INFORMATION REQUIREMENTS FOR FUNCTION ALLOCATION DURING MARS MISSION EXPLORATION ACTIVITIES

by

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For my family; your support made this possible.

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LIST OF ABBREVIATIONS

AH	Abstraction Hierarchy
ANOVA	Analysis of Variance
APXS	Alpha Proton X-ray Spectrometer
BASALT	Biologic Analog Sciences Associated with Lava Terrains
BR	Breaking Rocks
BS	Bagging Samples/Biological Sterilization
ChemCam	Chemistry & Camera
CheMin	Chemistry & Mineralogy X-Ray Diffration/X-Ray Fluorescence Insturment
CTA	Cognitive Task Analysis
CWA	Cognitive Work Analysis
DAN	Dynamic Albedo of Neutrons
DSN	Deep Space Network
EI	Instrument Use
EO	Observation
ET	Translation
EVA	Extravehicular Activity
EV	Extravehicular
GDTA	Goal-Directed Task Analysis
Hazcam	Hazard Avoidance Cameras
IRB	Institutional Review Board
ISL	Instrument Systems Lead
ISS	International Space Station
IV	Intra-vehicular
JPL	Jet Propulsion Laboratory
KoP	Keeper of the Plan
LSD	Least Square Difference
LTP	Long-Term Planner
MAHLI	Mars Hand Lens Imager
MARDI	Mars Descent Imager
Mastcam	Mast Camera
MEDLI	Mars Science Laboratory Entry Descent and Landing Instrument
MER	Mars Exploration Rovers
MB	Mössbauer Spectrometer
MI	Microscopic Imager
Mini-TES	Miniature Thermal Emission Spectrometer
MSC	Mission Support Center
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
Navcam	Navigation Cameras
Pancam	Panoramic Camera
PATH	Planetary Aid for Traversing Humans
PDC	Payload Downlink Coordinator
PDL	Payload Downlink Lead

PUL	Payload Uplink Lead
RAD	Radiation Assessment Detector
RAT	Rock Abrasion Tool
REMS	Rover Environmental Monitoring Station
RP	Rover Planner
SAM	Sample Analysis at Mars
SEXTANT	Surface Exploration Traverse Analysis and Navigation Tool
SIMCOM	Simulation Commander
SME	Subject Matter Expert
SOWG	Science Operations Working Group
STAG	Supratactical Approval Gate
sTL	Science Theme Lead
SuTL	Supratactical Lead
TAP	Tactical Activity Planner
TDL	Tactical Downlink Lead
TUL	Tactical Uplink Lead
UAV	Unmanned Aerial Vehicle
WDA	Work Domain Analysis

ABSTRACT

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The desire to send humans to Mars will require a change in the way that extravehicular activity (EVA) is performed; in-space crews (including those within a vehicle or habitat monitoring others conducting EVA) will need to be more autonomous and that will require them to monitor large amounts of information in order to ensure crew safety and mission success. The amount of information to perceive and process will overwhelm unassisted intra-vehicular (IV) crewmembers, meaning that automation will need to be developed to support these crews on Mars while EVA is performed (Mishkin, Lee, Korth, & LeBlanc, 2007). This dissertation seeks to identify the information requirements for the performance of scientific EVA and determine which information streams will need to be allocated to in-space crew and which are the most effective streams to automate. The first study uses Mars rover operations as a homology—as defined by von Bertalanffy (1968)—to human scientific exploration. Mars rover operations personnel were interviewed using a novel method to identify the information requirements to perform successful science on Mars, how that information is used, and the timescales on which those information streams operate. The identified information streams were then related to potential information streams relevant to human exploration in order to identify potential function allocation or automated system development areas. The second study focused on one identified mission-critical information stream for human space exploration: monitoring astronaut status physiologically. Heart rate, respiration rate, and heart rate variability measurements were recorded from participants as they performed field science tasks (potentially tasks that are similar to those that will be performed by astronauts on Mars). A statistical method was developed to analyze this data in order to determine whether or not physiological responses to different tasks were statistically different, and whether any of those differences followed consistent patterns. A potential method to automate the monitoring of physiological data was also described. The results of this work provide a more detailed outline of the information requirements for EVA on

Mars and can be used as a starting point for others in the exploration community to further develop automation or function allocation to support astronauts as they explore Mars.

1. INTRODUCTION

For many space exploration organizations, an aspirational goal to extend human presence in space is to send humans to Mars. The U.S. National Aeronautics and Space Administration (NASA) has a current plan to send humans to Mars in the 2030s (National Aeronautics and Space Administration, 2017) and SpaceX has the ambitious goal of landing its first crew of astronauts on the Red Planet in 2024 (SpaceX, 2017). Not only will achieving human presence on Mars be one of the greatest feats of human engineering, it will also help in the scientific search for the origins of life, and whether life ever existed in our solar system on a planet other than Earth.

Supporting human life and scientific activity on Mars will require that astronauts leave the relative safety of the surface habitat in order to perform extra-vehicular activity (EVA). EVA gives an operational flexibility that cannot be achieved with rovers or other non-human exploration robots and is necessary when performing maintenance or scientific activities in space (Newman & Barratt, 1997). In fact, since the beginning of the spaceflight program, EVAs have been recognized as valuable tools to meet scientific and engineering goals; NASA has extensive experience supporting EVA. Despite that, the risk associated with performing EVA is higher than nearly all other activities that an astronaut can perform (Miller, McGuire, & Feigh, 2017).

There have been hundreds of EVAs performed to date with the majority of them being for structural assembly, maintenance and repair, payload deployment/retrieval, or engineering or technology purposes (Miller, 2017; Wilde, McBarronn, Manatt, McMann, & Fullerton, 2002). The Apollo missions were the only instances of humans performing EVA on another planetary body, and only 9 of those EVAs cans be classified as planetary exploration EVAs where some level of scientific activity was performed. The remainder of the Apollo EVAs were proof-of-concept EVAs to demonstrate system capabilities (Miller, Claybrook, Greenlund, Marquez, & Feigh, 2017). Despite the lack of experience that humans have performing scientific EVAs, those types of EVAs will be paramount for human scientific exploration (Lim et al., 2018).

Current models of EVA, and all EVAs performed to date, have a small crew in space (maximum of 7-8 on Space Shuttle missions; the International Space Station (ISS) has a crew of 6 during nominal operations; normally 2 astronauts leave the spacecraft to perform the EVA at one time) who are supported and directed by a large group of experts on Earth with whom the crew has near-constant communication (Onken & Caldwell, 2009; Woolford, Sipes, & Fiedler, 2012). Not only is there evidence that this model of operations would not be scalable for multiple EVAs being performed over a longer duration mission (Caldwell & Onken, 2011), but the distance between Earth and Mars causes a 4-22 minute one-way delay on communication transmissions. These operational and time-delayed communication constraints challenge the Mission Control-centered model of EVA as delays on this timescale will not allow for voice communications between crew and Mission Control and makes it infeasible for ground crews to monitor life-support systems or respond to emergencies. It is also unlikely that communication or data transmissions will be continuously available throughout an EVA, as communication dropouts are far more likely with Martian operations and there may be lengthy communication blackouts (Mishkin et al., 2007). If a crewmember's health or life are at risk, it will not be possible to wait for instruction from Earth.

It is inevitable that astronauts will need to act more independently on Earth when performing EVA on Mars, including scientific EVA. This will necessitate that crewmembers will become responsible for tasks that have been, until now, performed by Mission Control personnel. It is more than likely that these additional responsibilities will need to be given to co-located astronauts who are not leaving the surface habitat or spacecraft, known as intra-vehicular (IV) crewmembers. It will be imperative that the IV crewmembers are able to effectively monitor all relevant information so they can not only focus on keep themselves and extravehicular (EV) crewmembers safe, but also meet the scientific objectives of EVA.

The systems required to keep humans alive on Mars will have high levels of complexity (Mishkin et al., 2007), but, as noted above, will have fewer individuals with limited attentional resources responsible to monitor the systems, respond to abnormalities, and re-plan activities if necessary. Due to the amount of information that IV crewmembers will need to monitor to ensure these complex systems are functioning correctly, human mission to Mars "…will require an unprecedented use of automation and robotics in support of human crews." (Mishkin et al., 2007, p. 1). This is not a novel statement and work has been done to develop automation and decision support tools for planetary EVA (Marquez, 2007; Marquez et al., 2019; Miller, 2017). However, without identifying all the necessary information streams for supporting human operations on Mars, how that information is used, and where it comes from, it is difficult to begin designing and developing coordinated, cohesive function allocation.

There has been some work trying to generalize the EVA work domain in systems engineering terms in order to develop decision support tools. These work domain analyses presented very broad pictures of EVA (that applied to all types of EVA being performed in any location) and did not delve into the specific information streams within EVA and how it is used, until they began developing the specific decision support tool of interest, and then only the information handled by the developed tool were considered (Marquez, 2007; Miller, 2017).

The identification of the necessary information required to perform scientific EVA on Mars will not only demonstrate the functions IV crewmembers will have to fill but will indicate which functions are not as time-sensitive and can be left under the purview of Mission Control. Those who wish to develop human-machine function allocation will need to be able to identify which information streams are mission-critical and are good candidates for automation development. Due to the importance of scientific EVA for human missions to Mars and the importance of EV-IV crewmember collaboration within that type of EVA, it was determined that scientific EVA performed on Mars would be the focus of this study.

In order to determine the necessary information streams to perform scientific EVA on Mars, it is necessary to look at representative occurrences of science being performed on planetary bodies. Though few examples of humans performing planetary scientific EVA exist, science has been performed on Mars using robotic landers since the 1970s and rovers since 1997. NASA has experience with four different rovers performing science on Mars: *Sojourner*, the Mars Exploration Rovers (*Spirit* and *Opportunity*) and the Mars Science Laboratory (*Curiosity)* (Mishkin, 2003; Perl, 2011; Tate, 2011).

Investigating how rover personnel (including rover operators, engineers, and scientists) use information to have rovers effectively perform science on Mars may be a good homology (as defined by von Bertalanffy (1968)) to the information requirements for IV crewmembers overseeing human scientific EVA on Mars. Not only do rover personnel have experience with science being performed more autonomously (there are few uplink opportunities for ground to communicate with a rover and therefore commands for the entire Martian day are uploaded at once to the rover) in space, but they also have experiencing reconciling scientific goals and operational constraints to perform effective science on Mars. There also exists a type of Mission Control for rover operations with large groups of experts and many sources of information that are consulted before rover commands are drafted (Perl, 2011).

By determining the information required for rovers to perform effective science on Mars, it is possible to determine if and how those information streams are homologous to humans performing effective science, and potentially which additional information streams will need to be considered when humans are sent to Mars.

Until proper human-machine function allocation is developed for reducing overall mission risk and hazards for astronaut performance, it is unlikely that humans will be sent to Mars and it is less likely that they will be able to perform effectively during EVA. At the very least, the quality and quantity of the science that will be able to be performed will decrease, but it could also increase the risks to the health and safety of the astronauts.

The following chapter presents a literature review on the current work being done in this area and identifies the gaps which will be addressed by this research. Chapter 3 outlines the research questions addressed in this dissertation and the methodology used to address those questions. The results of the methods following in this research are then presented in Chapters 4 and 5. Chapter 6 discusses these results and the limitations of the studies performed before conclusions and takeaways are presented in Chapter 7.

2. LITERATURE REVIEW

Mars Exploration Challenges

The Martian environment is an extreme environment that is unique when compared to human experience in other environments. Like workers in other extreme environments—for example, scientists during Antarctic expeditions—astronauts will be faced with extreme temperatures, isolation due to limited contact with individuals outside their immediate group of coworkers, and challenging terrain. In fact, Antarctica has been previously considered as a location for future planetary exploration analogs to test life support technologies, the effects of isolation, the performance of science in a hostile environment (Andersen, McKay, Wharton, & Rummel, 1990).

In addition to these factors, there are aspects that are unique to the Martian environment that make it more difficult to support long duration human missions. Not only is another planet much more remote and difficult to reach than any terrestrial location, there is also only a thin atmosphere with little oxygen to breathe, little accessible water for drinking/bathing, and a gravitational force just over a third the strength of Earth's (Dunford, n.d.; Williams, n.d.). Also, depending on where Earth and Mars are in their respective orbits, communications between astronauts and Earth-based Mission Control could take as long as 20 minutes to be transmitted, each way. It is also important to consider that due to the distance between Earth and Mars, transmissions using the current Deep Space Network (DSN) may be limited in the amount of data they can relay (Crane, 2017), and there will be periodic outages when communication is not possible (for example, the approximately month-long communication blackout when Mars and Earth are on opposite sides of the Sun) (Gangale, 2005).

These communication delays and transmission limitations make the task of supporting human life and human scientific exploration on Mars more difficult even than previous manned space missions in low-Earth orbit, or to the Moon. This increased difficulty will translate into increased risk and numerous challenges to performing extravehicular activity (EVA) on Mars. One of the major ways that these challenges will need to be addressed is by increasing the levels of crewmember autonomy and independence from ground-based control across nearly all aspects of the mission architecture—something that will make human missions to Mars drastically different from other human missions that have been executed previously.

Changing Models of Extravehicular Activity

Current EVA Model

Extravehicular Activity (EVA) consists of astronauts leaving the relative safety of a spacecraft or, in the case of a mission to the Moon or Mars, surface habitat, in order to perform various tasks (McBarron, 1994). During EVA, the astronaut's spacesuit is the only thing keeping him or her alive, and therefore EVA is considered one of the riskiest things an astronaut can do in space (Miller, McGuire, et al., 2017).

Most injuries aboard the International Space Station (ISS) are sustained during the performance of EVA—usually injuries due to overexertion (such as muscle or tendon strains) or contact with the spacesuit (blisters or abrasions) (Chappell, Norcross, Abercromby, & Gernhardt, 2015; Newman & Barratt, 1997). The exertion required to perform tasks in a heavy, pressurized spacesuit is also compounded by the fact that long periods of time spent in low gravity causes reduction in red blood cell production, the degradation of muscles, and a decrease in bone mass (Gunga, 2015). There is also evidence that the performance of physical tasks may be more difficult in a reduced-gravity environment due to requiring more stabilization actions and a reduction in traction with the ground (Chappell & Klaus, 2013). In addition, there is a lack of understanding of the exact physiological demands of EVA (Abercromby et al., 2016).

Despite the risks, EVA offers a level of versatility that allows for the completion of tasks that are more complex than those that could be accomplished solely by robotic aids or rovers (Newman & Barratt, 1997). It is also anticipated that future endeavors into space, especially Mars, will place at least an equal importance on scientific goals and exploration as engineering endeavors (Lim et al., 2019; Love & Bleacher, 2013). The increased complexity of tasks that humans can complete, and the increased desire for more scientific return are among the main motivations for sending humans to Mars.

There have been hundreds of EVAs performed to date; however, the NASA Apollo missions are the only ones that were focused around the performance of EVA on anther celestial body. In total, only 9 EVAs from Apollo 15-17 can be classified as planetary exploration EVAs (Miller, Claybrook, et al., 2017). The rest of the Apollo EVAs were generally proof-of-concept EVAs to demonstrate technological advancements, and outside Apollo, no EVAs have taken place on other planetary bodies (Miller, 2017; Wilde et al., 2002). It is, however, the planetary exploration EVA that will be most relied upon for the performance of science during human missions to Mars.

In addition to having little experience in planetary exploration, there have been no EVAs that have been performed with significantly time-delayed communications (outside of analogs performed on Earth with the purpose of simulating various aspects of deep space EVA). For this reason, EVAs to date have been heavily scripted with a large group of scientific and engineering experts in Mission Control on Earth in direct communication with, and directing, the astronauts through the entire operation (Caldwell & Onken, 2011; Lim et al., 2019; Woolford et al., 2012). The ISS also relies on ground controllers for daily vehicle systems management and long term maintenance plans (Mishkin et al., 2007).

In the current model of EVA, there are extravehicular (EV) crewmembers who are outside the spacecraft or surface habitat, performing the required activities. Generally, there is also at least one intra-vehicular (IV) crewmember who remains inside the spacecraft or habitat to coordinate with the EV crewmembers, provide support with donning/doffing of spacesuits, or operate robotic aids (such as the Canadarm on the International Space Station). Both IV and EV crewmembers in the current EVA architecture coordinate heavily with Mission Control (Flight Controllers, specifically) throughout the EVA. EVAs are generally planned months in advance of their actual execution by Mission Control and then practiced multiple times by EV and IV crewmembers on Earth. Pre-EVA preparation tasks are also lengthy and involve battery charging, spacesuit checks, systems checks, and procedure review by both EV and IV crewmembers. Mission Control will have 24-hour console operation a few days before the EVA until a few days after the completion of the EVA. The day-of pre-EVA tasks that are performed by the in-space crew are done so under the supervision of Mission Control to ensure that they are done correctly and include the configuration of oxygen, power, and communication systems, the preparation and donning of the spacesuits, and prebreathe activities. Mission Control will also monitor and direct the EVA throughout its execution (Bell, Coan, & Oswald, 2006).

While this "ground-heavy" model is ideal for operations in low Earth orbit (a large group of experts who are safely on Earth, can monitor astronaut safety, and limit the amount of cognitive resources required from in-space crew), it is dependent on prompt and rapid two-way voice and data communications. For this reason, this model will need to be altered, a least in some way, when humans are on Mars and round-trip communications can take 40 minutes, with possible bandwidth limitations to those transmissions.

Not only will the time-delayed communication not allow for the step-by-step instruction of crewmembers during EVA, but it also will not allow for Mission Control to monitor safety-critical systems such as life support, consumables, and power levels, as they will be updated too late if there is a problem. In addition to this, crewmembers will need to be prepared to handle emergencies and problems should they arise; in a time-critical situation, astronauts will not be able to wait for detailed instructions from Mission Control on how to fix or address an anomaly.

Uncertainty is an unavoidable element of any human mission to Mars, including uncertainty that cannot be mitigated in advance. Every one of the Apollo EVAs, despite detailed planning, needed to be re-planned or the astronauts needed to respond to unexpected occurrences (Marquez, 2007). This demonstrates that no matter the level of planning done in advance of sending humans to Mars, it is nearly certain that something unexpected will occur and, unlike the Apollo missions, astronauts may need to address the emerging problem or behavior with limited input from Earth.

There are also benefits to allowing the crew to act more autonomously. As a new planet is explored scientifically, it can be assumed that the astronauts on the surface (who are, essentially, "in the field") will be able to observe features and locations of interest that may not have been captured in imagery or other kinds of location observations. For more general mission operations, increased autonomy will allow crewmember flexibility in accomplishing their day-to-day tasks; this reduction in communications between Earth and Mars will increase the efficiency of the completion of these necessary tasks. This presents further evidence for the need of a more "crew-centered" model of EVA (Caldwell & Onken, 2011) as this knowledge gleaned from the field may lead to the generation of more valuable science.

Caldwell & Onken (2011) define autonomy as the ability of a person or computer to make an independent decision regarding whether or not to perform a task, and when and how to perform it. The 5 conditions of autonomy are summarized and presented in Table 1. Most EVA operations fall in levels 1-2 (although a select few may fall into level 3) where Mission Control provides step-by-step instructions (level 1) but the astronaut always has the option to veto the order from Mission Control should they deem it necessary (level 2). Other activities on board the spacecraft can reach higher autonomy levels.

Table 1: Conditions of Autonomy (Caldwell & Onken, 2011)

Level	Name	Description
1	No Autonomy	A human/computer has no autonomy to make decisions (i.e. receiving step-by-step instructions)
2	Veto	A human can veto another human/computer's decision
3	Operational Sequence	A human/computer may decide how to conduct the simple steps in a task in order to meet the prescribed goals (i.e. determining the best possible time to take a photo)
4	Task Activity	A human is told the overarching goal, but may reach it according to his or her own decisions
5	Goal Determination	A human decides the goals and the tasks to reach the goals

It is evident that levels 1 and 2 autonomy will not be acceptable for Mars operations due to delays on communication transmissions. Most Martian EVA operations will need to fall into level 4 and potentially level 5 in the case of unexpected occurrences or emergencies where there has not been a clearly defined contingency goal (Caldwell & Onken, 2011).

Caldwell & Onken (2011) also defined command levels, summarized in Table 2. Generally, Mission Control commands fall on levels 1 and 2 during EVA. Like the levels of autonomy, it will be necessary for Earth-generated commands to be at higher levels during Martian operations. Commands will either need to be tactical or strategic in nature to account for the one-way light-time delays on communications.

Table 2: Command Levels (Caldwell & Onken, 2011)

Level	Name	Description
1	Immediate	Command is actionable for only a few seconds to a minute
2	Short-term	Command is actionable for only a short period of time (ten or so minutes)
3	Tactical	Command is actionable for a longer period of time, up to several hours
4	Strategic	Command is actionable for a whole day or longer

It is not a new concept that mission control will need to move out of a controlling role and evolve into a supportive one, allocating more responsibility to in-space crewmembers (Caldwell, 2000; Mishkin et al., 2007). In fact, certain Mars analogs have begun to refer to the Mission Control Center as the Mission *Support* Center (MSC) in their operations to reflect this change (Lim et al., 2019).

Interestingly, there have been robotic exploration activities performed on Mars both presently, and in the past, with varying levels of autonomy.

Rover Operations on Mars

There have been 4 successfully landed Mars rovers to date: the Mars Pathfinder rover, *Sojourner* (landed July 4, 1997), the twin Mars Exploration Rovers (MER), *Spirit* (landed January 3, 2004) and *Opportunity* (landed January 24, 2004), and the Mars Science Laboratory (MSL) rover, *Curiosity* (landed August 6, 2012) (Garber, 2015). *Sojourner,* the first and smallest of the 4 rovers, was operational for 83 days until the Pathfinder mission ended on September 27, 1997 (National Aeronautics and Space Administration, n.d.-d). MER-A, *Spirit* travelled 7,730 meters before losing contact with JPL on March 22, 2010 (National Aeronautics and Space Administration, 2011) and as of February 2019, the *Opportunity* mission was considered complete after JPL lost contact with the rover in June of 2018 due to a dust storm and was unable to reestablish contact. *Opportunity* travelled 45.16 kilometers (National Aeronautics and Space Administration, 2019). *Curiosity* is still operational and has traversed 20.83 kilometers as of

June 2019 (National Aeronautics and Space Administration, n.d.-g; Thompson, 2019). There is also a future rover planned for 2020.

