent simulations. Not only is training designed with spaces between practice, training is also designed to provide variability of practice throughout the training flow.

Applied Training Principle: Variability of Practice.

Variability of practice refers to a training design that provides varying conditions under which a task is practiced so that the task is not always practiced in the same manner (Kole et al., 2019). Although variability of practice slows the acquisition process, according to Kole et al. (2019) it is a "particularly powerful" training principle in that it applies to both procedural and declarative memory tasks and supports both retention and transfer. Variable practice conditions include variations in the task itself, variations in the conditions under which the task is trained such as the sequencing of the task with other tasks, or even variations in similar but different tasks (Barshi, 2015; Healy & Bourne, 2012; Kole et al., 2019). All of these variable conditions are integral parts of the training approach described here and are present throughout the entire training flow. An example is a simple maintenance task, which is first learned in its most basic form under ideal conditions and is reintroduced in later simulations with significant variability. Part of the variability might come from executing a more complicated version of the trained maintenance task; another part of the variability might come from executing a repair task on the same equipment using an untrained procedure.

Applied Training Principle: Rehearsal.

Providing ASCANs with the opportunity to practice their skills is an important component of the training design (Salas et al., 2006), and each simulation is an opportunity to provide the ASCANs with variable and spaced rehearsal of their training. Because the entire training flow is structured to follow segments of the mission, everything is a rehearsal of the mission whether it is a short Orion ascent simulation, a full-day Saturday housekeeping simulation, or a full-mission, multi-day simulation. Since ASCANs are trained as a crew, along with LCC and MCC, from the very beginning of their training and throughout, they are also able to rehearse team skills that are critical to mission success.

Vignette 3: Critical Operations: Piloting Orion, Performing Robotics Operations, and Executing EVAs

With a clear context of an overall mission, an understanding of their vehicle's hardware, software, systems, and equipment, and an understanding of the importance of working as a team, the ASCANs are ready to be trained for some of the most complex, high-risk tasks they will perform during their mission: piloting spacecraft, performing robotics operations, and conducting on-orbit and planetary surface EVAs. Skills associated with these tasks are among the most difficult to train and will require many hours of dedicated practice in laboratory or part-task trainers. While the overall design of training in the context of mission operations remains, one way of structuring training for these tasks is to select a subset of skills, or even a single skill, to focus on. Classroom training and self-study provides any necessary background and knowledge for skill acquisition, and these sessions are paired with part-task or laboratory training allowing for instructor-led, dedicated practice. Training continues to include mission simulations during which the ASCANs practice their newly acquired skills as individuals and as a team in a mission-oriented context, unaided by their instructors, along with ongoing practice and training of nominal mission operations.

For example, although it is expected that the Orion vehicle will be fully automated and that astronauts will only be required to monitor the vehicle systems and issue nominal commands, there are scenarios in which they may be required to fly the vehicle, and therefore they will need training on the piloting skills necessary to do so. Because ASCANs have been provided training to monitor and command the vehicle from the start of their training, at this point in the training flow, they are familiar with the layout of the vehicle interior, the interfaces and displays for monitoring and commanding the vehicle, and the vehicle systems. All of that knowledge is used and built upon as they are trained to pilot the vehicle. For example, ASCANs will require training on flying a rendezvous and docking in their Orion vehicle in the event that the automated rendezvous and docking software fails. ASCANs practice this task in a part-task trainer with their instructor until they can perform the simplest version of the task. As soon as they have achieved a level of proficiency, the training is transitioned to a mission simulation environment.

Relocating a robotic arm to a new attachment point on the same vehicle requires astronauts to use a rotational hand controller and a separate translational hand controller along with video displays and data overlays to maneuver (or “fly”) the free end of the robotic arm to a new attachment point and then release the fixed end of the arm. This task is among the easier to learn tasks because there is no relative motion between the end of the robotic arm being "flown" and an attachment point on the same vehicle. ASCANs are provided instructor-led training, with repeated practice, on this task to a measured proficiency level in a robotic part-task trainer. After demonstrating proficiency relocating the robotic arm in a part-task trainer, ASCANs are provided scenarios to use this skill in their MTV or Mars Surface Habitat simulation training as they continue to learn more challenging robotics tasks such as capturing a moving object.

EVA training is also designed to train skills to a proficiency level before moving into a mission timeline simulation. Hours of dedicated practice in the simulated μ-gravity environment of the Neutral Buoyancy Laboratory are provided to allow the ASCANs to develop the skills to maneuver in their spacesuits to locations outside the vehicle and to operate EVA equipment. Instructors provide feedback on the ASCANs' skill development, and provide progressively more challenging tasks as the training continues. Additionally, rather than training EVA tasks and skills separately from other systems, EVA training is integrated with other vehicle systems and payloads training, such as training vehicle external repairs, or conducting geological surveys, providing ASCANs with practice in the context of the mission.