Currently, the Mars 2020 rover is being developed for launch in 2020. Mars 2020 is expected to cover much more distance and collect more samples than any previous rover mission and therefore a significant amount of effort is going towards ensuring that operations and decision-making are optimized (Williford et al., 2018).

Different rovers were designed to accomplish different tasks and where therefore designed with different scientific instruments and camera systems. Table 3 summarizes the instruments and cameras on board each rover and their general purpose (National Aeronautics and Space Administration, 1996, n.d.-a, n.d.-b, n.d.-c, n.d.-e, n.d.-f).

Table 3: Rover Instruments and Cameras

Instrument/Camera	**Acronym/ Short**	**Purpose**	**Rovers**
Laser Striping and Camera Systems	-	Used to detect hazards in front of the rover and for navigation	Sojourner
Alpha Proton X-ray Spectrometer	APXS	Reveals elemental chemistry of rocks and soils	Sojourner, MER, MSL
Navigation Cameras	Navcam	Black-and-white stereo pair of cameras for ground navigation	MER, MSL
Hazard Avoidance Cameras	Hazcam	Black-and-white cameras on front and rear of rover to identify possible hazards	MER, MSL
Panoramic Camera	Pancam	Takes color images of Mars	MER
Microscopic Imager	MI	High resolution camera that magnifies views of Martian rocks and soils.	MER
Miniature Thermal Emission Spectrometer	Mini-TES	Measures different spectrums of infrared light emitted from different minerals in rocks and soils (specifically to look for minerals formed in water).	MER
Mössbauer Spectrometer	MB	Determines the makeup and quantities of iron-bearing minerals in geological samples	MER
Rock Abrasion Tool	RAT	Grinds into the surface of rocks for analysis of fresh mineral surfaces	MER

Table 3 continued

Magnet Array	-	Collects dust for analysis	MER
Mast Camera	Mastcam	Takes color images and color video footage of Mars	MSL
Mars Hand Lens Imager	MAHLI	High resolution camera that magnifies views of Martian rocks and soils; has both white and ultraviolet light sources	MSL
Mars Descent Imager	MARDI	Took color video during the rover's descent toward the surface; now used for surface imaging	MSL
Chemistry & Camera	ChemCam	Fires a laser and analyzes elemental composition of vaporized materials; takes photo of area analyzed	MSL
Chemistry & Mineralogy X-Ray Diffraction/X-Ray Fluorescence Instrument	CheMin	Identifies and measures the abundances of various minerals in drilled/scooped samples	MSL
Sample Analysis at Mars Instrument Suite	SAM	Mass spectrometer/evolved gas analysis; searches for carbon compounds that are associated with life in drilled/scooped samples	MSL
Radiation Assessment Detector	RAD	Measures and identifies all high-energy radiation on Mars	MSL
Dynamic Albedo of Neutrons	DAN	Searches for signs of water by measuring hydrogen in the ground	MSL
Rover Environmental Monitoring Station	REMS	Weather station measuring atmospheric pressure, humidity, temperature, winds, and UV radiation	MSL
Mars Science Laboratory Entry Descent and Landing Instrument	MEDLI	Collected engineering data during the spacecraft's entry into the Martian atmosphere	MSL

With different rovers operating at different times over the course of two decades, there are differences in the exact ways that surface operations are supported. After a search of the literature, the author was able to find detailed information on *Sojourner* (Mishkin, 2003), MER (Mishkin, Limonadi, Laubach, & Bass, 2006; Perl, 2011), and MSL (Chattopadhyay et al., 2014) surface operation procedures. The following generalization of surface operations is taken from literature on the operations processes for these missions.

Rover operations can be broken down into three timescales: strategic, supratactical, and tactical. (It is important to note that these timelines are specific to rover operations and do not equate numerically to similar use of these terms in other applications.) Strategic and tactical timelines are relevant to both MER and MSL operations, while the supratactical timeline relates only to MSL operations. The tactical planning process operates on a scale of one Martian day (sol) and is the reactive process of responding to new data received. Strategic planning occurs over the course of several weeks to months and ensures that aspects of long-term planning (science campaigns, long-term management of resources, etc.) are taken into account. Supratactical planning was developed for MSL to "bridge the gap" between the strategic and tactical timelines and was therefore designed to incorporate both long-term and reactive planning. This additional timeline was deemed necessary for the MSL mission to offload some planning requirements from the tactical timeline due to the increased complexity and numerous instruments aboard that rover, and the distributed nature of the large operations and science team involved. The supratactical process looks ahead to the next two to ten sols of activities (Chattopadhyay et al., 2014; Mishkin et al., 2006).

Martian rovers receive commands once every sol—these commands have to contain all orders for the rover for the entire sol including terrain traversing, scientific exploration tasks, data transmissions back to Earth, and "housekeeping" commands (e.g. angling solar panels towards the sun)—and these commands are based largely on the success of the rover in fulfilling the previous day's tasks. In addition to this, MER and Pathfinder missions were solar powered and therefore restricted to operations during the day (this is not the case with MSL, which uses a radioisotope power source) (Perl, 2011). Despite MSL's radioisotope power source, it too is largely limited to operating during the Martian day due to power requirements for heating the rover at night (Chattopadhyay et al., 2014).

After the rover sends data (instrument scans, photos, etc.) back to Earth, there are both engineering downlink assessments (ensuring the rover is operating within expected values in variables such as power, component temperature, etc.) and tactical science downlink assessments (where images, scans, and other data are assessed by scientists). Both engineers and scientists will plan the following sol's activities based on the results of the downlink assessments in the science operations working group (SOWG) meeting. Members of the engineering team will be present at the SOWG meeting in order to assess the feasibility of desired science operations based on the current status of the rover (Mishkin et al., 2006).

After the SOWG has determined their goals for the sol, there is a smaller meeting with the SOWG lead, engineers, and instrument experts to validate the feasibility of the plan (whether there is enough time left before the required uplink to make all the commands, for example) and determine orders of operations which will most efficiently use the rover's time. After the finalization of a plan, commands to be uploaded to the rover are sequenced, reviewed, and approved before they are uplinked to the rover (Mishkin et al., 2006).

Perl (2011) took a systems-of-systems approach to analyzing MER operations in order to optimize MSL operations, and generated a description of high-level personnel required to generate instructions for the Mars Exploration Rovers (see Table 4).

Table 4: Engineering and Science positions (MER) (Perl, 2011)

SOWG Chair	Leader of the SOWG and main science representative throughout sol planning.
SOWG Documentarian	Science representative and assistant to the SOWG chair, ensures proper transfer of sequences between meetings.
Long-Term Planning Leader (LTP Lead)	Science position whose responsibility is to review the current sol path and current campaign as well as long-term goals.
Keeper-Of-the-Plan (KoP)	Engineering lead who maintains or modifies plan based on continued or new sequences.
Tactical Activity Planner (TAP)	Works with the uplink leads on ensuring new sequences are safe for the vehicle.
Tactical Downlink Leader (TDL)	Analyzes incoming data to assess current safety of the vehicle.
Tactical Uplink Leader (TUL)	Works with the engineering personnel to ensure new sequences are safe for the vehicle.
Payload Downlink Leader (PDL)	Analyzes incoming science data from the instruments to access completion of objectives.
Payload Uplink Leader (PUL)	Works with science personnel to create new plans for each instrument on the rover.

With this list of high level personnel, a task analysis flow diagram for a MER sol planning cycle was created, as shown in Figure 1.

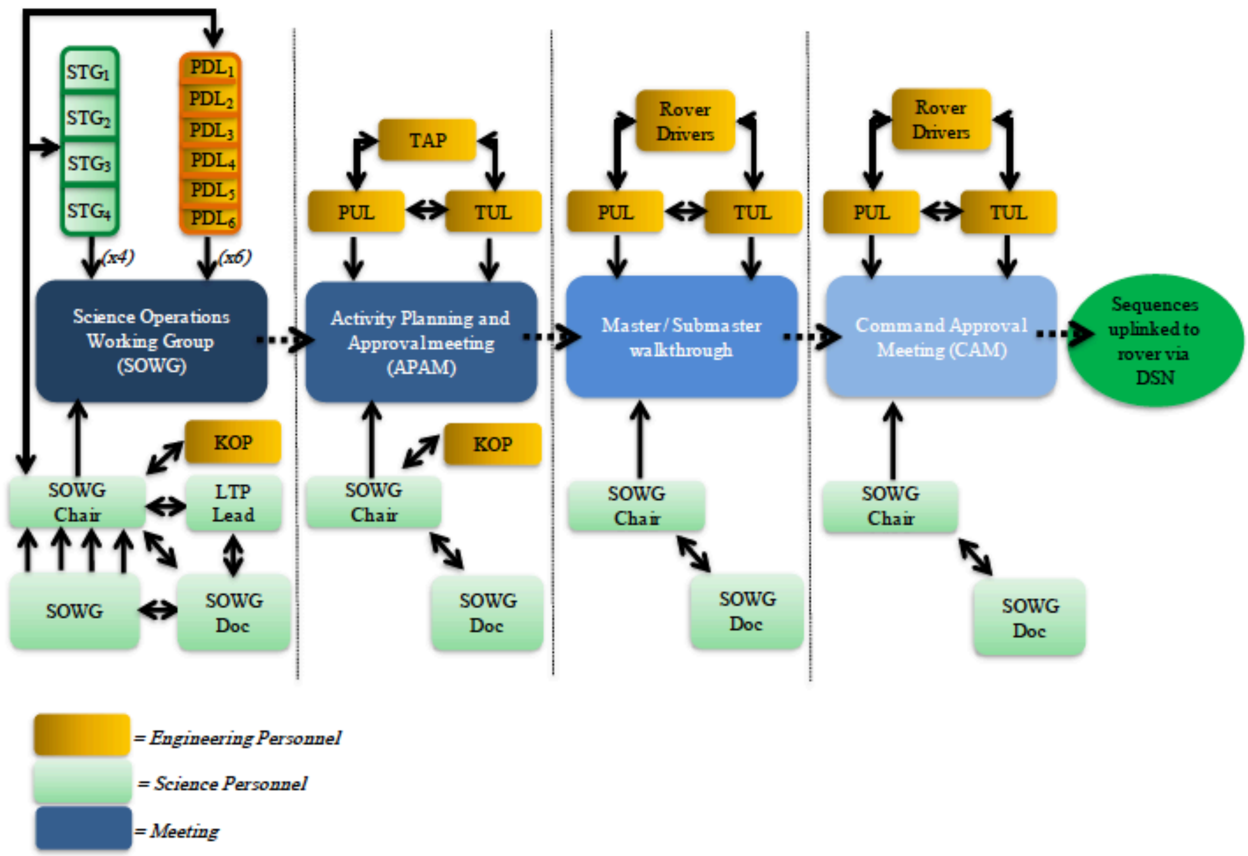

Figure 1: Task analysis flow diagram for one MER sol planning cycle (Perl, 2011)

The supratactical process occurs each day in parallel to the tactical process shown in Figure 1, so that any supratactical plans can take recent rover data into account. Look-Ahead Planning (the core aspect of supratactical planning) manages the ordering of activities over the course of the next two to ten sols, keeping track of the resources and constraints, dependencies between certain activities, and the most efficient way to plan desired rover activities. The supratactical team will meet with tactical planners in order to discuss planning guidelines for the tactical timeline and the priorities or dependencies of future desired activities. The two teams will also coordinate throughout the day to ensure the Look-Ahead Plan remains up to date. Supratactical planners will also interface with those who are planning strategic activities based on scientific priorities. Along with a Look-Ahead Plan (covering 2-10 sols worth of activities), the supratactical process will also generate a skeleton plan, which is a more detailed plan for the upcoming sol, which is used as the basis for tactical planning (Chattopadhyay et al., 2014).

The Supratactical Approval Gate (STAG) is where new rover capabilities or activities being performed for the first time are approved and assessed for readiness to be executed by the rover on Mars. Chattopadhyay et al. (2014) demonstrates of a new rover activity moves through the strategic, supratactical, and tactical processes during MSL operations, shown in Figure 2.

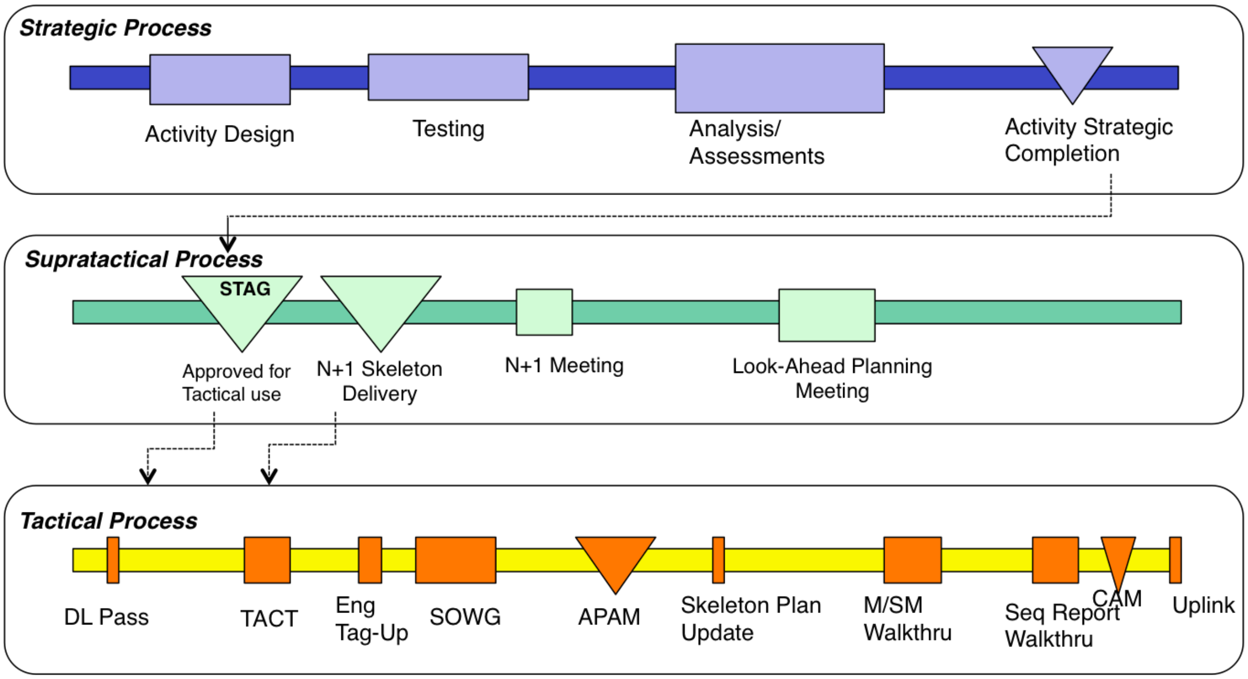

Figure 2: Strategic, Supratactical, and Tactical Processes (Chattopadhyay et al., 2014)[1]

It is also important to note that due to the delayed communications and the methods by which rovers are commanded, command levels 3 and 4 are used and, it can be argued that rovers operate with level 3 or 4 autonomy for certain tasks. For example, rovers are not "driven" across the Martian surface; they are given waypoints and end states in commands and then use stereo-vision cameras and other technologies to avoid obstacles and reach the given destination (Marquez, 2007; Mishkin, 2003). Therefore, despite the fact that rover operations on Mars deals with robotic (rather than human) exploration, it is likely that new models of EVA (and

[1] Republished with permission of American Inst of Aeronautics and Astronautics (AIAA), from Chattopadhyay, D. et al. (2014). The Mars Science Laboratory Supratactical Process. 13th International Conference on Space Operations, SpaceOps 2014; permission conveyed through Copyright Clearance Center, Inc.

earthbound Mission Support) will need to adopt some strategies that have been practiced for many years with robotic exploration.

The current Mars rover operations set up is very similar to the current EVA model in terms of being very controlled by large groups of personnel on Earth. The rover operations system may be more useful, however, in determining the informational requirements for successful completion of science-driven EVA, since personnel involved with rover operations have experience performing science on Mars (whereas Mission Control personnel have little experience with planetary exploration).

Function Allocation for Human Space Exploration Tasks

As many responsibilities will have to shift away from Mission Control and onto the in-space crew, the question arises regarding who will take over these roles. The currently planned mission architectures state that small crews (3-6 astronauts) will be sent on human missions to Mars (Hoffman & Kaplan, 1997; Salotti, Heidmann, & Suhir, 2014). These numbers have been determined due to the large cost (in terms of dollars and resources) of sending more astronauts, and the need to have experts in certain fields for a successful mission (for example, you will need a scientific expert for the science performed on the surface, an engineering/operations expert to maintain systems, a medical expert to ensure timely access to medical aid, etc.). While certain crewmembers can be cross-trained in various fields of expertise, the depth of knowledge available in each field will be larger if more individuals are sent, and the level of redundancy increases.

With small crew sizes, it is inevitable that a smaller number of people will need to take over the roles that had previously been assigned to many people on Earth. They will need to take in large amounts of information from different sources, understand what that information means, and project how the current state of the system will affect the completion of the EVA. This indicates that these crewmembers will need a high level of situation awareness—defined as "…being aware of what is happening around you and understanding what that information means to you now and in the future" by Endsley, Bolté, & Jones (2003, p. 13).

There will need to be some determination as to which functions are allocated to in-space crewmembers, and which remain the purview of Mission Control. A major factor in that determination will be the temporal rates at which each information stream responds.

Miller (2017) summarized generalized work functions into which functions were significantly impacted during time delayed communications on different timescales (Table 5). If this table were expanded to include more specific information streams and the timescales on which they affect EVA (seconds, minutes, hours, days, etc.), then a specific timescale could be specified and all the information streams responding on a shorter timescale than the one selected would need to be allocated to IV crewmembers. Those information streams that respond on longer timescales than the one selected, could remain the responsibility of Earth-based personnel.

Table 5: Impacts of delayed communications on work functions (Miller, 2017)

	Communication time-delay scale				
Generalized Work Function	Present-day <O(seconds)	O(seconds)	O(minutes)	O(tens of minutes)	Deep-Space >O(tens of minutes)
Archiving			Significantly Impacted		
Life support System Monitoring		Significantly Impacted			
Life Support System Operations		Significantly Impacted			
Timeline Tracking & Alteration		Significantly Impacted			
Timeline Task Execution		Significantly Impacted			
Inventory Management			Significantly Impacted		
Egress & Ingress		Significantly Impacted			
Translation, Orientation, and Stabilization		Significantly Impacted			
Anomaly Response and Resolution		Significantly Impacted			
Generating Signals			Significantly Impacted		
Receiving Signals			Significantly Impacted		
Shelter and Resource Supply			Significantly Impacted		
EVA Preparation and Post-Processing			Significantly Impacted		

As is apparent in the current function allocation during EVA (where Earth-based personnel direct the activities), Mission Control has high levels of situation awareness as they have access to the majority of the necessary information and have the personnel and resources to comprehend it and predict its effects on the EVA. When considering a small group of in-space crewmembers on Mars, however, this level of situation awareness will need to be transferred to a much smaller group of people as the time delays on communication eliminate the possibility of Mission Control so closely monitoring EVAs (as well as pre-EVA activities and mission activities in general).

As stated previously, extravehicular (EV) crewmembers, being outside the safety of the surface habitat, will be in an extremely dangerous situation. It is well known in human factors and psychology literature that stress negatively impacts attentional resources and situation awareness. Anxiety and stress impair performance on most types of tasks. This is due to a failure to maintain attention in the face of excessive concern, a reduction in responsiveness to peripheral stimuli due to attention narrowing (impairing the ability to multi-task), and a reduction in information processing and working memory capacities. This results in detriments to sensory-motor tasks, difficulty planning, and a decision-maker who is under stress is likely to make a decision without first considering all available information about outcomes to be expected (Bacon, 1974; Helmreich & Merritt, 2000; Hockey, 1986; Idzikowski & Baddeley, 1983; Janis, 1993; Keinan, 1987). The effects of detriments in performance due to stress also increase significantly (effects larger than just adding together the separate effects of each stressor) if there are many stressors present, instead of just one, indicating that it is imperative that the number of stressors on the crewmember(s) making important decisions should be minimized (Hockey, 1986). It is therefore not only unwise, but arguably impossible to transfer the increased level of situation awareness responsibility directly to the EV (or even EV plus IV) crewmembers.

It will therefore fall onto the co-located astronauts on Mars who remain inside the surface habitat or planetary rover, the IV crewmembers, to take on the additional roles that can no longer be fulfilled by Earth-based personnel. In addition to the usage of IV crewmembers during current EVAs aboard the ISS, there is evidence that having an IV crewmember during operations performed with simulated time-delayed communications in the context of an EVA analog is beneficial to the performance of the simulated EVA (Abercromby, Chappell, & Gernhardt, 2013) as those individuals can coordinate with Earth-based personnel and EV crewmembers more effectively. Miller (2017) also assumed that IV crewmember would take on some roles currently allocated to Mission Control during deep-space missions characterized by time-delayed communications. Outside of this literature, there were no other sources found by the author that focus on the role that IV crewmembers will have during a manned mission to Mars, despite the fact that such roles will be significant.

Task Demands for Mars-Based Crew

Despite the lack of literature on the future roles of IV crewmembers, it is clear that they will need to monitor information streams that will affect operations on the scale of seconds, minutes, to potentially hours (i.e. path planning, timeline management, consumable monitoring, etc.). Mishkin et al. (2007) suggested four general timescales for a mission (different timescales than those associated with rover operations): strategic (on a scale of months to years), tactical (weeks to months), short-term (hours to days), immediate (seconds to minutes). It was specified that in-space crew will need to be responsible for all immediate concerns and will share short-term activities with Mission Support. Caldwell & Onken (2011) developed similar frequencies of communication with slightly different timescales (i.e. strategic communications actionable for a whole day or longer, tactical communications actionable for several hours, etc.), specifying that IV crewmembers will be responsible information streams acting on all but the strategic frequency.

It is also important to remember that, unlike Mission Control personnel, the IV crew themselves will still be in a relatively dangerous situation and, in addition to being largely responsible for the safety of the EV crewmembers and the successful performance of EVA, they will also need to ensure that they are kept in-the-loop as to the status of the habitat/spacecraft, the location and status of any robotic assets, environmental conditions that may cause harm to crew or other assets, and communication system status, among other concerns. They will also likely be responsible for ensuring that the long-term and short-term goals of the mission are being met during the performance of the EVA. Fatigue is an additional risk, as no true "off-duty" time exists. Crewmembers may switch between EV and IV tasks, but they will not be able to go home and rest while others perform those duties. With this number of information streams that will be need to be monitored, and the small group of IV crewmembers, it is unlikely that it will be possible to successfully complete Martian EVA without some form of robotic assistance and/or automation function allocation.

The need for robotically-augmented crews on Mars has been previously expressed. Mishkin et al. (2007) asserted that the complexity of Martian systems would overwhelm and exhaust an un-augmented crew during nominal operations—even without considering anomalies that could potentially, and will likely, occur. Observations from a Mars analog simulation mission also noted that in a low-risk situation where many information streams were not included, there were still too many mission-critical information streams for the two IV crewmembers to manage without external aid from personnel outside the simulation (Hill & Caldwell, 2018).

While there has been some indication that there will be too much information associated with complex Martian systems for IV crewmembers to handle unaided, the author was unable to find literature specifying what all those information streams are, where they come from, what they mean, and on what timescales they operate or affect space operations. This would be useful in determining which information streams are most effective to automate, and which are better left to the human IV crewmember to process.

There is a lack of literature on specific information streams for EVA in general and the space community has a lack of experience with scientific planetary EVA (especially in deep space). This indicates a need for some sort of characterization of EVA in terms of the information required to perform scientific and operational tasks. This characterization would allow for more effective preparation for function allocation, robotically-augmented systems, and other kinds of automation that, as demonstrated in the literature, would be required for the successful completion of EVA in general. There have been some attempts to describe the EVA work domain, described below.

Characterizations of the EVA Work Domain

Both EVA work domain characterizations found by the author use the principles of *Cognitive Work Analysis* (CWA) (Marquez, 2007; Miller, 2017). CWA was developed for computer-based work in complex sociotechnical systems with an intention to apply to a broad range of application areas. It focuses on identifying the technical and organization requirements that need to be satisfied if a device is going to effectively support a human's work tasks within a specified complex system (Vicente, 1999). Being that the Martian EVA system can be easily categorized as complex, it appears as though this method would be a good start for characterizing the work done during EVA.

Both Marquez (2007) and Miller (2017) performed the first phase of a CWA called a *Work Domain Analysis* (WDA) which looks to represent a system independently of any particular worker, automation, task, goal, or interface (Vicente, 1999). This lack of specification as to the task or goal being completed, and by whom, have resulted in both WDAs considered here being very general, and not specifying the informational requirements required for effectively determining which information streams to automate.

Marquez (2007) looked at EVA inputs (mission resources, mission objectives, safety margins, exploration cost models, and planetary environs) and constraints (mobility and operational obstacles) to develop an EVA framework summarized in Figure 3. This was applied to the development of a decision support aid for path planning during EVA. More specific information requirements were not outlined until the development of the path planning tool.

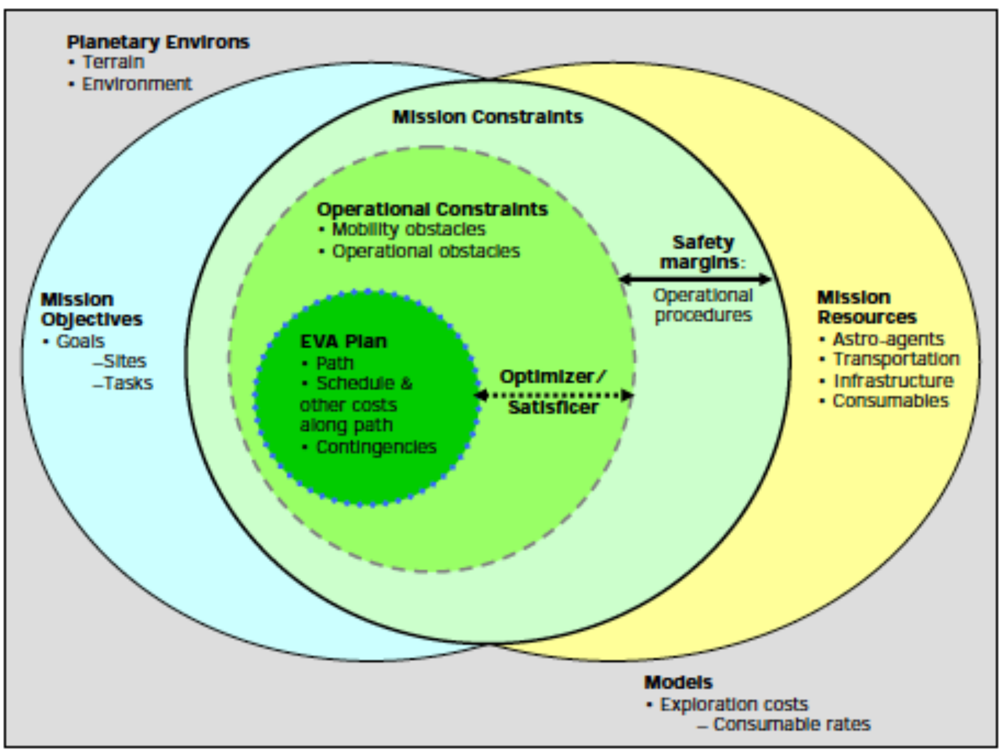

Figure 3: Planetary EVA Framework (Marquez & Newman, 2007)[2]

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[2] Republished with permission of SAE International, from Marquez, J.J. and Newman, D. (2007) Recommendations for Real-Time Decision Support Systems for Lunar and Planetary EVAs, SAE Technical Paper 2007-01-3089, SAE International; permission conveyed through Copyright Clearance Center, Inc.

Miller (2017) performed a more traditional WDA where he created an *abstraction hierarchy* (AH) model, which describes the work domain (here the EVA work domain) at levels of abstraction to encompass domain characteristics to more completely comprehend the demands and constraints before developing a decision support aid. The AH model decomposes the work domain into functional purpose (what the work domain was designed to do), abstract function (the underlying values and priorities to achieve a system's purpose), generalized function (individual process to meet priorities), physical function (resources involved to complete processes), and physical form (physical characteristics of the resources).

Following Marquez (2007), Miller (2017) kept the work analysis extremely abstract until the specific areas in which a decision support aid was being developed (for the generalized functions shaded in Figure 4) were specifically addressed. When considering life support monitoring and timeline tracking, Miller (2017) did go in depth regarding the knowledge and information requirements for EVA flight controllers to effectively monitor these functions, how that information is used to make decisions, and what an effective decision support aid would need to do to effectively present the required information and what that information means in context.

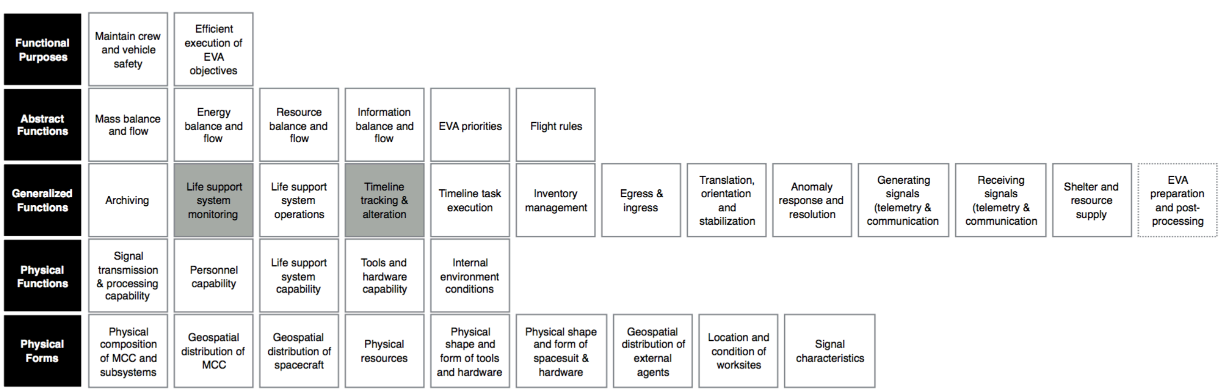

Figure 4: Abstraction hierarchy of EVA work domain (Miller, McGuire, et al., 2017)

Miller (2017) also generated an information flow model with the current model (Mission Control-centered) of EVA aboard the ISS, shown in Figure 5. It can be seen that this information flow model demonstrates who communicates with who during an ISS EVA, but not what information is being transmitted between individuals, or where information is coming from within the system.

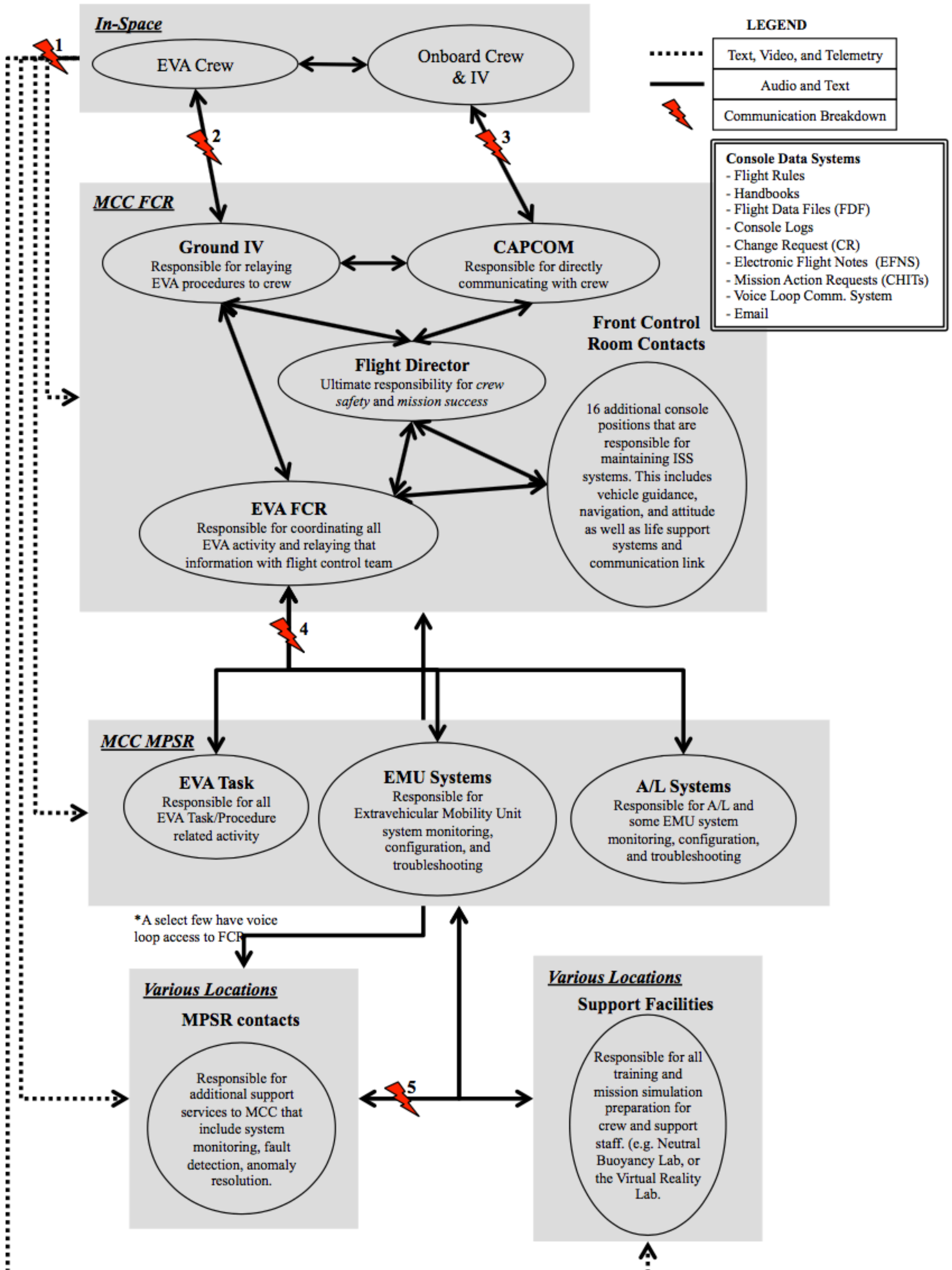

Figure 5: ISS EVA Operations Information Flow Model (Miller, McGuire, & Feigh, 2015)[3]

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[3] Republished with permission of IEEE, from Miller, M. J., McGuire, K. M., & Feigh, K. M. (2015). Information flow model of human extravehicular activity operations. *2015 IEEE Aerospace Conference*; permission conveyed through Copyright Clearance Center, Inc.

As demonstrated with these two EVA work domain analyses, it is not generally possible to derive overall information requirements when looking at EVA from a very general point of view. Attempting to do so would lead to an analysis similar to those presented above, which is not the goal of this research. In order to gain information at the level of specificity required in order to address the problem considered in this research, the problem space will need to be scoped.

Due to the importance that will be placed on scientific activities during Martian EVA, as specified earlier in this literature review, the goal of this research will be to focus on scientific EVA performed on Mars. This may limit the information requirements generated by this analysis to information specific to this type of EVA. However, this approach will achieve the desired level of specificity and it will address an identified gap in the literature. Also, it is likely that many information streams (such as consumable monitoring, timeline tracking, path planning, environmental conditions monitoring, data transmitting, etc.) will be common to many different types of Martian EVA.

Now the question is raised as to the best way to perform this analysis, and one of the primary questions related to this is who are the best subject matter experts (SMEs) to approach to gather this information. Miller's research studies used flight controllers as SMEs, observed ISS EVAs, and examined past Apollo EVAs to develop an EVA WDA (Miller, 2017; Miller, Claybrook, et al., 2017; Miller, Claybrook, Suraj, & Feigh, 2016). Marquez also examined past Apollo EVAs as well as terrestrial analogs to develop a WDA (Marquez, 2007). Neither study used ISS IV crewmembers as SMEs. Generally, all these sources of expertise and information are well-versed in the current model of EVA (Mission Control-centered) and are ideal references for research done assuming the current EVA model. These subject matter experts and sources of information, however, have little experience with planetary scientific EVA as none have been performed since the Apollo program. Some terrestrial analogs, who work on operations under time-delayed communication conditions, may have some insights into evolving models of EVA.

Interestingly, Marquez (2007) also looked at the planetary exploration done during MER missions while performing the WDA. It was noted that the goals of the rovers are scientifically driven, which is not the case with the majority of EVAs that take place on the ISS. Due to the fact that the work in this case was focused on developing a path planning tool, the consideration was largely placed on how the rover is controlled and driven across Mars and Table 6 was generated to determine the variables associated with MER path planning.

Table 6: Planetary EVA variables based on MER exploration (Marquez, 2007)

Variable Category	Variable Specifics
Astro-agent	Robotic agent (tele-operated rover); capabilities of agent (instrument- or task-related)
Goals	Determined by on-going exploration
Terrain	Rock density, ground bearing strength, homogeneity, slope, elevation, spectral data
Transportation	Minimum ground bearing strength, maximum traversable slope, maximum speed (function of terrain), power requirements, admissible slippage
Environment	Wind; seasonal solar supply
Consumables	Power supply/source, life cycles of robotic agents' components

The majority of the variables in this table could easily apply to a human traversing the surface of Mars as well as a rover. Goals for human exploration would also change based on the results of previous EVAs and terrain characteristics, environmental conditions, consumable levels and the ability to traverse certain areas would be a concern for astronauts as well.

In fact, some of the MER team roles described in Table 4 could be similar to those that IV crewmembers will adopt during scientific EVA on Mars (e.g. SOWG members/chair, tactical downlink/uplink leader, payload downlink/uplink leader, tactical activity planner). For example, the tactical uplink leader ensuring waypoints for a path is safe for the rover to take, is not unlike an IV crewmember providing waypoints or directions for an EV crewmember requesting assistance with path planning.

Table 7 summarizes examples in which the author believes roles associated with the MER mission could be representative of roles that will need to be taken by IV crewmembers during Martian EVA. This is not meant to be an exhaustive list of examples, simply an illustration of the similarities that may exist between IV crewmembers and some rover scientists/engineers.

Table 7: Homologous roles between MER and IV crewmembers

MER Team Role	Example of related IV crewmember role
SOWG members/chair	IV crewmember consulting with EV crewmember on where to sample/points of interest
TAP/TUL	IV ensuring oxygen levels are sufficient to complete planned tasks, with margin
TDL	IV monitoring physiological data from EV crewmembers to assess physical safety
PDL	IV crewmember assessing incoming instrument data during EVA
PUL	IV crewmember advising EV crewmember on which instrument to use in a specific situation

While there will, of course, be differences between Mars rover operations and scientific EVA performed by humans on Mars, it appears to be reasonable to say there could be many similarities in terms of information requirements between the two systems. Due to the increased experience of rover personnel with the performance of science on Mars, more autonomous activities of assets on Mars, and their experience with time-delayed communications, the author believes that looking to the Mars Rover system for information requirements is an effective place to begin looking for information requirements for IV crewmembers on Mars.

Physical and Cognitive Work Analysis Requirements

Work Analysis Methods

There are many different ways in which jobs, tasks, and roles can be analyzed—too many to give a comprehensive overview here. *Work analysis* is a general field of human factors engineering and industrial psychology that looks specifically at analyzing the types of work that people do and the requirements required to perform that work (Wilson, Bennett, Gibson, & Alliger, 2012).

There are many work analysis methods that encompass the term *task analysis.* The general purpose of a task analysis is to describe tasks and to identify the characteristics of an activity and to determine what needs to be done in order to accomplish a goal (Hollnagel, 2012). Hollnagel (2012) enumerated 3 conditions that indicate a need for a formal task analysis if one or more are met:

1. Accomplishment of a goal required more effort than one person can provide
2. Tasks become too complex for one person to control or comprehend
3. Technology becomes so complex that the situation changes from requiring someone to use the technology, to needed to understand, master, and control the technology

As discussed previously in this section, the role of being an IV crewmember during Martian EVA could fit all three of these criteria, indicating that a task analysis may be beneficial for this application. However, when wanting to determine the information streams that IV crewmembers will need to monitor, it is important to consider which method may be the most effective, if an appropriate pre-defined method exists.

Physical Work Analysis and Physiological Monitoring

The earliest forms of task analysis—for example, descriptions of physical tasks using Therbligs (first reported in 1919)—involve looking at physical movements or simple tasks required in order to achieve a goal. It is recognized that although these methods were extremely useful in the more efficient completion of physical labour or simple computer tasks at the time they were developed, many work functions have evolved to the point where the cognitive aspects of performance by the operator of a system, rather than physical movements, are of primary concern (Hollnagel, 2012). It is certain that one of the early approaches to task analysis would not be helpful when looking at rover exploration of Mars, nor would it be helpful in the definition of information requirements for IV crewmembers on Mars.

However, there may still be a place for physiological measurement for monitoring of work. It is possible to monitor physical loads and effects on the body; while these types of physical monitoring are not formal methods of work analysis, they have links to occupational health and safety protocols and the design of safe and optimal working conditions.

Physiological monitoring has been used to monitor humans in space since the beginning of both NASA's and the Soviet Union's space exploration programs. The United States programs measured pulse, respiration rate, blood pressure and body temperature; the Mercury 3 and 4 flights' biological sensor harnesses had some of the most advanced technology for physiological monitoring available at the time, including electrodes to measure heart rate, a respiration sensor, and a deep body temperature probe (Douglas, 1961; Holt & Lamonte, 1965). The Soviet Union measured cosmonaut pulse using an electrocardiograph and measured skin temperature (Karandeyev, 1965).

Understanding astronaut physiological response during the execution of an EVA is important as it will inform more precisely the amount of consumables needed for in-space activities. Miller, Claybrook, et al. (2017) determined that consumable usage during Apollo missions were far outside expected values. While it was acceptable to transport large amounts of extra consumable supplies during a relatively short mission to the Moon, doing so for a mission to Mars (which will occur over years) would be inefficient. Larger amounts of consumables would limit the amount of scientific equipment or other resources that could be brought on the mission.

The benefits of measuring physiological parameters in remote or extreme environments are also recognized today. Various physiological parameters can not only give an indication as to the health of a person, but can aid in the early detection of anomalies or health risks (such as hypothermia or hyperthermia), and be used to perform telemedicine and remote diagnoses if required (Cermack, 2006, 2012). With the distance between Earth and Mars, it could be years after an adverse event before an astronaut can gain access to advanced medical treatment, making the opportunity for avoiding these adverse events and administering treatment remotely as invaluable for a human mission to Mars. However, physiological data streams will warrant nearly immediate action if severe anomalies are detected and will therefore need to be one of the information streams allocated to IV crewmembers.

Though NASA standards for physiological parameters deemed most useful to monitor in space were not found, Cermack (2012) asserted that the most useful parameters to measure to ensure the health and safety of humans working in extreme environments are heart rate, blood oxygen levels, respiration rate, blood pressure, core body temperature, body accelerations, stress level (usually measured objectively using heart rate variability), and vigilance (the ability to maintain concentration over a long period of time).

The author's previous work, and the work upon which this dissertation is built—described in Hill (2017) and Hill & Caldwell (2019)—demonstrate that statistical differences are detectable in heart rate, respiration rate, and heart rate variability measurements taken in the field based on the type of field science task being performed (however, this work did not quantify those differences or indicate which tasks elicited higher/lower response values). It is therefore possible that using data such as this would be useful in monitoring working astronauts in space.

Statistical Analysis of Physiological Data

However, analysis of physiological data is not straightforward. Traditional statistical methods used to determine differences between different levels of a factor—such as an ANOVA or t-test—require that data be both independent and normally distributed (Kutner, Nachtsheim, Neter, & Li, 2005). When collecting physiological data at a frequency high enough to allow for health and safety monitoring, the data sets are not independent and do not always follow a known distribution. The effective analysis of dependent data sets requires complex statistical models.