Each of the three tasks described above (piloting, performing robotics operations, and conducting EVAs) require unique perceptual-motor skills, and there are specific training principles that inform the design of training to support the acquisition, retention, and transfer of such skills.

Applied Training Principle: Focus of Attention.

While there is some research that supports that novices should maintain an internal focus of attention by focusing on their body movements when first learning a motor skill, Kole et al. (2019) state that once individuals have had at least some practice with learning a motor skill, they should maintain an external focus of attention in performing the task, focusing on the outcome of their actions rather than their body movements. This shift in focus of attention supports both retention and transfer of the trained tasks. Starting robotics training with the easiest to learn task is not only consistent with the easy-to-difficult ordering principle (see above), it is also consistent with the focus of attention principle in that it provides the ASCANs with the opportunity to focus initially on how their hand movements on the hand controllers affect the movement of the robotic arm. As they develop competency in robotics operations, instructors can shift training to have the ASCANs focus on the trajectory of the robotic arm rather than on their body movements.

Applied Training Principle: Deliberate Practice.

While researchers may debate the importance of innate factors such as general intelligence and working memory capacity in achieving expertise (e.g., Campitelli & Gobet, 2011; Macnamara, Hambrick, & Oswald, 2014), they do agree that deliberate practice over a prolonged period of time is important for expert performance (Ericsson et al., 1993). As stated by Ericsson et al. (1993), "The level of performance an individual attains is directly related to the amount of deliberate practice" (p. 370). Deliberate practice is more than simple repetition; it is highly effortful, focused practice relevant to the skill being trained and requires motivation to engage in. "In contrast to play, deliberate practice is a highly structured activity, the explicit goal of which is to improve performance" (p. 368). ASCANs' training is such a deliberate practice. For example, if an ASCAN is having difficulty with a high yaw rate in controlling the robotic arm, an instructor (or an adaptive simulator) can adjust the yaw rate until the ASCAN can successfully maneuver the arm. ASCANs are motivated to improve their performance knowing the skills they are learning are necessary for their missions. Furthermore, the instructors provide them with practice that is both spaced and variable (see above) on skills, or subsets of skills, designed to be both relevant and challenging, requiring focus and effort, namely – engaging the ASCANS in deliberate practice.

Applied Training Principle: Feedback.

Because effective feedback is necessary for acquisition and retention of trained skills (see, e.g., Healy et al., 2014; Schmidt & Bjork, 1992), ASCANs are provided extensive feedback on their performance throughout their training. Salas et al. (2006) provided criteria for effective individual and team feedback that included ensuring feedback is constructive (i.e., focused on the individual or team performance in training but not critical of the person or people), is focused on the desired outcome of the training, and is actionable and task focused ("should provide trainees with the necessary knowledge that allows them to adjust their learning strategies to meet the expected performance levels" (p. 482).) (see also, Salas et al. (2012). Timing of feedback is also critical, and is dependent both on the skill or task being trained and on the level of skill development in the learner (e.g., novice versus expert). For novices, frequent, trial-by-trial feedback can support efficient skill acquisition (Healy & Bourne, 2012), and instructors can transition to more challenging tasks as the learner's performance improves (Ericsson et al., 1993). For proficient and competent learners, less frequent summary feedback is more effective than continuous feedback at supporting retention and transfer (Healy & Bourne, 2012). Healy and Bourne (2012) hypothesize that delayed feedback may be preferable to immediate feedback due to the spacing effect (see above). Delayed feedback may be very effective especially following exhausting training such as Neutral Buoyancy Laboratory EVA training runs.

As ASCANs master their piloting, robotics, and EVA skills, instructors shift the training fully back to the mission simulation environment. The most time-critical events that ASCANs must be trained for are the skills necessary to respond to medical emergencies, vehicle emergencies (fire, rapid depressurization, and toxic atmosphere), EVA emergencies (incapacitated crew member, suit failure) and major vehicle or system failures. Instructors again provide ASCANs training on this content in the mission simulation environment, training the correct procedures and protocols, including the very challenging decision-making that is needed to work outside published procedures to respond to unanticipated problems.

Conclusion

Training for a mission to Mars is a formidable challenge. For deep space missions, astronauts will require training to operate at a level of autonomy that has never been needed before, and they will need initial and refresher training to retain those skills for missions longer than have ever been flown before. Training for medical emergency, vehicle emergency, and major system malfunction will need to be provided pre-mission and continually maintained and refreshed throughout the mission. Training for complex skills for activities such as EVAs, robotics operations, complicated repair and maintenance, and scientific research will need to be provided pre-mission and refreshed prior to task execution or trained initially in-mission. And, training to live and work together as a team to accomplish mission objectives will be critical for mission success. We provide here three vignettes of a “crew-centered, mission-oriented” design approach based on empirically derived principles of training that could provide astronauts with the training needed to meet the challenges of NASA’s future deep space, exploration missions to Mars. To turn the description of this training approach into a sustainable curriculum change, NASA’s Spaceflight Training organization, instructors, and instructional designers will have to engage in its development and implementation.

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