Absent a known distribution of some physiological data sets, a nonparametric method of analysis should be used. One such method to determine whether or not there is a difference between responses to a multi-level factor (e.g. whether there are differences between heart rate responses to certain field science tasks) is a bootstrap version of an ANOVA. The null hypothesis of a bootstrap ANOVA is that all levels of the factor of interest have the same mean response. The bootstrap ANOVA determines the empirical distribution of this data using that null hypothesis and assumes that the sampled empirical data used in the analyses are representative of the population.

This bootstrap method samples the data randomly *with replacement* in order to generate one replicate with the same number of data points as the original data set. Multiple replicates are then generated, and each are stratified to reflect the number of data points that are associated with each level of the factor of interest. An ANOVA analysis is then run on each replicate to calculate the least square mean difference (LSD) between each factor level and those LSDs are stored. Distributions are built empirically based on the stored LSDs, assuming that the true population difference between two levels of a factor is at the center of the distribution. Given these distributions, standard errors can be estimated for the LSDs and a confidence interval at a specified α-level can be generated to assess the statistical significance of the LSD tests (whether or not the LSD is statistically different than zero) (Xu, Yang, Abula, & Qin, 2013; Zhou & Wong, 2011).

The analyses described above are post-hoc analyses, meaning they are performed after fieldwork has been completed. There was no specific method found that could be used to analyze the data in real-time (as it was collected). However, it is possible that using post-hoc analyses could give an indication as to the nominal responses to tasks of a particular individual and automated support systems could be designed based on the post-hoc analyses to identify off-nominal responses to tasks. It is also possible that medical professionals could identify physiological responses that would indicate immediate risks to crewmember health (e.g. indications of a heart attack) that could also be included in the design of any automated monitoring system.

Cognitive Work Analysis

Cognitive task analysis (CTA) is an extension of traditional task analysis that looks at the knowledge, though processes, and goal structures associated with the performance of certain jobs. Along with worker observation associated with traditional task analysis, there is also often subject matter expert (SME) interviews that take place in order to gain detailed knowledge into the cognitive processes of the individual performing the task (Chipman, Schraagen, & Shalin, 2000; Hollnagel, 2012). While traditional task analysis focused largely on temporally organizing the results of the analysis (which tasks precedes which other tasks), CTA can also be organized hierarchically, where tasks are decomposed into subtasks until a level of elementary tasks has been reached (Hollnagel, 2012).

Goal-directed task analysis (GDTA) is a form of CTA that uses a hierarchical structure that decomposes goals into sub goals and then denotes the information required to achieve those sub goals. GDTA focuses on very specific decisions that are made to achieve goals (Endsley et al., 2003). The focus of GDTA on the information requirements for operators of a system to make decisions makes it much more relevant to the problem being addressed in this research. Endsley et al. (2003) also states that when designing for a role or job that does not yet exist (such as an IV crewmember during a mission to Mars) is it customary to perform work analyses on jobs that do exist and are anticipated to be similar to the not-yet-existing job (such as rover control personnel), which is extremely relevant to the current research.

In fact, the idea of using systems that resemble other systems to perform analyses or understand more complex systems has been around before GDTA. A *homology* was defined by von Bertalanffy (1968) as the application of laws that are derived from simpler or better understood systems to improve understanding of more complex (or less well understood) systems. When respective laws that govern different systems are formally identical, then models from one system can be applied to another. While von Bertalanffy (1968) was speaking of physical laws (such as comparing electrical flow with the flow of a fluid), this can also apply to more general laws or information requirements (as shown with the typical work analyses methods of using existing roles to approximate non-existing ones).

A largely acknowledged problem with task analysis methods (including CTA and GDTA) is that they were developed to deal with linear work environments where an assumption could be made that there would be some order and regularity (Hollnagel, 2012). It is also imperative for task analyses that there be a pre-defined elementary task level, and that there is a specific goal defined for the system (Hollnagel, 2012). It is uncertain as to whether these requirements can be met when considering Martian EVA or rover operations. It is, however, safe to assume complexity and some challenges to the meeting of those criteria. Not only are there many uncertainties as to what the specific goals are going to be, but it cannot be assumed that those goals are going to remain the same day-to-day, that they are well-defined, or that they don't conflict. The levels of uncertainty associated with a system containing what will inevitably be some of the most complex technology, with components working on different planets and under time delayed communications, makes it difficult to determine specific enough goals to create the basis of a task analysis. It is a requirement that performance be flexible in a system such as this, rather than rigid, which makes it ill-suited to previously defined task analysis methods. It may be possible to use such methods in the future, when experience with human planetary exploration reveals regularities in operations that are currently undefined.

Cognitive work analysis (CWA) and work domain analysis (WDA) (discussed previously) seem like options that can overcome the shortcomings of task analysis methods in this scenario; these methods were developed to look at complex, sociotechnical systems and allow for worker flexibility. CWA focuses on identifying technical and organizational requirements that need to be satisfied for a device to work effectively within a system (Vicente, 1999, 2000). As discussed previously, both Marquez (2007) and Miller (2017) performed WDA, which is the first part of the CWA, and both produced abstract representations of the EVA work domain. Miller (2017) also performed a control task analysis, which is the second step of CWA, for the functions of timeline tracking and consumable monitoring. Control tasks are the goals that need to be achieved, regardless of how they are achieved and by whom (Vicente, 1999). None of the other aspects of CWA were addressed as they required more specific information as to how goals will be achieved, who will perform the goals, and what competencies the actors will require, which cannot be completely specified in a system that does not exist yet.

The control task analysis portion of the CWA begins to run into the same problems associated with GDTA. There is an assumption that goals are well-defined. In the case of timeline tracking and consumable monitoring, it can be assumed that goals are well-defined and will not vary over-much from those that are related to these functions during EVA aboard the ISS—meaning that flight controllers who have experience with these functions could likely be considered SMEs for that function that IV crewmembers will need to perform. Other functions characterized in the WDA may not be as well-defined at this stage in the development of Martian EVA systems to determine specific goals.

It is the objective of this research not only to determine what information is required to achieve overarching mission success goals, but also to determine new goals and elaborate agendas for effective support of EVA operations. Denoting the information streams that will required for scientific EVA on Mars is a necessity. It will be extremely important to have robust systems on Mars, due to the dangerous and uncertain environment in which it takes place. In this way, a pre-determined work analysis may not be ideal for the goals of this research, and the depth of information that is necessary. There is evidence that semi-structured ethnographic interviews with subject matter experts—such as the approach described in Rubin & Rubin (1995)—is a more appropriate method of data collection to fulfil the desired goals of this research. These interviews allow for the interview questions and research direction to vary based on the information received from interviewees, which offers a level of flexibility to the collection of data.

So, while the research may begin with a specific direction in mind, that direction can change given the results of interviews. Though this is a flexible method of gathering data, it also does not prescribe a structure through which to present results, which will also vary based on the information discovered throughout the interviews.

Supporting Distributed Supervisory Coordination for Autonomous Crews

A significant motivation behind the research on the information streams required for scientific EVA on Mars is that if a sufficiently specific map of the information and the sources from which it comes from can be generated, then it can be a starting point for the development of automation specifically for supporting IV crewmembers during human missions to Mars.

In general, there are information streams that are better suited to be automated than others. Fitts (1951) identified the tasks that computers perform better than humans (and vice versa) in the 1950s, summarized in Table 8. While this list is a good general guide to which tasks are best suited to humans and machines, technology has advanced considerably since the 1950s, making it so that machines are able to effectively perform some of the tasks previously listed in the first column. However, Fitts' list is still foundational in determining what should and should not be automated, despite the advances in computer technology, which is why it is included here.

Table 8: Fitts' list (Fitts, 1951)

Humans are better at:	**Computers are better at:**
Detecting small amounts of visual or acoustic energy	Responding quickly to control tasks and applying force smoothly and precisely
Perceiving patterns of light or sound	Repetitive and routine tasks
Ability to improvise and use flexible procedures	Reasoning deductively
Store large amount of information and recall relevant facts at appropriate times	Handling many complex tasks
Exercising judgment	Storing information briefly and then erasing it completely

When a human interacts with an automated subsystem, it is not unlike a supervisor giving directions to human staff—the more intelligent the staff members, the more likely the supervisor is to delegate or provide higher level goal directions rather than specific physical task movement instructions. In the late 1950s, automation began with stability augmentations for aircraft, electronic filtering of noise in signals, and the generation of simple displays. However, now humans can set desired system states and simply need to monitor the system to ensure that is it doing what it should. (For example, a pilot can not only set an altitude on an auto-pilot, but can also have the computer land a plane and simply needs to ensure that the system is operating as intended.) Human supervisory control (human operators setting conditions for adjusting and receiving information from a computer that closes and inner control loop) is used presently in applications ranging from anesthesiology, chemical and nuclear plants, UAVs, cruise control, and robotic operations (Sheridan, 2012).

As proposed by Parasuraman, Sheridan, & Wickens (2000), there are different classes of functions that can be automated, the most appropriate depending on the application, data type, and information source. There are also commonly cited levels of automation first proposed in Sheridan & Verplank (1978) and simplified in Parasuraman et al. (2000). The automation function classes are summarized in Table 9 and the levels of automation in Table 10.

Table 9: Automation Function Classes (Parasuraman et al., 2000)

Automation Class	**Description**
Information Acquisition	Sensing and registration of input data
Information Analysis	Inferential processes, prediction
Decision Selection	Selecting from lists of alternatives
Action Implementation	Performing a selected action

Table 10: Levels of Automation (Parasuraman et al., 2000)[4]

	Level	**Description**
High	10	Computer decides everything, acts autonomously, ignoring the human
	9	Computer informs the human on if it, the computer, decides to
	8	Computer informs the human only if asked
	7	Computer executes automatically, then necessarily informs the human
	6	Computer allows the human a restricted time to veto before automatic execution
	5	Computer executes a suggestion on if the human approved
	4	Computer suggests one alternative
	3	Computer narrow down selection to a few alternatives
	2	Computer offers a complete set of decision/action alternatives
Low	1	Computer offers no assistance: the human must take all decisions and actions

Parasuraman et al. (2000) also propose an iterative framework for designing automation using the above levels and types of automation, shown in Figure 6. Once a more specific outline of the information streams within Martian EVA are available, this framework will be useful in determining the automation type and level that is most appropriate for each information stream.

[4] Republished with permission of IEEE from Parasuraman, R., Sheridan, T. B., Wickens, C. D. (2000). A Model for Types and Levels of Human Interaction with Automation. *IEEE Transactions of Systems, Man, and Cybernetics - Part A: Systems and Humans*. 30(3); permission conveyed through Copyright Clearance Center, Inc.

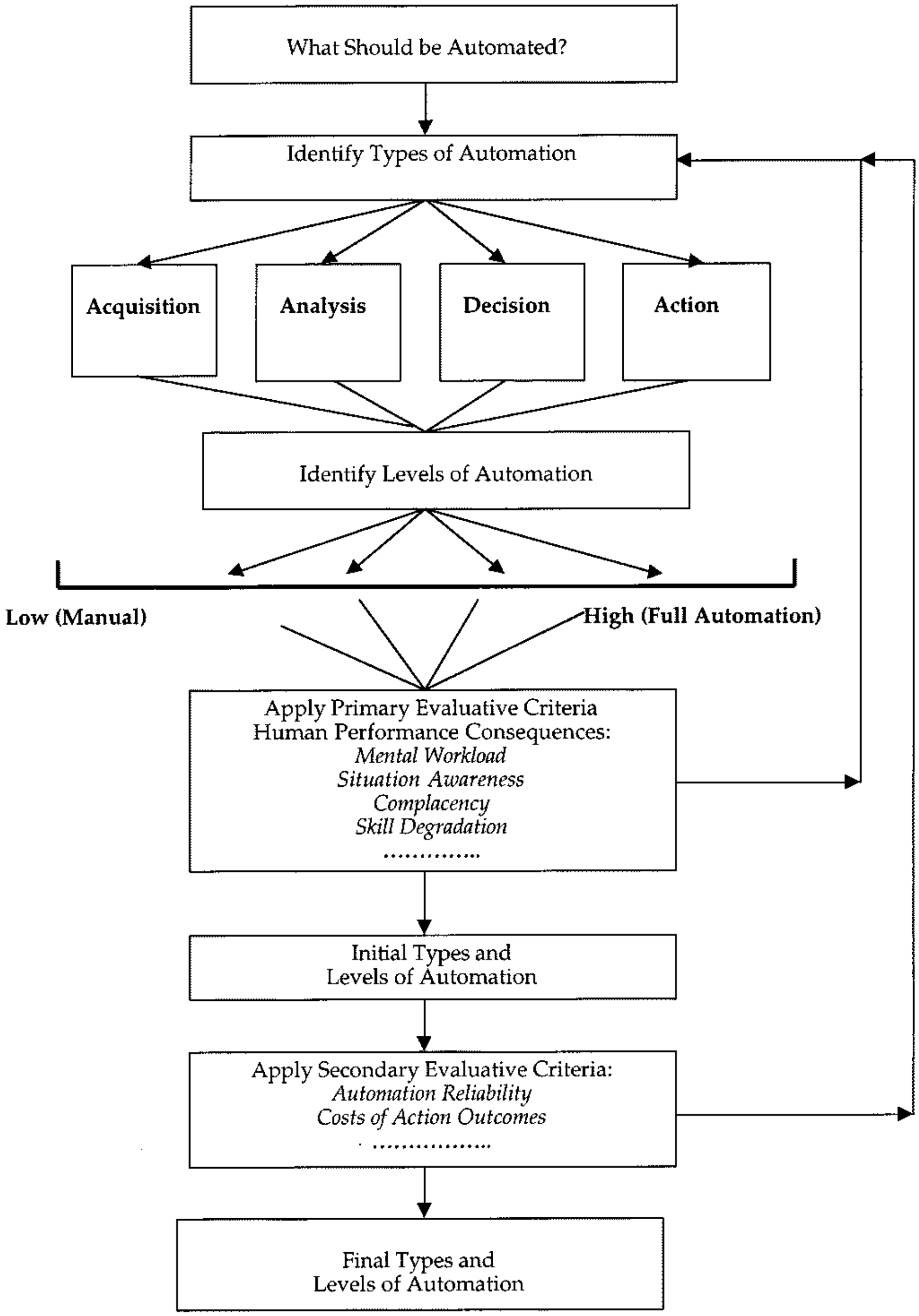

Figure 6: Framework for designing automation (Parasuraman et al., 2000)[5]

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[5] Republished with permission of IEEE from Parasuraman, R., Sheridan, T. B., Wickens, C. D. (2000). A Model for Types and Levels of Human Interaction with Automation. *IEEE Transactions of Systems, Man, and Cybernetics - Part A: Systems and Humans*. 30(3); permission conveyed through Copyright Clearance Center, Inc.

There have also been studies on some of the pitfalls of automation that will need to be considered when designing automation for Martian EVA. It will be imperative that displays are designed to keep the operator in-the-loop and can be adaptable to change the format and/or logic of the display to fit the situation. It will also be important to use the automation together to ensure that the attentional demands of the IV crewmembers will be not too high or too low (which can cause problems with vigilance and monitoring tasks), or on the sensitivity with which the displays are observed (Cuevas, Fiore, Caldwell, & Strater, 2007; Parasuraman, 1987; Parasuraman et al., 2000; Sheridan, 2012).

Existing Work on EVA Automated Support Systems

Some of the existing work on support systems to enable Martian EVA has been mentioned in this chapter, but will be more completely reviewed here.

There has been work done to develop timeline tracking and management tools for Mars analog projects. One such development is Playbook (Marquez et al., 2019). Playbook aims to assist astronauts in completing assigned tasks. It allows for plans to be generated, viewed, and changed and planning constraints can be implemented to ensure that no tasks violate those planning constraints. The status of specific tasks (e.g. in progress, completed, etc.) can also be logged in Playbook to compare actual performance to planned performance. Playbook also includes a chat interface.

A software tools called xGDS was developed to support analog EVA operations. The software allows for users to generate scientific traverse plans on maps, track/store EV crewmember positions throughout an EVA, and store relevant data such as video files, photos, science instrument data, and relevant operational data. All of the stored data is housed within searchable databases for access within a simulated EVA, or for post-hoc analysis (Marquez et al., 2019).

The author also found references to the development of path planning tools (Marquez, 2007; Marquez et al., 2019). Marquez (2007) describes a path planning prototype named PATH (Planetary Aid for Traversing Humans) which inputs terrain maps, obstacle maps, cost function models, and environmental conditions to generate a planned path. The terrain and obstacle maps used in the prototype were based on lunar terrain and PATH only considers obstacles from terrain slope. Different cost models considered terrain visibility, distance travelled, the time it takes to follow the path, the metabolic cost of the route, or terrain slope.

Similarly, Marquez et al. (2019) describes another path planning tool called SEXTANT (Surface Exploration Traverse Analysis and Navigation Tool) which uses cost functions based on distance, time, or energetics. It worked closely with xGDS (described above) to model the energy expended for a human to follow the desired path and would create a more granular route that minimized energy expenditure.

Automation of Physiological Monitoring

There will likely be many information streams that not only operate on timescales that will make it necessary for IV crewmembers to monitor them, but that also lend themselves well to automated monitoring. It is likely that the monitoring of EV crewmember physiological parameters during EVA will be one of those information streams.

There have also been papers showing that machine learning algorithms and data mining can be used to predict or diagnose anomalies or disorders such as major depressive disorder (Kim et al., 2017), delirium (Oh et al., 2018), the need for lifesaving interventions in trauma patients (Liu, Holcomb, Wade, Darrah, & Salinas, 2014), cardiac arrest (Ong et al., 2012), and sepsis mortality risks (Gultepe et al., 2014). It follows that it may be possible not only for automation to monitor physiological parameters during EVA, but that machine learning algorithms could potentially be developed that identify anomalies, predict adverse events as EV crewmembers perform their tasks, or alert crewmembers to when they exceed action limits set on physiological parameters.

Though it is not possible to set universal action limits on most physiological parameters due to the effects of many individual characteristics such as age, sex, physical fitness level, and genetic factors (Agelink et al., 2001; Almeida & Araújo, 2003; Carter, Banister, & Blaber, 2003; Cornelissen, Verheyden, Aubert, & Fagard, 2010; De Meersman, 1992; Harms, 2006; Kostis et al., 1982), individual action limits could theoretically be set for each astronaut based on previously taken measurements. The astronauts chosen to go on missions to Mars will be known well in advance of the mission taking place. Therefore, large amount of physiological data could be collected on each individual during the performance of various tasks and in various physiological states in order to develop a more complete picture of normal and abnormal physiological responses for each individual, as well as the distribution of that data. Depending on the distribution of the data, simple upper- and lower-bound action limits could be determined for each individual astronaut and a simple automated system could alert IV crewmembers if the physiological parameters of EV crewmembers are outside nominal values. While the generation of specific action limits or automation algorithms is not a goal of this research, the determination of whether or not simple automation could be a possible solution to monitoring this data in real-time could inform future automation development.

3. METHODOLOGY

The previous chapter reviewed literature on extravehicular activity, Martian rover operations, work analysis methods, function allocation, and physiological monitoring. This literature review reveals three main gaps for further research:

1. Existing literature does not clearly and completely outline the information streams necessary for scientific activities on Mars and current formal methods—such as Goal-Directed Task Analysis (Endsley et al., 2003) or Cognitive Work Analysis (Vicente, 1999)—are insufficient in addressing that gap,
2. No literature was found on how information streams that enable rover scientific operations compare to proposed human scientific operations on Mars,
3. Existing physiological monitoring information from prior planetary EVA is insufficient to differentiate physiological responses to different EVA tasks or indicate potential methods of automated monitoring.

As outlined in the literature review, there will be large amounts of information currently monitored by Mission Control that will need to be allocated to IV crewmembers on Mars due to time delays on communication and the fact that IV crewmembers will be the only acceptable personnel to take on the additional responsibilities. It would be ideal to delegate as much information as possible by allocating it to Mission Control, meaning that timescales on which information acts or responds is an important area for investigation. Also, even if certain long-acting information streams can remain under the purview of Mission Control, there will still be too many short-acting information streams that IV crewmembers will be responsible for. It is inevitable that automation and computer function allocation will need to be developed in order to support IV crewmembers on Mars. There is some indication that the monitoring of physiological parameters for health and safety and EVA optimization could be effectively automated.

The following sections will outline the research questions addressed by this dissertation, the studies to address these research questions, and the proposed methodologies for data collection.

Research Questions

This dissertation will aim to answer the following research questions:

Research Question 1 (RQ1): how do the information streams necessary for effective rover scientific operations on Mars compare to the information streams that will be necessary for human scientific operations on Mars?

- **RQ1.1** How do the information streams necessary for effective rover operations on Mars differ from human operations on Mars?
- **RQ1.2** How are the information streams necessary for effective rover operations on Mars similar to human operations on Mars?

Research Question 2 (RQ2): what information streams are necessary to ensure a rover is operating as intended on Mars?

- **RQ2.1** What information streams inform long-term (strategic) operations goals?
- **RQ2.2** What information streams inform short-term (tactical/supratactical) operations goals?
- **RQ2.3** Over what timescales is this information used?

Research Question 3 (RQ3): what information streams are necessary to ensure a rover is performing effective science on Mars?

- **RQ3.1** What information streams inform long-term (strategic) scientific goals?
- **RQ3.2** What information streams inform short-term (tactical/supratactical) scientific goals?
- **RQ3.3** Over what timescales is this information used?

Research Question 4 (RQ4): Are physiological data from astronauts during EVA effective candidates for automated monitoring?

- **RQ4.1** Are there statistical differences in physiological responses across EVA-like tasks between or within individuals?
- **RQ4.2** Is there a simple method to allow for the automated monitoring of physiological responses?

RQ1: Comparison to Human Missions to Mars

The first research question builds on the identified similarities between rover operational and scientific personnel and IV crewmembers during Martian EVA. It seeks to determine how similar the information streams within the Mars rover system may be to an imagined Martian EVA system. By asking which information streams may be similar, from the perspective of the rover system SMEs, it may identify those common information streams that will need to be monitored during human missions to Mars. Even the identification of information streams that may differ will be useful in that it will identify areas in which the space exploration community may have less experience, especially across time-delayed communications. These identified differing information streams can indicate areas in which more research will need to be done to ensure that sufficient attentional resources (either by IV crewmembers, Mission Control personnel, or computer automation) are dedicated to the monitoring of that information.

RQ2 & RQ3: Information Streams for Rover Operational and Scientific Considerations

The second research question looks to define the information required to set operational goals, determine if a rover is meeting the set goals, and the timescales on which the information operates. In this case, operational considerations are those involved in ensuring that a rover's systems are operating as intended, are capable of performing the tasks required of them, have all necessary resources available to them, and are not at risk of becoming inoperable. In the case of a Mars rover, operational considerations, especially those that deal with the security of the rover, are extremely important because if the rover becomes inoperable or unable to perform the tasks assigned to it, then no more exploration can be done and little or no further information about the planet can be gleaned.

The third research question seeks to determine the information required to set scientific goals, determine if a rover is meeting the set scientific goals, and timescales on which the information operates. In this case, scientific considerations are those that involve the performance of science on the surface of Mars, including sampling, scanning, analysis, and experimentation. Rovers are created with a set of objectives in mind that guide the setting of long-term and short-term goals, and, as stated in the literature review, the motivation in sending humans to Mars is largely science-based. That makes understanding the information requirements to perform effective science on the surface important. The information streams revealed from answers to RQ2 and RQ3 will inform much of the comparisons made through RQ1 (what identified information streams are similar or different from EVA operations on Mars).

Information and goal timescales are important aspects to both RQ2 and RQ3. As outlined in the literature review and earlier in this chapter, there will be large amounts of information that will need to be monitored by IV crewmembers on Mars and it is important to determine which streams can remain the responsibility of personnel on Earth. Therefore, determining what information is involved in setting longer-term goals (e.g. goals that stretch across days and/or multiple EVAs) would be useful in determining what can remain under the purview of Mission Control or Mission Support. Those information streams that operate on short timescales are those that will require some attention when it comes to automation and function allocation between machines and humans.

RQ4: Physiological Response & Monitoring

After the identification of important information streams required for scientific rover operations on Mars, and how those relate to human scientific operations on Mars, the author is assuming that one of those information streams will be physiological monitoring due to its usefulness for health and safety, and its history of use in space exploration in the past (as described in the previous chapter). The fourth research question builds on the author's previous work by increasing understanding of the differences in physiological responses to EVA-like tasks, and whether or not that data lends itself to simple automated monitoring algorithms (such as setting upper- and lower-bound action limits on physiological responses).

To answer all four of these research questions, two separate studies were performed. The first study used semi-structured interviews with rover engineers and scientists to address the first 3 research questions. Research Question 4 was addressed by collecting physiological responses of individuals performing field science tasks under simulated Mars conditions as a part of NASA's Biologic Analog Science Associated with Lava Terrains (BASALT) research project.

Study I Methodology: Information Streams for Rover Operations and their Comparison to Human Missions to Mars

RQ1 looks to identify different (RQ1.1) and similar (RQ1.2) data streams between rover operations and those that will be anticipated to be important for future human operations on Mars. RQ2 and RQ3 seek to answer what information streams are necessary to ensure that rovers are operating as intended and performing effective science. The sub-questions associated with these overarching research questions look to address how the identified information streams affect long-term (RQ2.1, RQ3.1) and short-term (RQ2.2, RQ3.2) goals, and on what timelines they operate (RQ2.3, RQ3.3).

These questions were addressed using individual, semi-structured interviews with rover scientists and engineers. It was the goal of using qualitative interviews in order to gain richer and more specific details from subject matter experts than would be gained through the use of a questionnaire, or some other form of data gathering that does not allow for probing of sub-questions from the interviewer. As described in Rubin & Rubin (1995), this method of collecting data also allows for the questions asked to evolve or change based on what the interviewer learns throughout the process.

Interviews followed the questions outlined in **Appendix C** (for engineers) or **Appendix D** (for scientists). The interview questions for both scientists and engineers began with demographic questions in order to track the experience and areas of expertise of the subject matter experts interviewed and continued with the questions addressing information streams and their effects on goals, and the comparisons between rover and human Martian operations.

After receiving IRB approval from Purdue University (protocol # 1807020864), potential participants were contacted through email (whether that be through an electronic introduction or simply the author sending inquiries as to whether a potential participant would be interested in participating in the study) following the email script in **Appendix A**, and through snowball sampling (Goodman, 1961) with contacts at the National Aeronautics and Space Administration.

Participants were screened through email prior to the interview to ensure they were eligible for the study by ensuring they had direct experience with the surface operations of a Mars rover. Participants were then given the information sheet (**Appendix B**) to review and sign. With the permission of the participant, interviews were recorded so they could be transcribed for use in a qualitative data analysis tool for the purposes of performing a thematic analysis. The goal was to interview 10 rover scientists and 10 rover engineers (estimated to be 5-10% of the total relevant worldwide population of subject matter experts). Due to the limited pool of experts from which the study drew participants, this was deemed to be a realistic, yet still large subset of the available population. Recruitment occurred between September 2018 and May 2019.

Participants were de-identified by giving each an alpha-numeric code with which their transcription and audio files were labelled. Any details that could lead to the identification of the participant (names, specific job titles, team names, etc.) were excluded from the transcription file to protect participant anonymity. Interview transcription files were analyzed in QSR International's NVivo 12 for Mac © qualitative data analysis program. Data were then coded using thematic open coding methods (Saldaña, 2009). Codes were developed iteratively as data was gathered and analyzed and then checked for consistency and accuracy after all data analysis was complete. The resulting code book describing all the codes used is provided in **Appendix E.**

It was anticipated that the results from this study would generate a list of different information streams necessary for the successful completion of rover operations on Mars, whether or not those information streams apply to scientific EVA on Mars, and on what timescales those information streams operate. With this information, it would be possible to determine which information streams can remain under the purview of Mission Control during human missions to Mars, and which will need to become the responsibility of IV crewmembers or automation.

Study II Methodology: Physiological Response & Monitoring

RQ4 looks to identify whether statistical differences exist between physiological responses to different EVA-like tasks (RQ4.1) and whether the distribution of those responses could allow for the establishment individual action limits (RQ4.2). This research question was addressed by collecting and analyzing physiological data from individuals performing field science tasks.

Chronologically, this study began before the first study. However, this study is labelled as the second study due to the fact that it fits nicely as an elaboration on a specific information stream as it relates to the framework established for the first study (identifying the information streams and then investigating one further). It is therefore more logical to present Study I before this study in order to establish the framework of this dissertation and how this study fits within it.

To collect physiological data during the performance of EVA-like tasks, physiological monitors (the Zephyr™ BioHarness™) were integrated into NASA's Biologic Analog Sciences Associated with Lava Terrains (BASALT) research project (Hill, Caldwell, Downs, Miller, & Lim, 2019). The aim of BASALT was to investigate the performance of science and meeting scientific objectives under simulated Martian EVA conditions (Lim et al., 2019). Some of those simulated Mars conditions was the structure of the EV/IV crewmember teams, and delays of 5 or 15 minutes placed on all communications between simulated-Earth and simulated-Mars. The general simulated-EVA architecture is shown in Figure 7.

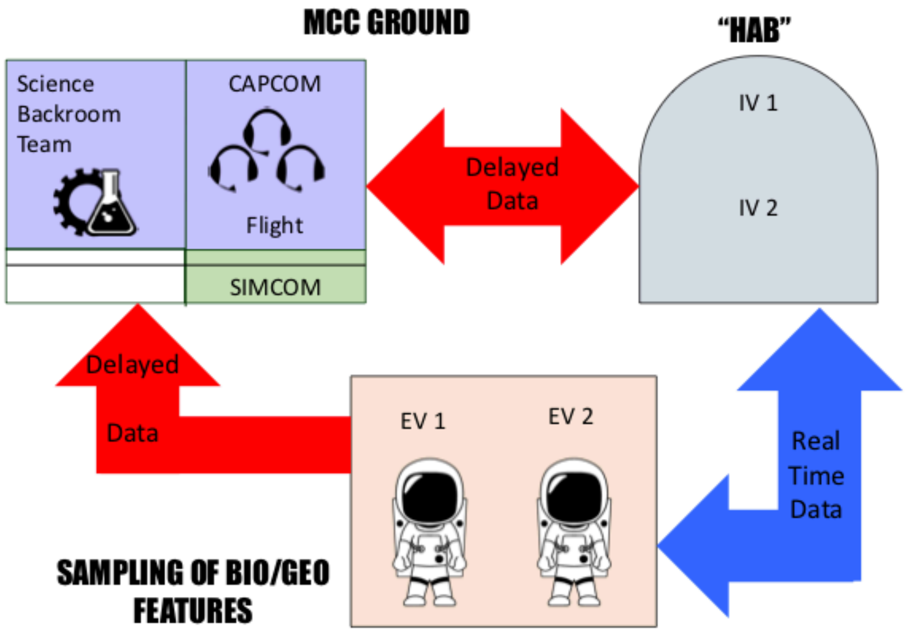

Figure 7: BASALT Architecture, from Hill, Caldwell, Miller, & Lees (2016)[6]

The EV crewmembers performed scientific field research on basalt lava flows while the IV crewmembers in the simulated surface habitat or rover, coordinated with them in real-time. The simulated mission support team contained not only simulated operations personnel (such as a flight director, and a capsule communicator) but also scientific experts who used the geological samples taken by the EV crewmembers in the field for their own research. The Simulation Commander (SIMCOM) was able to communicate will all parties out of the simulation in order to ensure that everything ran as expected and all participants were safe. For a more detailed description of the BASALT research project, see Lim et al. (2019).

While the EV crewmembers performed field science tasks within the project (which are predicted to be similar to the tasks astronauts will have to perform while on Mars), the BioHarness™ recorded heart rate, heart rate variability (calculated using a rolling 300 beat standard deviation of normal-normal intervals), and respiration rate data from the participants at a frequency of 1Hz. Not only are these physiological parameters among the important

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[6] Republished with permission of Springer Science and Bus Media B V, from Hill, Caldwell, Miller, & Lees. (2016). Human Interface and the Management of Information: Applications and Services: 18th International Conference, HCI International 2016 Toronto, Canada, July 17-22, 2016. Proceedings, Part II; permission conveyed through Copyright Clearance Center, Inc.

parameters to measure for health and safety of personnel in extreme environments (as discussed in the previous chapter), but it was determined that they were also likely to respond more readily than other parameters (such as core body temperature, which was also collected) to changes in tasks. It was also determined that tracking activity levels (in accelerations) would be more descriptive of the task being performed, rather than the physiological response to it. No commercial off-the-shelf device was found that could measure all desired parameters—such as pulse oximetry or total O_2 volume intake— in a safe and unobtrusive way. Blood oxygenation was not measured as it was deemed unacceptable to incorporate another device on the EV crewmembers who already had to carry large amounts of hardware. The very nature of vigilance makes it extremely difficult to measure unobtrusively.

Data were collected after receiving IRB approval from Purdue University (protocol # 1603017366) over the course of 3 deployments: the first in Idaho in June 2016 and the second and third in Hawaii in November 2016 and November 2017, respectively. At the beginning of each day, crewmembers would don the BioHarness™ and wear it while the performed the simulated EVA. The tasks performed in the field by the EV crewmembers in BASALT are outlined in Table 11. In addition to the five tasks listed, baseline measurements were also taken using the BioHarness™ when crewmembers were not in the field (during the car ride to the field site, or during meetings out of the field). The author observed the performance of the field science tasks from the Mission Support Center in order to assign time stamps to collected data to associate data points with the tasks being completed.

Table 11: BASALT EVA Tasks

Task Abbrev.	Task Name	Task Description
ET	Translation	Crewmembers translating within the EVA environment (walking, climbing, etc.)
EO	Observation	Crewmembers observe the EVA environment and provide those observations to the MSC (photography, vocal descriptions, contextual video, etc.)
EI	Instrument Use	Crewmembers use handheld instruments to determine the geological composition of possible sampling locations.
BR	Breaking Rocks	One crewmember wields a rock hammer and breaks smaller samples off a larger, desired sampling location.
BS	Bagging Samples/Biological Sterilization	Crewmembers don gloves and sterilize using alcohol before sampling at a desired location; while one crewmember breaks rocks, the other collects the samples and puts them into numbered, cataloged sample bags.

At the end of each field day (simulated EVA), data were downloaded off the physiological monitor and stored securely on the author's computer. Data were removed from the devices each day to ensure enough storage space for subsequent days, and to protect participant data. The devices' batteries charged overnight. For more specific details on the integration of physiological monitoring into BASALT, see Hill et al. (2019).

Originally, the goal of this research was to determine whether or not differences existed between physiological responses to different field science tasks. The author's prior research has demonstrated that while differences do exist between physiological responses to these tasks, they are inconsistent and unpredictable (Hill, 2017). Past work also did not quantify these differences; more data has been collected since the author's prior analyses were performed. The methods of data analysis have also been refined to address challenges with the data.

Before analyzing the data, the timestamps taken during the performance of the field science tasks were assigned to the raw data points. The BioHarness™ also assigns a confidence percentage to each collected data point indicating the confidence of the device that it is recording the true value of the physiological parameter, with 100% being perfect certainty. Data points that were not associated with one of the tasks listed in Table 11 or had a confidence value of less than 50% were eliminated and not used in any analyses.

By collecting the data points once every second, data points were not independent of each other. In order to weaken the dependence of the data set, mean responses were calculated for each occurrence of each task and all statistical analyses were performed on the calculated mean responses, instead of the raw data.

As many factors that can affect physiological response (as discussed in the previous chapter), data sets from different participants were not combined. For the participants who were subjects in more than one analog deployment, a Kolmogorov-Smirnov test was run in order to determine if data sets from the same participant, but collected during different deployments, followed the same distribution. If the distributions of the data sets were not found to be statistically different, then the data sets were combined into a single case. An α-level of 0.05 was used for participants who participated in 2 deployments (a single comparison between 2 data sets), and 0.017 for participants who participated in all 3 deployments (three comparisons between 3 data sets). This more conservative α-level was to offset the family error rate that occurs with multiple comparisons and was calculated using the following equation, where α is the desired α-level, and N is the number of comparisons:

$$\alpha = \frac{0.05}{N}$$

After determining the number of cases on which to perform statistical analyses, the distribution of each case, for each physiological parameter was generated and compared to a normal distribution to determine whether or not the data was normally distributed. The fact that many data sets were not normally distributed indicated a need to use a non-parametric analysis method.

The differences in the mean physiological responses to each task were calculated using a bootstrap, one-way ANOVA model for each case, for each physiological parameter. This resulted in the generation of pairwise comparisons between each task for each case. Due to the fact that there is no p-value associated with the pairwise comparisons, the bootstrap model also generated confidence intervals for the differences in the physiological responses to each task. Due to the large number of comparisons (15 for each case), a conservative 99.98% confidence interval was generated. If zero fell within that confidence interval, then the difference in the physiological response two the two compared tasks was not considered to be statistically different.

After examining the statistical differences between responses to tasks, the case distributions generated to check normality were observed to determine whether the distributions of the data indicated the possibility of the development of individual action limits. All statistical analyses were generated using SAS® software, Version 9.4 of the SAS System for Windows.

The following chapter will present the results of Study I, which will seek to answer RQ1, RQ2, and RQ3. Chapter 5 will present the results of Study II to address RQ4. Chapter 6 will provide discussions on these results and how they address the research questions, as well as limitations of each study.

4. STUDY I RESULTS

The following sections present the results of Study I, which used semi-structured qualitative interviews to identify potential similarities and differences between human and rover Mars missions (RQ1) and what information streams are necessary to enable robotic scientific exploration of Mars (RQ2 & RQ3).

Pilot Testing

There were two individuals who participated in pilot testing the moderator guide post-IRB approval. Both were planetary science graduate students, one of whom had some direct experience with Mars rover operations and would have been an appropriate participant in the study (both were familiar with how rover operations were conducted). The participants in pilot testing helped to clarify some of the language in the questions to ensure that their meanings were clear from the perspective of a scientist and to ensure no erroneous assumptions were being made in the wording of the questions.

Due to the limited pool of participants from which to draw and limited access, no rover engineers were used for pilot testing.

Participant Demographics

Participants were contacted by the author through email and, when possible, through snowball sampling. There was a total of 20 participants in the study (N=20)—breaking down into 11 scientists (n=11) and 9 engineers (n=9)—who participated in interviews from September 2018 to May 2019. Participant recruitment ended when all known potential participants had been contacted at least twice, and no more responses were elicited.

All individual potential participants were contacted two or three times with at least two weeks in between each contact. No further contact was made if no reply had been received. The majority of the engineering participants were found through internet searches for individuals involved in rover operations, and email contact. Three engineering participants were found through another participant who recommended they be contacted and provided their contact information.

The majority of scientists (6 out of 11) were recruited by having a contact of the author send an email to many of their MSL contacts. Two other participants were recruited by the author in person, one was suggested by a contact of the author, and the other two participants were found via internet searches.

Table 12 summarizes the number of participants contacted by the author (or contacts of the author), the number who replied, and the number who chose to participate. These numbers reflect only the number of participants that the author is certain were contacted. If other participants circulated the recruitment email without expressly stating they did, those numbers are not reflected in Table 12.

Table 12: Participant contact & reply numbers

	# Contacted	# Replied	% Replied	# Participated	% Participated
Engineering	54	14	25.9	9	16.7
Science	52	14	26.9	11	21.2

Interviews occurred through video conferencing software, telephone, and in person. In addition to this, two engineering participants were willing to answer the questions but were unable to schedule time for an interview, and therefore filled out the questions over email, allowing the author to ask some follow-up or clarification questions if needed. A breakdown of how interviews were conducted is shown in Table 13.

Table 13: Interview modality

	Engineering	**Science**	**Total**
Phone	2	6	8
Video Conferencing	5	4	9
In Person	0	1	1
Email	2	0	2

All 20 participants had worked on the MSL project, with varying numbers working on other missions. Table 14 demonstrates the numbers of participants who worked on various rover missions and Table 15 outlines the years of experience participants have working on rover operations.

Table 14: Participant Mission Involvement

Rover	Engineering	Science	Total
Sojourner	1	2	3
Opportunity	5	6	11
Spirit	5	5	10
Curiosity	9	11	20

Table 15: Participant Rover Mission Experience

Rover Experience (years)	Engineering	Science	Total
<1	1	0	1
1-5	1	2	3
6-10	1	4	5
11-15	5	2	7
16-20	1	2	3
>20	0	1	1

The average number of years of experience on rover operations is 10.75 years (10.6 years for engineers and 10.9 for scientists). Experience varies from 0.5-18 years for engineers, and 5-22 years for scientists.

Nineteen different roles were included in the participants recruited for this study—most participants had served in more than one role in rover operations. A breakdown of the different roles filled by participants, the number of participants who had served in each role, and a description of the general responsibilities and concerns of that role (as described by the participants themselves), is shown in Table 16. It is important to note that Payload Uplink Lead (PUL) is listed twice due to the fact that both scientists and engineers fill this role.

Table 16: Study Participant Roles

	Role	Role Description	Number of Participants
Engineering	Instrument Systems Lead (ISL)	Performs assessment of instrument health at the system level during rover downlinks.	1
	Mission Lead /Tactical Mission Manager	Tasked with recognizing whether there are any risks that have been missed/overlooked. Ensures that planned activities align with longer-term goals and meet constraints.	3
	Payload Downlink Coordinator (PDC)	Receives information from all instrument representatives to ensure they are operating nominally.	1
	Payload Uplink Lead (PUL)	Responsible for uplink of instrument commands and ensuring the instruments are being commanded safely.	1
	Rover Planner (RP)	Moves and drives the rover and rover arm. Also called “Rover Driver”.	4
	Science Planner	Creates a plan to include as much science as possible within resource and commanding constraints.	2
	Strategic Mission Manager	Creates long-term plans to maximize scientific return while ensuring long-term rover health and safety.	1
	Supratactical Lead (SuTL)	Puts together the framework/plan for the next 3 planning cycles.	1
	Tactical Activity Planner (TAP)	Works with uplink leads to assess safety of sequences.	1
	Tactical Downlink Lead (TDL)/Space Systems Engineer	Performs assessment of vehicle health and safety during rover downlinks.	1
	Tactical Uplink Lead (TUL)	Leads tactical planning from the engineering perspective.	2

Table 16 continued

Science	Strategic Campaign Lead	Coordinates science and engineering details of a particular campaign.	2
	Documentarian	Assists SOWG Chair by recording activities in the SOWG meeting.	1
	Instrument Rep	Ensures instrument is used properly.	1
	Keeper of the Plan (KoP)	Translates desired science into planned activities.	2
	Long-Term Planner (LTP)	Concerned with strategic planning and ensures tactical operations aid in achieving strategic goals and do not interfere with overall mission goals. Strategic science representative.	1
	Payload Downlink Lead (PDL)	Assesses instrument data quality and performs data pre-processing if needed.	6
	Payload Uplink Lead (PUL)	Responsible for uplink of instrument commands and ensuring the instruments are being commanded safely.	6
	Science Theme Lead (sTL)	Major representative for a specific scientific theme group (e.g. geology).	3
	Science Operations Working Group (SOWG) Chair	Major tactical representative for the entire science team during tactical planning. Leads science team through discussion and selection of scientific activities.	3

In addition, scientists who participated in the project were also asked about their area of scientific expertise and the types of scientific activities in which they had taken part (e.g. field science, remote sensing, etc.). This was done because it is predicted that human operations on Mars will also be heavily influenced by how field scientists perform operations on Earth. Therefore, it was useful to know how many field scientists were included among the participants. Table 17 and Table 18 outline the activities and fields of scientific study participants.

Table 17: Scientific Activities of Study Participants

Science Activities	Participants
Field Science	8
Remote Sensing	9
Lab Science	5
Modelling	1
Data Analysis/Mapping	1

Table 18: Scientific Fields of Study Participants

Scientific Field	Participants
Geology	9
Planetary Science	3
Physics/Astrophysics	1
Astrobiology	1
Chemistry	1

Planning Timescales

Participants were asked about various goal planning timelines and on what timescales those goals operate. These questions were primarily meant to clarify what participants perceived as being the tactical, supratactical, and strategic timelines (whether they aligned with the literature or not).

Table 19 outlines what participants consider to be the timescales for strategic, supratactical, and tactical planning. Participants often gave a time interval and therefore a participant could have asserted that the specified timeline fit in multiple rows in the table. Cycle "n" indicates the current planning cycle. Sol "n+*x*" represents the number of planning cycles after the current planning day/cycle over which the timescale stretches (e.g. n+1 is the planning cycle after the current planning cycle). Planning cycles may stretch over multiple sols, such as when rover commands are being uploaded for a weekend's worth of activities. This is why "planning cycle" is used instead of "day" or "sol".

A heat map was overlaid on the table to demonstrate the timelines that most participants asserted belonged to specified timescales (red cells indicate more participants, yellow cells indicate fewer).

Table 19: Planning Timescales

Cycle	Strategic	Supratactical	Tactical
n	1		19
n+1		5	12
n+2		7	5
n+3	3	6	5
n+4	6	4	1
n+5 - n+10	11	2	
>n+10	15		

Because of the imprecision of some of the language used by participants, "n+*x*" timelines were not always specified. In this case, the author allocated certain language to certain timescales. For example, when participants said "tomorrow" that was considered to be n+1, "a week out" was noted at n+4, and "months and years" or timelines over two weeks were labelled as >n+10.

All participants interviewed had experience with tactical planning, and therefore there were more responses regarding the timescales of tactical planning than supratactical or strategic. There were far fewer supratactical responses likely due to the fact that supratactical was often talked about with tactical planning. Supratactical planning also did not apply to MER operations and therefore it was likely that participants who had experience on multiple missions generalized their responses to timescale-related questions.

There was significantly more overlap in the timescales mentioned between supratactical and tactical than either timeline with strategic. Again, this may be due to the fact that supratactical is closely tied to tactical planning and was developed to offload some tasks from the tactical planning process. In addition to this, all information streams mentioned by participants as being relevant to the supratactical planning process were also mentioned as being relevant to the tactical process. For that reason, the following sections will present tactical and supratactical information streams together, and strategic information streams separately.

Strategic Information Streams

Participants were asked to describe the information needed and used in order to plan, re-plan, and achieve strategic goals. After coding and analyzing the themes in the responses, 20 different information streams were described.

Figure 8 plots the number of participants (broken down into scientists and engineers) who discussed each information stream. Figure 9 plots the percentage of both scientists and engineers who discussed those same information streams.

The following sections summarize each information stream, how it is assessed/collected, and how it is used in the strategic planning process.

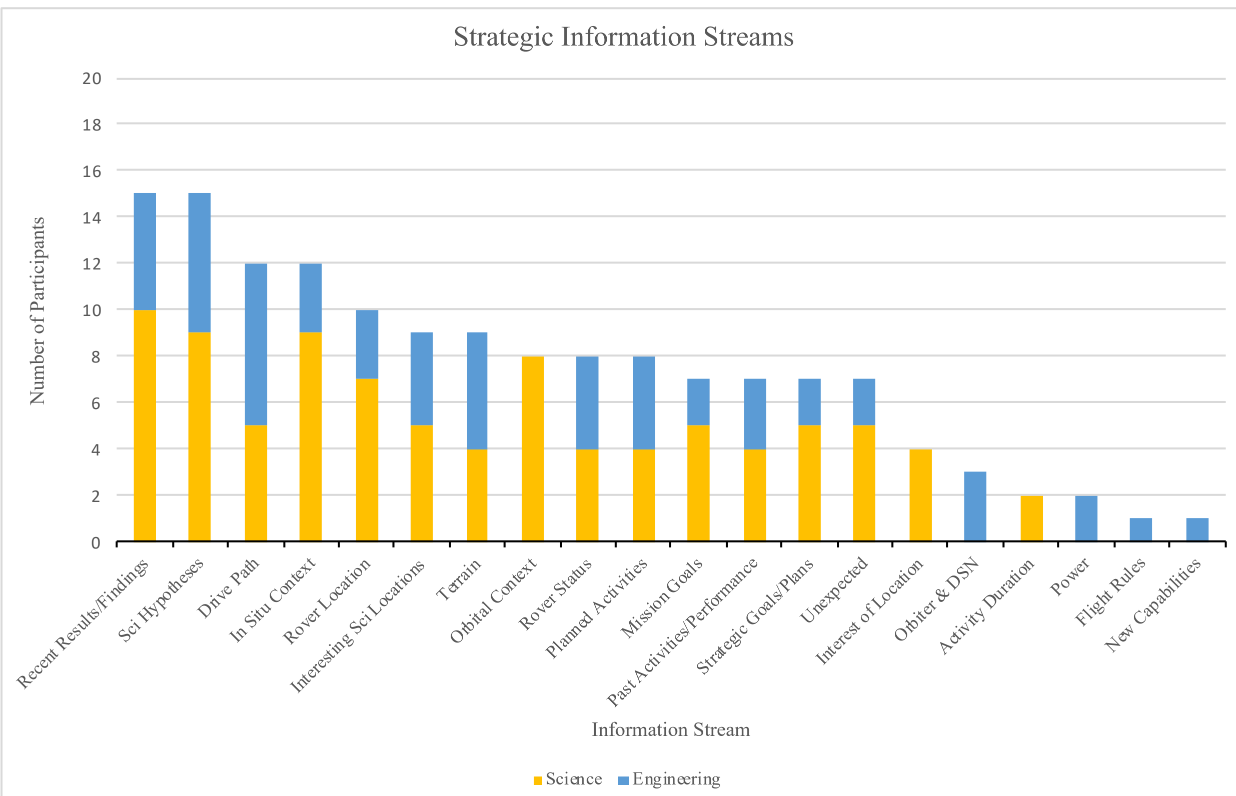


Figure 8: Strategic Information Streams (Participant Numbers)

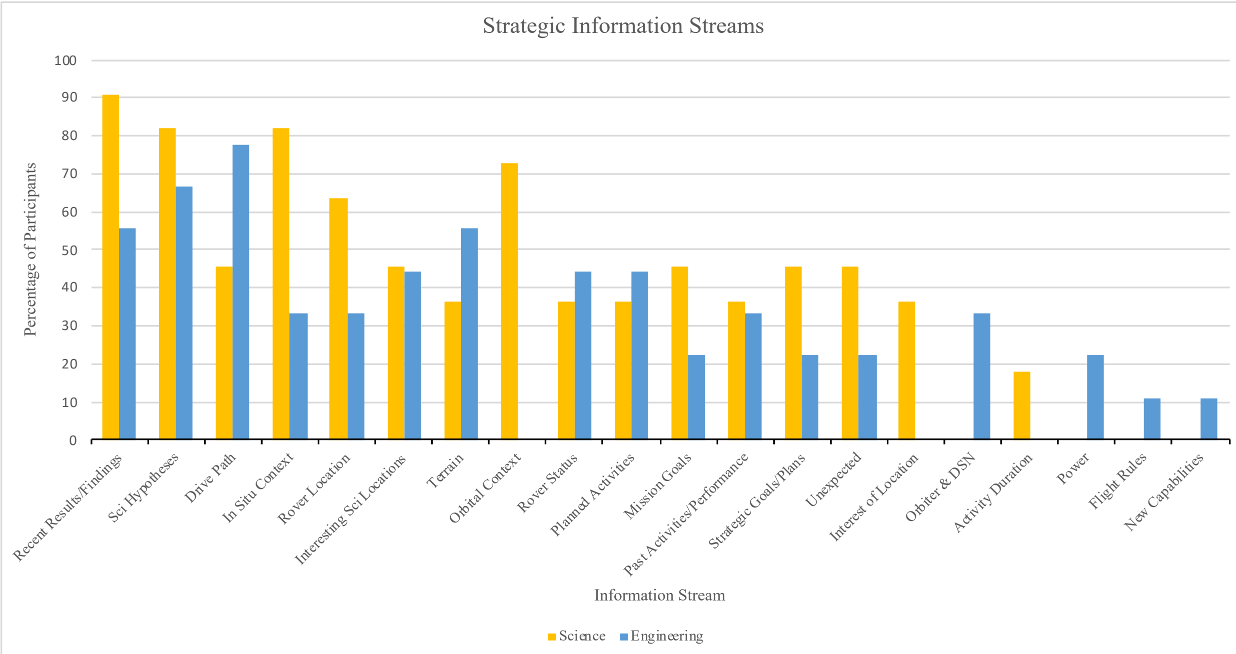


Figure 9: Strategic Information Streams (Participant Percentages)

Recent Results/Findings

Recent results and findings refer to the results of recent rover tests/experiments with instruments or features seen in recent images. This especially includes finding that may be surprising or interesting and that affect the established strategic plan. Some participants would refer to this information stream as "discoveries". This information stream is the most commonly mentioned strategic information streams among scientific study participants (90.9% of participating scientists mentioned this information stream) and is tied for the most mentioned strategic information stream among all participants (15 participants discussed this information stream).

Scientific discoveries can raise more research questions, open other investigation paths, or influence the amount of time spent in a particular area or focused on a particular feature. It is one of the major reasons that strategic plans need to be re-evaluated. Two participants used the term "dinosaur bone" in reference to how surprising and exciting discoveries can change the course of a strategic plan. To quote one participant: "…the joke was always if we find the dinosaur bone, everything is off."

Scientific Hypotheses

This information stream is tied for the most mentioned strategic information stream for all participants (15 participants), and it was mentioned by 81.8% of participating scientists and 66.7% of engineers (making it the second most mentioned strategic information stream among engineering participants). It refers to the research questions that scientists are trying to answer, the hypotheses they are testing, and the priority given to each research question/objective. It also includes how certain rover activities relate to answering those questions. Due to the fact that rover missions are scientifically-driven, the current scientific hypotheses being tested significantly influence the chosen locations on the surface for exploration, the time spent in those locations, and the activities performed by the rover. While some scientific hypotheses and research questions were the motivation behind the entire mission and do not change, there are others that evolve from discoveries made on the surface and discussion amongst scientists involved in the missions. Hypotheses and research questions may also differ depending on where the rover is on the surface.

Drive Path

This information stream was discussed by the largest percentage of engineering participants (77.8%). The drive path encompasses the planned or outlined traverse path of the rover—where it is going to go and what route it is going to take. This also includes the distance to certain areas and estimates regarding the time it will take to complete a drive.

The drive path is determined and tracked by looking at orbital maps. Time estimates of how long it will take the rover to reach a certain destination is determined by the speed of the rover, the challenges of the terrain, and whether the rover will stop at any points of interest along the way. This information stream is used to select interesting scientific locations at which to pause along the longer-term route, ensure that the rover is not spending too long in the same location, and give the general team an estimate as to when certain activities will take place. It is also important, from an engineering standpoint, to understand where the rover will be at certain times of the Martian year.

In Situ Context

This information stream was mentioned by 81.8% of participating scientists and relates to the results of activities done by the rover that provide contextual information for planning. This includes how instrument analysis results obtained tactically fit together to create a clearer picture of the Martian environment, images that put features viewed from orbit into context, and science trends that can influence the planning of future activities. This information stream does not include results of activities that quickly or dramatically change the strategic plan due to them being unexpected—those are included in the "recent results/findings" information stream.

This information stream, while being relevant to both groups, is used slightly differently by scientists and engineers. Engineering personnel use in situ context largely to place the vehicle in the landscape and gain a better understanding of the terrain in the direction of the drive. Scientists use in situ context to develop of clearer understanding about the Martian environment, refine hypotheses, and develop answers to research questions.

Rover Location

This information stream encompasses the location of the rover on the surface with respect to points of interest or the planned drive path. It also includes general features that may surround the rover to help position it in the landscape. The rover's position is generally assessed using orbital data and rover images. It is important to know the rover location in strategic planning as it will give an indication as to how far the rover is from a desired scientific location, whether it has left a particular area of interest, or whether there are any potential hazards to the rover in the current location.

Interesting Scientific Locations

Determining the location of interesting scientific locations on the Martian surface informs strategic planning as it is a significant motivation behind moving the rover to a certain location, can affect the drive path, and informs some of the scientific research questions that will be investigated or whether certain hypotheses can be tested in the desired location. These interesting sites are chosen by scientists largely using orbital images. Rover engineers also need to know the location of areas deemed interesting by the science team, as it will inform the planning of the long-term drive path so that the rover can safely reach scientifically valuable locations. Conversely, scientists will also identify potential waypoints for the rover to stop along a pre-determined drive path that may be scientifically interesting.

Terrain

This information stream refers to whether or not the rover can traverse a certain terrain or area of a map. This is assessed using orbital data and images taken from the rover cameras as well as experiential knowledge gained from tests performed on Earth and past traverses. It is important to be able to assess the ability of a rover to traverse a certain expanse of terrain in strategic planning, as it will affect the drive path and may limit the ability of the rover to explore certain features or areas of interest if they are not reachable by the vehicle.

Orbital Context

The information stream encompasses the data gathered from orbit (often well before the rover even arrives on the surface) that provides contextual information or information for planning rover activities. Orbital context is used to put in situ data, drive routes or rover location, and scientific areas into the larger context of the Martian surface. This information stream was only discussed by scientific participants.

Rover Status

This information stream concerns the overall physical status of the rover, including vehicle body, arm, and instrument status. This also includes vehicle degradation over time and unresolved anomalies. The long-term status of the rover can influence, sometimes significantly, the achievement of strategic goals and can change the approach that needs to be taken to meet existing goals. Multiple participants discussed the failure of an actuator on the MSL drill instrument that altered long-term planning of activities in an area where drilling was desired until the anomaly could be fixed. A participant also discussed the Spirit rover's wheel motor failure which influenced the terrain the rover could traverse and ultimately led to the mission failure.

Planned Activities

The information stream refers to the specific activities that the team wants to perform in a certain area or during a certain time period. Knowing currently planned activities can help in planning future activities that would occur after currently planned activities and can provide context into how the investigation of a current area or a current set of activities contributes towards a strategic goal. There may also be a strategic approach to the performance of tactical activities (e.g. drill every 25 meters) which would influence the strategic plan.

From an engineering perspective, it is important to know the activities planned by the science team to ensure that they are fit into the longer-term plan, that there is a sufficient amount of resources (e.g. time, power) in order to perform the planned activities, and that the rover's approach to performing activities is altered if necessary. Certain activities also need to be performed in a specified sequence over a certain period of time, which will impact the strategic plan.

Mission Goals

Each rover mission is funded with certain overaching goals in mind. These mission goals include both primary and extended mission goals, and most are related to answering scientific questions (although some can be engineering achievement goals). Keeping the larger mission goals in mind is important during strategic planning as it ensures that, at some level, all activities being planned are contributing towards the achievement of the goals set for the mission. They ensure that those planning scientific activities are not distracted for too long a period of time by a "shiny rock" (as characterized by one participant) that may not help answer the larger scientific questions. These mission goals (and their associated timelines) also help ensure that the rover is not spending too much time or energy in a particular location or performing a certain set of activities to the detriment of the achievement of the overarching mission goals.

Past Activities/Performance

The past activities performed by the rover and how the rover performed while performing those activities can influence strategic planning. Knowing what activities have been completed by the rover in a particular area can help determine whether other activities should or should not be performed. Not only are there some activities that need to be performed in a specific sequence (e.g. during a drilling campaign), but performance on previous activities can be used to predict how the rover will perform in a similar situation (e.g. driving over the same type of terrain, drilling a rock with a similar hardness) or whether there are trends in the rover's performance over time. Rover performance is largely assessed using telemetry from the rover (where the rover can perform a system check on itself).

Strategic Goals/Plans

This information stream reflects the use of current or past strategic plans (including sol-paths and decision trees) in the planning, re-planning, or achievement of strategic goals. By understanding the current strategic plan, it keeps all rover operations personnel on track and provides a place to begin planning current strategic plans.

Unexpected Occurrences

This information stream encompasses unexpected events or conditions that occur with either the Martian environment (e.g. a dust storm) or the rover hardware/software (e.g. a software glitch or actuator failure). These kinds of occurrences can affect the strategic plan if they affect the rover's health and safety or ability to perform certain activities.

Interest of Location

Related to the "Rover Location" and "Interesting Scientific Locations" this information stream refers to whether or not the current location of the rover is scientifically interesting and, if so, what is scientifically interesting about that location. This can affect the strategic plan because if the location is not scientifically interesting, then it is unlikely the rover will remain in that location for an extended period of time and more driving will need to be integrated into the plan. If the site is scientifically interesting, the features that make it scientifically interesting (e.g. geological interest vs. astrobiological interest) will affect the types of activities performed in the area. Scientific interest is assessed by using a combination of in situ data—including images and instrument results—and orbital data.

Orbiter & DSN

Orbiter relays and Deep Space Network (DSN) availability was discussed by 3 engineering participants. It is important to have a strategic communications plan that takes into account when orbiters are within range to communicate with the rover, where those orbiters will be in reference to the rover (to ensure the rover is in the best position to communicate with the orbiter), and the availability of the DSN to transmit data from Earth to Mars. The ability of a rover to make contact with an orbiter will affect whether or not data collected on the surface can be transmitted back to Earth, and it is therefore important to ensure that communication opportunities are identified and used as efficiently as possible. This information stream also considers the interaction between different landed assets on the surface and whether or not relay communications need to be shared. For example, one participants spoke of the InSight lander having landed near the current position of the Curiosity rover, and how both teams need to share orbiter access.

Activity Duration

Activity duration is the time required in order to complete a certain planned activity or set of activities. Strategically, activity duration is considered in terms of how much time will be invested investigating a certain question, spending time in a particular area, or exploring a certain feature. This information stream is often compared to the scientific value of a certain area or target (discussed in a later section) to assess whether the scientific return warrants the time investment. The time investments considered for this information stream in strategic planning is on the scale of days to weeks to, occasionally, months.

Power

Power availability onboard the rover influences both tactical and strategic planning, although only 2 engineers mentioned power considerations on a strategic timeline. This information stream includes the state of charge of rover batteries, the amount of power required by certain activities, and factors that can affect power availability. Strategically, power availability is concerned with how long-term conditions may affect power generation (e.g. terrain elevation blocking the sun, power cell degradation, seasonal influences on power generation, etc.).

Flight Rules & Constraints

Like human EVA, rover operations have flight rules that govern how their operations can be run, usually in the interest of the health and safety of the vehicle. This information stream encompasses those flight rules and any other mostly constant constraint that affects the long-term planning of rover activities. It is important that these constraints be known and considered during strategic planning, so they are not violated.

New Capabilities

One engineering participant discussed how strategic development efforts to enhance vehicle capabilities or recover lost capabilities can affect strategic planning. The knowledge of capability readiness would inform strategic planning regarding the approach to certain activities, and when certain activities may occur.

Strategic Re-Planning Occurrence

Participants were asked about how often strategic plans need to be re-evaluated or changed. This led to interesting conversations as to what it means to re-plan a strategic goal. The majority of participants agreed that at the highest level, strategic goals are relatively stable and very rarely are they completely re-planned, unless there is some unexpected occurrence, exciting scientific discovery, or if upper mission management determines that there is a change in priority. There was also widespread consensus amongst participants that a certain amount of adjustment of strategic plans on the supratactical/tactical timeline is nominal and that this is taken into account when creating strategic plans (e.g. by leaving out the specific details of the procedure to achieve the goal, by creating backup plans to account for different activity results). Strategic plans are created to allow for slight changes in strategy or timeline due to results from the surface; this is called “ventilating the plan”.

Though most participants differentiated between slight adjustments to the strategic plan and completely changing the original plan, there were some that did not. Three participants discussed how the fact that strategic plans operated over such long time periods made them “malleable” and there was constant re-planning of strategic goals. It is the author’s belief (by interpreting the context in which this was said) that these participants viewed the adjustments to the plan on the tactical/supratactical level mentioned above as being a re-plan of the original strategic plan, whereas the majority of participants did not view it this way.

Another participant differentiated how often strategic plans changed depending on the types of activities being performed. This participant stated that "On the majority of days the plan changes based on received data if we have been driving. If we are in the same place, we sometimes follow a plan that has been laid out for multiple days to be performed in a certain sequence, such as drilling." It was unclear if this participant was referring to a complete change of the strategic plan or simply making tactical/supratactical adjustments to the strategic plan based on received rover data.

Tactical & Supratactical Information Streams

Similar to the strategic timeline, participants were asked to describe the information needed and used in order to plan, re-plan, and achieve tactical and supratactical goals. After coding and analyzing the themes in the responses, 28 different information streams were described.

Figure 10 plots the number of participants (broken down into scientists and engineers) who discussed each information stream. Figure 11 plots the percentage of both scientists and engineers who discussed those same information streams.

The following sections summarize each information stream, how it is assessed/collected, and how it is used in the strategic planning process. While there was significant overlap in the information streams mentioned in both the tactical and supratactical processes, not all tactical information streams were mentioned in a supratactical context. The descriptions of each information stream will specify whether each information stream was referenced with respect to only the tactical timeline, or both tactical and supratactical.

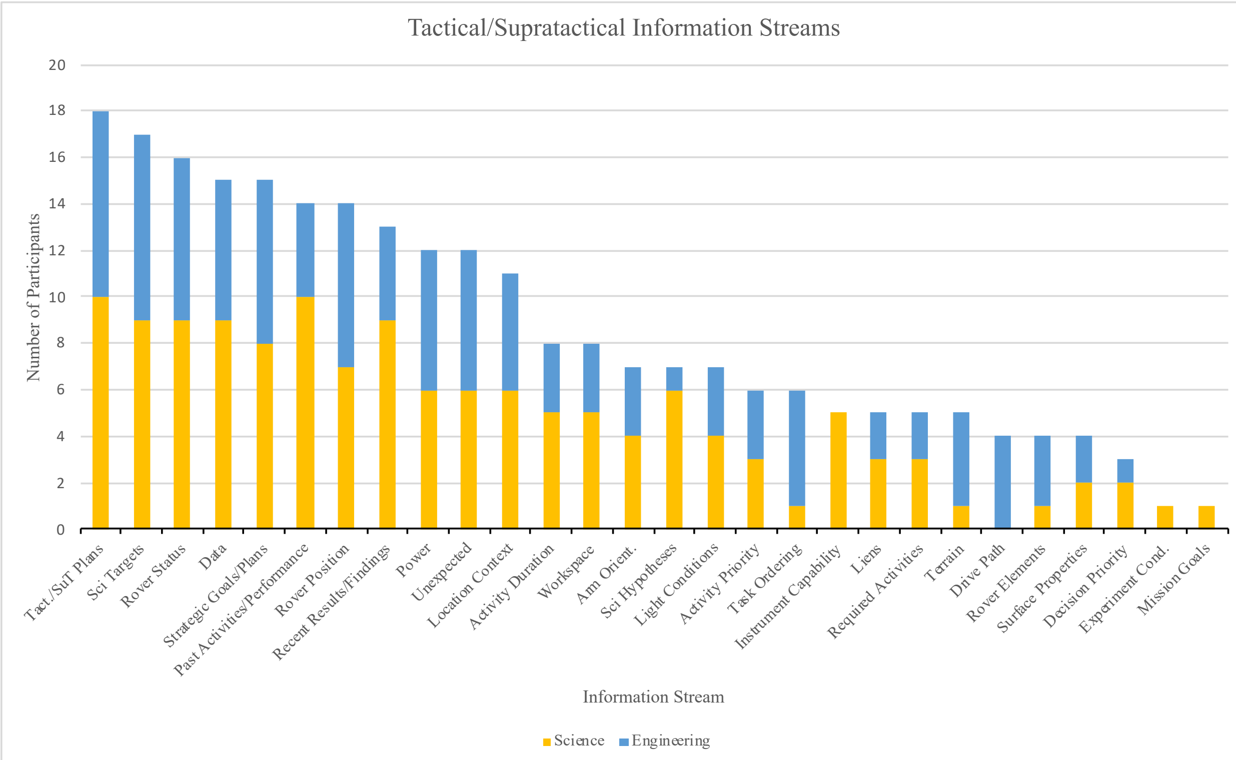


Figure 10: Tactical/Supratactical Information Streams (Participant Numbers)

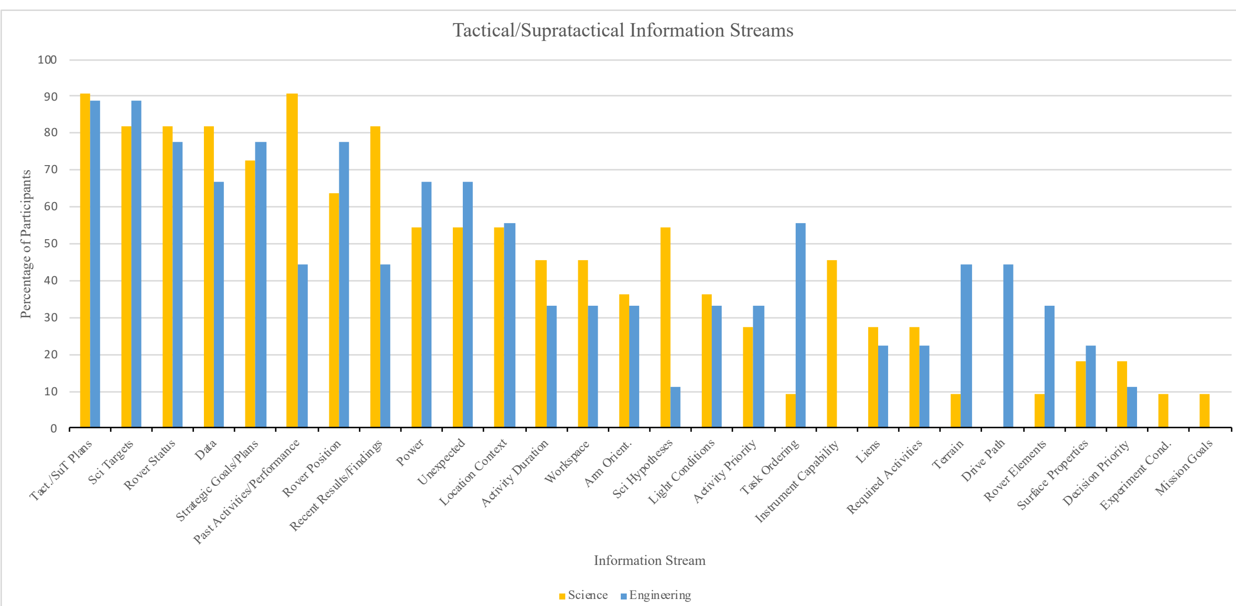


Figure 11: Tactical/Supratactical Information Streams (Participant Percentage)

Tactical/Supratactical Plans

This information stream is the most commonly mentioned among all participants and is tied as the information stream mentioned by the largest percentage of both engineers (88.9%) and scientists (90.9%). It was mentioned in the context of both tactical and supratactical planning, and it consists of existing or current tactical/supratactical plans (including existing contingency plans).

Each tactical planning cycle begins with a “skeleton” plan that was generate the previous planning cycle (some participants refer to this plan as being a tactical product and others say it is a supratactical product) which is the basis upon which the rest of the planning for the day takes place. The skeleton plan will provide time windows for the performance of scientific and engineering activities. There also tend to be multiple plans available depending on the results obtained from the previous cycle’s activities. Supratactically, it is important to consider how changes made to the current plan may affect multiple tactical planning cycles.

At the end of each planning cycle, both tactical and strategic plans are updated based on the activities performed by the rover, the results of those activities, and the anticipated activities for the next cycle.

Science Targets

This information stream is the second most mentioned information stream among all participants and is tied for the information stream mentioned by the largest percentage of engineering participants (88.9%). It consists of the specific activities the team wants to perform, and on which targets. It applies to both tactical and supratactical planning timelines.

The selection of specific activities to perform on specific targets (e.g. shoot this rock with this instrument or drill in this specific location) is a significant aspect of tactical and supratactical planning. From a science perspective, targets and observations with the highest expected science return are chosen. The selection of targets occurs through a discussion with the science team. For the rover engineers, once the specific targets and observations have been determined by the science team, it is then the job of the rover engineers to ensure that the observations are achievable (e.g. there are enough resources, the rover can safely reach that target) and develop a plan to achieve that goal. It is therefore extremely important that rover engineers (especially Rover Planners) accurately comprehend what the science team wants (e.g. what particular spot on a particular rock and at what time of day) and what the vehicle needs to do to perform those tasks.

Rover Status

This information stream concerns the status of all rover systems, including onboard instruments, and whether they are functioning nominally or whether or not there are anomalies that need to be resolved/investigated. Participants discussed the information stream in relation to both tactical and supratactical planning. Most rover elements will generate "safe" or "sick" signals to indicate whether something is off-nominal with a particular rover system.

If certain rover components are not working as intended or need to be assessed, then it can limit the activities that can be performed with the rover. In cases where an anomaly needs to be investigated, the status of some rover systems can dictate certain activities that will be performed during that planning cycle in order to diagnose and/or remedy the anomaly within the system. Some anomalies will continue to be present for a long period of time (e.g. a drill actuator failure) affecting many future planning cycles. Persistent anomalies are therefore also relevant to planning on these timelines.

Data

Considerations surrounding data storage and transmission management is relevant to both tactical and supratactical planning. This information stream includes the amount of onboard storage on the rover, when transmission from Mars to Earth will occur, and the amount of data that can be transferred during those transmissions. It also includes considerations on the amount of data that particular activities generate. There is a finite amount of both onboard vehicle storage and the amount of data that can be communicated to Earth each day. This makes data management an integral part of tactical and supratactical planning and is one of the major activity-limiting resources.

Each sol the rover will take and store health and safety measurements. In addition to storing this information, the rover will also store onboard the results of recent scientific activities until it is possible to send those results back to Earth and the rover receives a command to delete a specified piece of information. This makes it extremely important to keep track of the amount of data generated per activity, the amount of information already stored on the rover, and what data has or has not made it to Earth. Fitting in desired science activities around the limitations on data storage and transmission (along with other resource limitations) is a critical aspect of tactical and supratactical planning.

Comparing the amount of data received during a transmission to the amount of data predicted is also a way to indicate if there is a problem with rover communications. Also, knowing when data transmissions are going to arrive on Earth gives individuals an opportunity to begin analysis on the data generated as soon as it is available.

Strategic Goals/Plans

Plans created at the strategic level filter down to inform planning on the supratactical and tactical timelines. They are often communicated through reports or presentations during meetings. There can be goals that are planned in advance that then need to be implemented tactically. Strategic plans can also limit the amount of time the rover can spend in certain area before it is planned to move on to another point of interest. In addition, certain areas may have certain high level goals associated with them which can inform the tactical and supratactical planning of activities. Having a strategic plan also provides some coherence amongst the activities being performed to ensure that all tactically executed tasks are contributing towards the achievement of the strategic plan.

Past Activities/Performance

Similarly to strategic planning, tactical and supratactical planning is influenced by the activities performed by the rover in previous planning cycles and how the rover performed while completing those tasks. This information stream was one of two information streams mentioned by the largest percentage of scientific participants (90.9%).

The past activities that have been performed by the rover indicates what data may still be stored onboard the vehicle that may still need to be downlink to Earth. In addition, due to task ordering constraints on some sets of tasks, knowing what was accomplished in a previous planning cycle can give an indication as to where the rover is in the process and will dictate what needs to be planned in the next cycle. Beyond relating to specific task ordering constraints, past activities can provide a basis for planning future activities. For example, if certain approaches had been attempted to answer a specific research question or gather a certain piece of data, then another approach may be more appropriate for the current planning cycle.

Not only is it important to consider the previously planned activities of the rover, but it is also important to analyze how the rover performed while accomplishing those tasks. When tasks are planned, there is generally an expected result and if that result was not achieved (e.g. the amount of data downlinked to Earth was not what was anticipated) then it may indicate a problem that needs investigation. Certain performance detriments may ripple through and affect future plans depending on the planning constraints or location of the rover. In addition, past rover performance on certain activities and under certain conditions can give better estimates of future rover performance under similar conditions.

Rover Position

This information stream relates to the position of the rover with respect to targets of interest and the planned drive path. It also includes the orientation of the rover in terms of cardinal direction and tilt. Participants mentioned this information stream when discussed both tactical and supratactical planning. Details on the rover position are gained largely through orbital imagery and rover imagery.

This information stream is used to assess whether or not the rover has reached a desired destination/area and, if it has not reached the desired location, how much farther the rover needs to drive to get there. If the rover is in the desired location, it is also important to assess how far away the rover is from a particular feature. This affects the activities that can be planned on the tactical and supratactical timelines during a given planning cycle. The rover heading (north, south, etc.) is important to consider in order to maximize communication windows with orbiters. The rover tilt can impact whether certain activities can be performed without compromising rover stability.

Recent Results/Findings

This information stream is the same mentioned in strategic planning and relates to the results of recent rover tests or new features seen in images. It includes findings that may be surprising or scientifically interesting and will affect/alter the established supratactical or tactical plan. Depending on the results of recent activities, it may be determined that an unusual result needs more investigation or more tests need to be run on a particular feature. However, it is also possible that recent findings indicate that a particular site is not as scientifically interesting as had been originally thought, and therefore the time spent in an area may decrease.

When it comes to tactical and supratactical planning, it is not only surprising results that are relevant to planning; even results that are not immediately surprising are folded into scientific discussions that determine the desired activities for the rover.

Power

This information stream refers to the power availability on the rover, the state of charge of the batteries, and the amount of power required by certain activities. It also includes factors that can affect power availability. Current power availability is assessed through rover telemetry and there are simulation tools that exist to help predict the future electrical power levels onboard the rover after the completion of specified tasks.

Electrical power is another activity-limiting resource and therefore all activities need to be planned in a way that fits within the available power onboard the rover. Similarly to rover performance on past activities, if power generation is lower than expected, then it may indicate a problem that requires investigation. Participants discussed electrical power in reference to both tactical and supratactical planning.

Unexpected Occurrences

This is the same information stream mentioned for strategic planning, and it is relevant to both supratactical and tactical planning as well. It encompasses unexpected events or conditions that occur with either the Martian environment (e.g. a dust storm) or the rover hardware/software (e.g. a software glitch or actuator failure). If something unexpected occurs it can significantly affect tactical/supratactical plans if it means the rover does not complete the tasks that were originally planned, future desired goals need to be pushed back to investigate the anomaly, or if something damages the rover or makes it unable to perform as intended for a period of time.

Location Context

This information stream was mentioned for tactical planning. It refers to the details of a particular location that are gleaned once the rover first arrives to a location after a drive. This includes determining whether or not the location is scientifically interesting and, if it is, what the scientific interest is of that location. This information stream does not include specific targets in the rover workspace, as that is described in a separate information stream.

Details of a particular location are largely communicated through rover images taken after a drive has completed. These images give context to features seen from orbit or from afar and allow both engineers and scientists to get a clearer picture of where the rover is and what features surround it. This information also gives scientists and opportunity to determine whether the site is still of scientific interest and what kind of activities or investigations they may wish to perform in the area.

Activity Duration

The information stream describes the considerations surrounding the time required in order for a rover to complete an activity/set of activities and the amount of time available to do those activities. It was mentioned in relation to both tactical and supratactical planning.

Time is another major activity-limiting resource. The rover only has a set amount of time to complete certain activities (determined by taking into account the availability of other resources, such as electrical power) and different activities take more time than others. A part of tactical and supratactical planning is to try and fit as many activities as possible within the time limitations. Driving certain distances or to a certain location also takes a certain amount of time, and therefore is another activity/set of activities where the time required is an important aspect of planning.

Workspace

This information stream refers to the potential targets (or lack thereof) within reach of the rover's instruments and was mentioned by participants in reference to tactical planning. In order to perform contact science on potential targets, those targets need to be within the work volume of the rover's instruments. Even remote sensing instruments have limits on the range in which they can work within. A significant portion of tactical planning is the selection of specific targets within the workspace and determining what activities to perform on specific targets. If there are no interesting scientific targets within the workspace, then that will also influence planning as the rover will have to be moved before more scientific activities can be performed.

Arm Orientation

This information stream was mentioned for both tactical and supratactical planning and refers to considerations surrounding the orientation or position of the rover arm and whether or not a movement of the arm can be done safely. Understanding the current position of the arm is important in ensuring the safety of the rover: there are certain instruments mounted on the MSL rover arm and if the arm became inoperable then the ability to use those instruments would be severely limited (if not making those instruments completely inoperable) and miscalculating the placement of the arm could physically damage the instruments. In addition, there are situations where extending the rover arm would affect rover stability and certain activities cannot be performed if the rover arm is not stowed (e.g. driving).

Operationally, the position and orientation of the rover arm can impact the ability to effectively use other instruments if the arm obstructs the field of view of a certain instrument or casts a shadow on a scientific target when it needs to be fully lit. The ability of the arm to reach a particular target given the current position of the rover is also something that needs to be considered.

Activity Priority

When activities are planned on the tactical or supratactical timeline, it is possible that not all desired activities will fit within engineering constraints or the resources available to the rover (power, time, etc.). For this reason, certain activities are given higher priority than others—be it because they are necessary for the health and safety of the rover or it has been assessed that they will provide more scientific return than others. It is important to know what priority all planned/desired activities have in order to be able to determine which activities to eliminate from the plan should the need arise. Unless the activity in question is for engineering purposes, priorities of activities come from discussions and consensus within the science team. Priorities of tasks may shift during the tactical planning process due to new information (e.g. the rover is in a dangerous situation, there is an anomaly with one of the instruments, an unexpectedly interesting feature is nearby). This shift in priority will often result in longer science discussions or the engineering team overriding scientific activities for the health and safety of the vehicle.

Scientific Hypotheses

This is the same information stream as was mentioned in strategic planning: the research questions being asked, the hypotheses being tested, and the priority given to each research objective. It also includes how certain rover activities relate to answering those research questions or testing those hypotheses. This information stream was only mentioned in reference to tactical planning. It is important for tactical planning as a significant factor behind deciding which activities to perform with the rover is how much the activity will contribute to answering a particular research question or testing a particular hypotheses.

Light Conditions

The position of the sun at a particular time will affect the light conditions around the rover or on a chosen science target. There are some activities that have desired light conditions for best results (e.g. some scientists may want a photo with a target in shadow while other targets may need to be in direct sunlight). Light conditions around the rover or on a particular target are determined using a combination of astronomical information, terrain maps, and rover orientation. This information stream was mentioned by participants in reference to both tactical and supratactical planning.

Task Ordering

There are constraints that exist in both tactical and supratactical planning that mandate certain tasks be performed in a certain sequence. These sequences of tasks can stretch over multiple planning cycles (e.g. drilling). This information stream is important in tactical and supratactical planning because if a multi-sol set of activities has been planned, it will inform the activity planning for multiple future sols.

Instrument Capability

Understanding the capabilities of an instrument onboard the rover and whether or not it can accomplish a certain task is important in tactical planning to ensure that the instruments are being used safely, in the intended manner, and that the desired task will be accomplished satisfactorily. This includes the field of view of cameras, the range of remote sensing instruments, the maximum hardness the drill can penetrate, and the types of experiments that can be run. The capabilities of instruments are known by those experts who have experience with the instrument and/or were involved in its design.

Liens

Due to the constraints on how many activities that can be performed by the rover each sol, a liens list is kept as a “checklist” of desired tasks that can inform the activities planned for future cycles. The liens list influences both tactical and supratactical timelines and the desired activities are communicated through handover reports and plans between individuals filling the same role (e.g. one SOWG Chair may inform the SOWG Chair on the next planning cycle which activities were accomplished, and which are left to be planned).

Required Activities

There are certain activities that the rover needs to perform in order to allow other activities to move forward (e.g. deleting data from the rover to make room for new data), or to ensure the health and safety of the vehicle. It is important to be aware of these activities for both tactical and supratactical planning to ensure that these required activities are fit into the plan and are not forgotten in favor of other desired activities.

Terrain

This information stream refers to details about the terrain surrounding the rover and whether or not the vehicle can traverse a certain terrain. This includes the risks and hazards associated with driving a certain direction or taking a certain path. Terrain details and traverse-ability are largely determined by looking at orbital images and images taken by the rover. Participants only mentioned this information stream with respect to tactical planning.

This information stream is especially important with Rover Planners who are responsible for moving the rover, although it affects all aspects of planning—if the rover cannot reach a certain desired area, then the plan will need to change to target another area.

Drive Path

This information stream is the same one mentioned for strategic planning, and it is used both tactically and supratactically. No scientists mentioned this information stream in reference to tactical or supratactical timelines, implying that it may be more significant to the engineering aspects of tactical and supratactical planning.

The longer-term drive path gives a map to those working on tactical and supratactical planning. The commands generated to drive the rover work towards keeping it on the strategic drive path and gives an indication towards how many planning cycles will consist of drive planning (due to how far away the rover is from a certain waypoint). It is also important to know in what direction the rover is going to drive, so that navigation images can be taken in the direction of the drive. Deviations from the strategic drive path are also important for supratactical planning as it allows Rover Planners to prepare to deviate from the plan.

Rover Elements

It is important to ensure that no commands sent to the rover cause different rover elements to interfere with each other. This not only includes physical interference (such as the arm blocking the field of view of other instruments) but also inference caused by task ordering constraints or required conditions for certain activities. For example, there are certain instruments that cannot be used while the vehicle is in motion and it is therefore necessary to ensure that they are shut off and/or stowed before commanding the vehicle to drive. This information stream was mentioned in reference to the tactical planning timeline.

Surface Properties

This information stream is concerned with the surfaces of the rocks and the ground on Mars, including the prevalence of dust in a certain area. This was only mentioned in reference to tactical planning and the information is gathered using rover imagery or running a “scratch test” to determine surface hardness.

The properties of the surfaces around the rover can influence the activities performed in the area. If the rocks are too hard to sample with the rover’s drill, then drilling will not occur in the area. Similarly, if the terrain around the rover is mostly sand or small stones, the rover’s scoop will be used to sample instead of the drill. The properties and textures of rocks may also indicate the scientific interest of the area. The prevalence of dust is also important to consider for the safety of camera lenses and instruments, and whether the solid surfaces of rocks will be visible.

Decision Priority

This information stream was only mentioned in reference to tactical planning. It refers to the fact that certain decisions that need to be made or certain pieces of information during tactical planning have higher priority than others and should therefore be addressed first. This priority can be determined by which decisions need to be made before others (e.g. what the rover is doing with its arm will influence how instruments are used) or what decisions or pieces of information are critical for the next planning cycle. This information stream can be used in conjunction with the data management stream as higher priority pieces of information will be sent to Earth on earlier orbiter passes than those of lower priority.

Experiment Conditions

This information stream was mentioned by one scientific participant in reference to tactical planning. Certain instruments run more complex experiments on collected samples (SAM, CheMin) and it is therefore important to ensure that the conditions required for the experiment (e.g., temperature) were met to ensure that the results of the experiment are accurate.

Mission Goals

This information stream is the same as the one described for strategic planning (the overarching goals of the entire rover mission). One scientific participant mentioned this information stream in relation to tactical planning saying that the overall mission objectives are kept in mind while planning to ensure tactically planned activities continue to contribute to the achievement of the larger mission goals.

Tactical/Supratactical Re-Planning Occurrence

Similarly to the occurrence of strategic re-planning, participants' answers varied depending on how they defined "re-planning". The majority of participants agreed that there was a large amount of flexibility built into skeleton plans that allowed for tactical planning to respond to new data from the rover. For example, a skeleton plan could assign a specific block of time for contact science, but the targets chosen and the specific tests run were determined by the science team tactically depending on what targets were in the workspace and the results of previous activities. Most participants did not consider this to be a "re-plan" and therefore said that for most cases, tactical and supratactical plans proceeded as they had been originally planned. There was also mention of the fact that for some planning cycles, multiple plans would be created and one would be chosen based on the results from the rover. Again, this was largely not considered to be a full re-plan and was well within nominal operations. These participants stated that tactical and supratactical timelines generally did not require complete re-plans where the original skeleton plan had to be re-made. And when a true re-plan was required, it was because of some unexpected anomaly with the rover.

Other participants did consider the adjustment of activities in response to rover data as being a re-plan and therefore stated that re-planning occurred constantly on the tactical timeline. Other participants said that re-planning occurrence depended on the types of activities the rover had performed the previous cycle; if the rover had just completed a drive, then the occurrence of re-planning was much higher due to a change in rover location when compared to cycles where the rover had been in the same location for multiple cycles.

Because supratactical planning looks farther ahead in planning than simply the following cycle, some participants did discuss how the components of the supratactical plan that contained plans for the next cycle or the next two cycles tended to require less re-planning than those portions of the supratactical plan considering planning cycles two weeks ahead.

Communication Channels

In addition to identifying the information streams involved in the planning processes, participants were also asked to identify how that information was communicated to them (communication channel). Figure 12 plots the number of participants who discussed each communication channel and Figure 13 presents that data in terms of participant percentages. The various identified communication channels are discussed below.

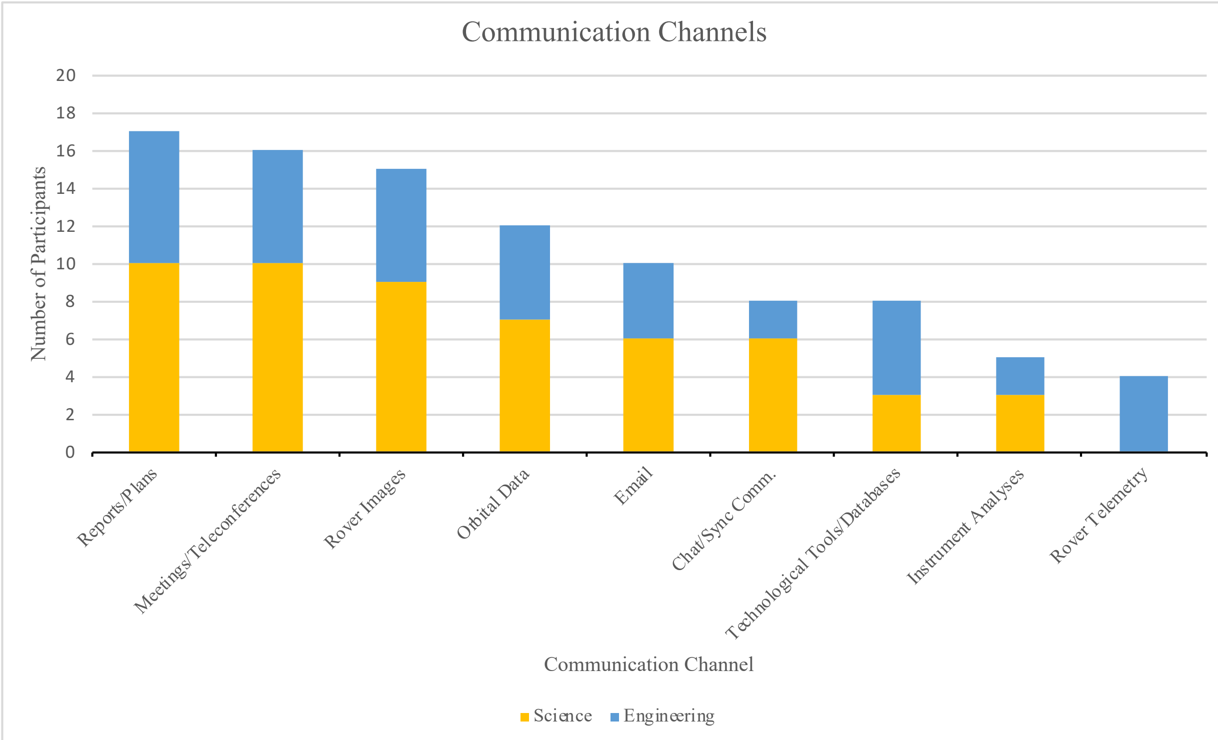


Figure 12: Communication Channels (Participant Numbers)

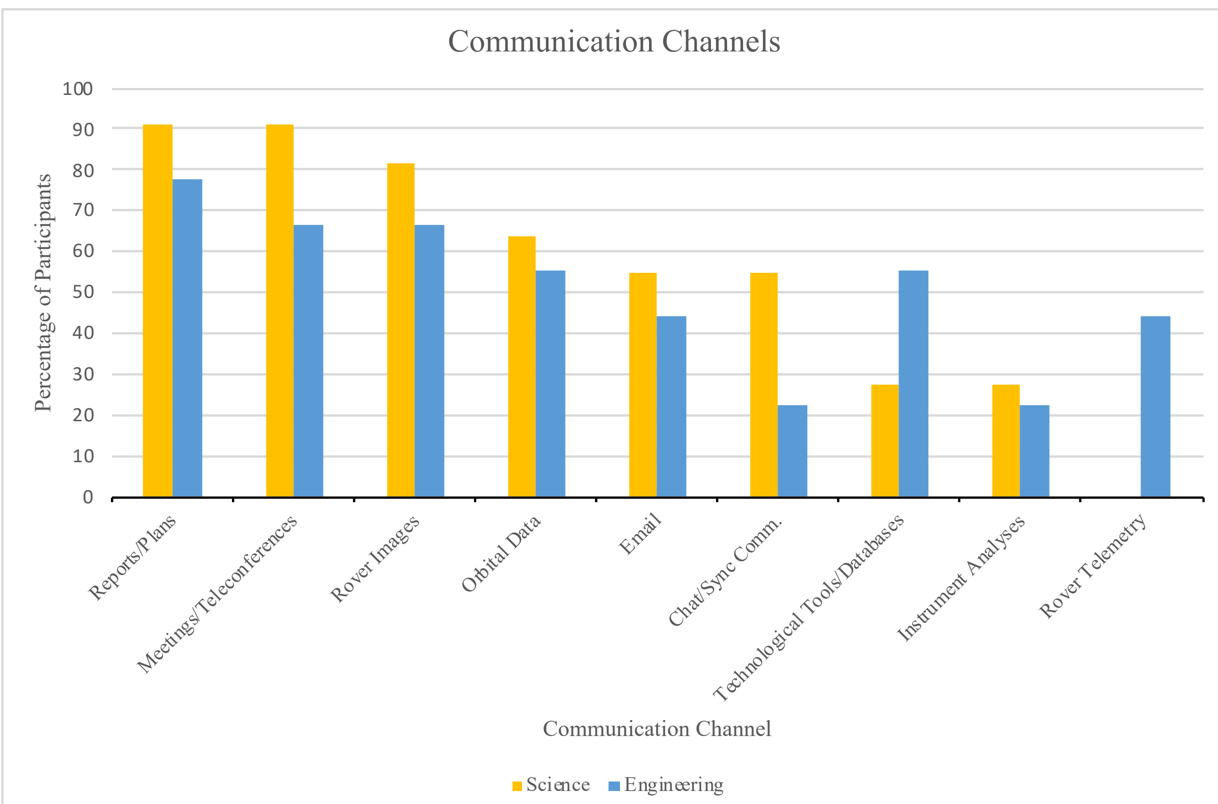


Figure 13: Communication Channels (Participant Percentage)

Reports/Plans

Though some reports are communicated in-person (e.g. the LTP report presented in the SOWG meeting) or through email (e.g. handover plans), there is also an online repository for different reports that are relevant to planning. Many of these reports also contain plans for future planning cycles. This was the most mentioned information source by all participants and was the information source most mentioned by engineering participants (77.8%) and tied for the most mentioned among scientific participants (90.9%). One of the first steps mentioned by most participants that is taken when they are in a staffed role is to read the handover report from the person who filled the role before them, as well as any other reports that are relevant to their specific role. These reports provide information on past activities, past rover status, results of past activities, and planned activities for future planning cycles. Plans and reports are therefore the starting points for many aspects of operations planning for most of the staffed operations roles.

Meetings/Teleconferences

A significant portion of tactical planning consists of meetings between large groups of people that take place both in-person and over the phone. This information source was one of the two most mentioned by scientific participants (90.9%), and this is likely due to the number of different information streams that are communicated to the larger team through these meetings. For example, in the SOWG meeting the Long-Term Planner will present the strategic plan, the results of recent activities will be discussed, activities will be selected to fill out the skeleton plan as well as the specific conditions required for those activities, the team will be informed of any rover anomalies that may affect planning, and future activities will be requested. These meetings provide opportunities for the larger team to contribute to the setting of specific rover goals and informing the future directions of the rover. There are also additional meetings for the purpose of presenting results from the analyses of instrument data or to discuss recent results with the team.

Rover Images

A significant amount of information is obtained by looking at images taken with the rover on Mars. Rover images communicate location context, potential scientific targets in the area, details on terrain in the drive direction, and some cameras are even used to observe the status of other rover elements. The images taken from the rover are used by rover scientists and engineers as their "eyes" on Mars.

Orbital Data

Orbital data is a significant source of information for strategic planning, though it contributes to the other timelines as well. Orbital data include maps (including terrain elevation maps) which are used to plan the drive path, select interesting scientific locations/waypoints, and track the rover's progression through the planned route. In addition to orbital images, there are also tools on orbiters that allow for preliminary identification of minerals on the surface, which is useful in identifying areas for further exploration.

Email

Email is another common way that rover personnel communicate with each not only during a planning cycle, but also between planning cycles. Many roles create "handover reports" which are often communicated to the proceeding person in the same role through an email. These reports inform the new person in the role what was accomplished, the results of the previous sol's activities, and what are the goals for the next cycle (including and role-specific information that is required). When synchronous communications are not available or impractical, roles will also collaborate with each other and pass information between roles using email. Upper mission management (e.g. project scientists, instrument P.I.s, etc.) may also send email communications to the entire team.

Chat and Synchronous Communications

As will be discussed in sections below, there is a lot of communication amongst personnel in different roles that occurs during rover planning. One of the ways through which they communicate is through one-on-one, face-to-face communication, or through a virtual, real-time chat tool (synchronous communication channels). This communication channel is used to facilitate collaboration between different roles and communicate various forms of information, such as changes to the current plan, what has previously been accomplished, the results of certain activities, and whether certain targets can be reached.

Technological Tools/Databases

Various technological tools and information databases have been developed to support rover operations on Mars. There are tools that predict the amount of data return based on the position of various orbiters, that simulate the activities that will be performed by the rover and give final condition estimates of resources (e.g. power), that help Rover Planners visualize the rover in the landscape to determine if targets are reachable, and tools that help with scheduling rover activities. There is also a tool that automatically creates derived products from certain data streams (e.g. making mosaics from multiple images taken on the surface). In addition to technological tools, there are also databases with information gained through experience; there is a database that outlines rover performance on different types of terrain and another that keeps track of activity dependencies and ordering constraints.

Instrument Analyses

The analyses performed on the instrument data transmitted from the rover can communicate information relevant to scientific planning including surface hardness and the chemical composition of potential targets. Further analysis of the raw data also contributes towards answering research questions and testing hypotheses or generating new questions or hypotheses.

Rover Telemetry

Rover telemetry encompasses engineering data from the rover, including rover status information (e.g. power, temperature, systems nominal etc.) and performance data. This data is used to assess the health and safety of the rover, whether all subsystems on the rover are working as intended, and how well the rover is performing when completing the planned activities. In addition, on the strategic timeline, rover telemetry can be mined in order to measure trends in performance/status.

Data Streams

In this dissertation, information streams are considered to be the relevant information that rover operations personnel need to accomplish their role. Data streams are specific sources of data that affect these pieces of information. For example, rover status is an information stream that a rover engineer needs to assess and monitor; rover telemetry (the downlinked data from the rover's various subsystems) is the major data stream that a rover engineer would use to assess the status of a rover. In some cases, communication channels (how the information is communicated) and data streams (where that information comes from) overlap. This is generally when considering data streams that do not require a significant amount of pre-processing or analysis to be understood. For example, rover images both communicate information (a communication channel) and are a specific data stream from the rover.

The following section present specific data streams discussed by participants, including any pre-processing or analysis that needs to be done on the data before it is used in the planning process (if applicable) and how often each data stream updates.

Instrument Data

Data from the instruments onboard the rover are what allow scientists to gain a better understanding of the Martian surface. New data from rover instruments is obtained whenever a specific instrument is used (although that information is transmitted to Earth only during available orbiter passes). For certain remote sensing instruments—such as ChemCam and APXS—new measurements are taken multiple times each planning cycle. Other instruments—such as CheMin, SAM, and DAN—are used rarely. CheMin and SAM are only used when the rover drills or scoops a sample from the surface for analysis.

In general, the raw instrument data is not useful for the majority of planning personnel and requires analysis from those who are experts with the instrument to generate products and interpret the information to present to the rest of the team. For example, the ChemCam data generates an elemental spectrum by shooting a target with a laser. It is difficult, even for an expert, to look at the raw spectra and quantify the amount of a certain element present in that target. Therefore, statistical models and computer algorithms are used to determine, based on certain factors, how much of a particular element is represented in a specific spectrum. The results of various instrument data analyses are often presented to the team on a weekly basis.

Orbital Images

Orbital imagery was mentioned by participants as both being used directly (with little pre-processing) and as needing some processing before use in planning. For example, some orbital images are simply a grayscale or color image of a particular area and that requires minimal pre-processing. However, there are derived products from combining orbital imagery with other orbiter data or by using processing tools that give mineralogical compositions of certain areas, create topographical maps, and calculate slopes in certain areas.

New orbital images are taken occasionally, but the majority of the orbital maps and images used for planning were acquired before the rover landed on the surface. Therefore, this data stream does not frequently update.

Rover Images

Because images act as the "eyes" of scientists and engineers on the surface, there is imagery that is taken nearly every single planning cycle. Participants discussed how both raw, unprocessed images and processed images are used in the planning process.

The navigation cameras on rovers are used in stereo-pairs which are meant to mimic how human eyes view depth. This makes it fairly simple to use and correctly interpret images with little to no processing done on those images. In addition, scientists often use flat-field corrected images taken of what is in front of the rover to assess potential targets and surface properties.

However, this is some processing that is done on some images to create derived products. Different filters can be applied to images to highlight different features of the image and 3D meshes, range maps, and elevation maps can be derived from images. These are helpful for Rover Planners determining where and how to move the vehicle.

Rover Telemetry

Updated rover telemetry is downlinked every planning cycle. It is the primary method by which the health and safety of the vehicle is monitored, and it is therefore a high priority data stream. Participants described this data stream as being used both directly and after processing. In terms of some telemetry values, the rover transmits voltages and data volumes in engineering units that can be used with little processing. However, there are telemetry data that are processed using scripts to quickly identify any warning messages or non-nominal responses (e.g. an instrument is "sick") and generate performance metrics.

Strategically, rover telemetry is not generally used, although it can be mined to assess trends in vehicle status.

Goal Sources

While there are many information streams that are used to plan, re-plan, and achieve goals, there are also occurrences where rover operations personnel are informed of goals that were previously planned or are still in effect. Participants were asked how they knew what the current goals were for the planning cycle and 7 different sources were identified. Figure 14 and Figure 15 show the number and percentage of participants that identified each goal source. A short explanation and description of each source is provided below.

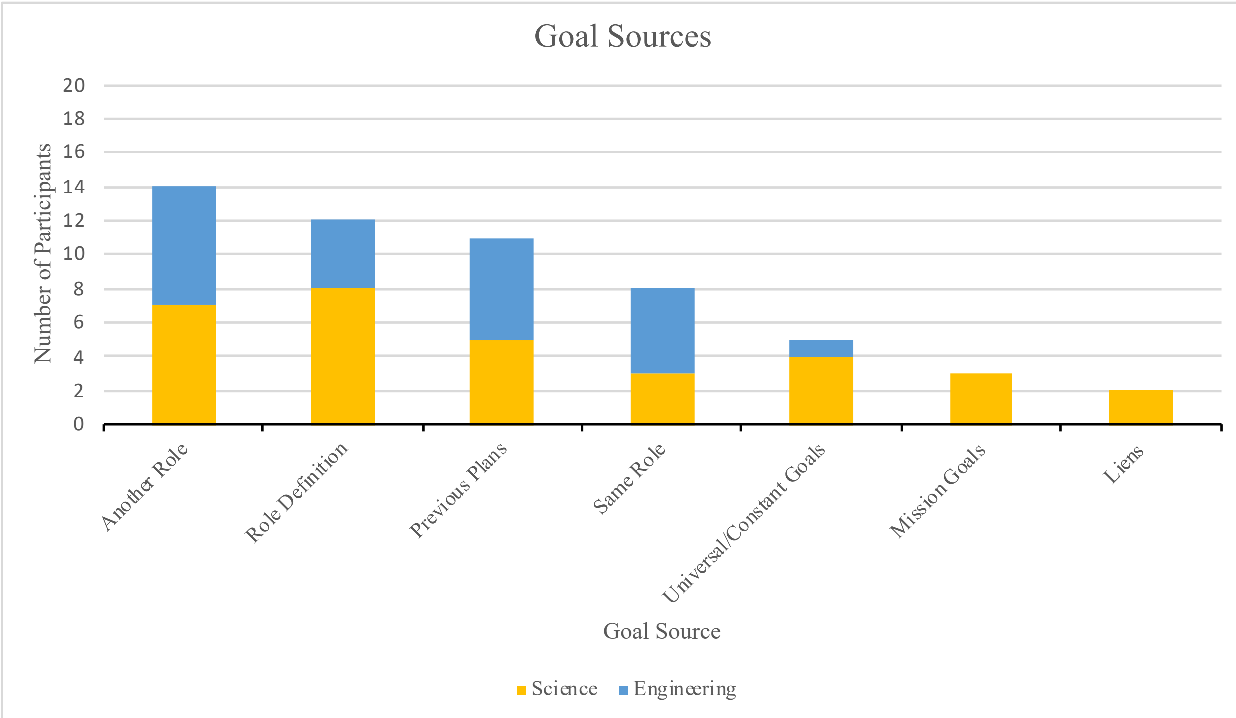


Figure 14: Goal Sources (Participant Numbers)

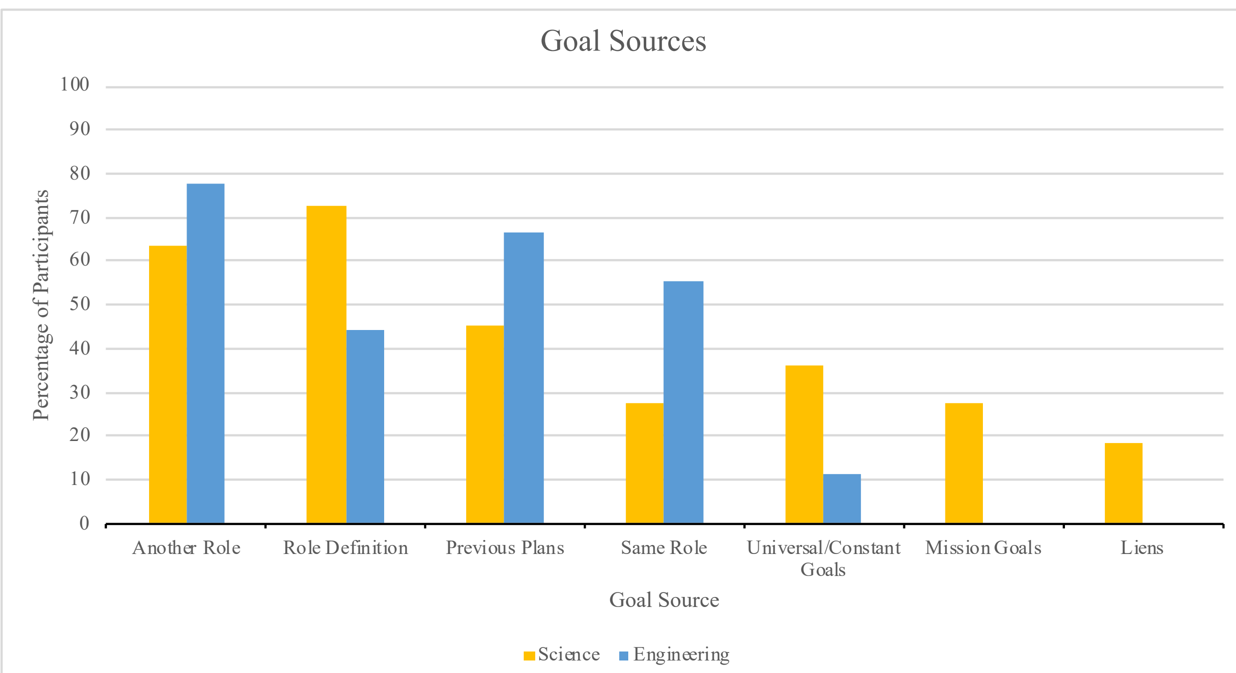


Figure 15: Goal Sources (Participant Percentage)

Another Role

Communication between different planning roles is prevalent and important in the rover planning process (as will be discussed in the next major subheading of this chapter). That is reflected by the fact that this goal source was the one mentioned by the largest number of participants and the highest percentage of engineers (77.8%). Many roles are informed of the current planning cycle's goals by another planning role (either in person, through email, or through a report created by the other role). A few examples of this include the Long-Term Planner role informing many other roles of the strategic goals, or the Project Scientist setting and communicating the overall mission goals.

Role Definition

Many staffed positions in tactical planning have detailed and rigorous procedures, and the goals of the planning personnel is dictated by the role they are filling. For example, Payload Uplink Leads' goals are always to maximize science while maintaining the safety of the instrument they are responsible for. Payload Downlink Leads always have the goal of interpreting their assigned data so it can be used for future planning. This goal source was the one mentioned by the largest percentage of scientists (72.7%).

Previous Plans

At the end of each tactical planning cycle, a skeleton plan is created for the next planning cycle which, if everything proceeds nominally with the rover's activities, outlines the goals for cycle n+1. Similarly, strategic plans will provide goals for a set of planning cycles. Many participants stated that they will look to the previous cycle's plans in order to assess their goals for the day.

Same Role

As mentioned above when discussing information sources, most roles create a handover report that is given to the person filling their role on the next planning cycle. That report communicates relevant information as well as goals for the next planning cycle. If all rover activities proceed nominally, the goals outlined in the handover reports are often those that are adopted in the next planning cycle.

Universal/Constant Goals

There are some goals that are universal and constant across participants. One of those goals is maintaining the health and safety of the vehicle and all the instruments aboard; all planning roles prioritize this goal at all times. Another example of a universal and constant role is the maximize the amount of good science exploration that can be completed by the rover each cycle (while still maintaining health and safety). There is no specific source for these goals, but these overarching goals inform many of the actions that planning personnel take during planning cycles.

Mission Goals

Especially for strategic planning, many of the goals stem directly from the overarching goals of the entire rover mission. Strategic campaigns are planned to contribute to achieving the mission goals and therefore the mission goals set before the rover landed on Mars can heavily inform the setting of strategic goals.

Liens

The liens list is essentially a “to do” list of activities that various people involved in planning want the rover to accomplish. Therefore, this list can provide clear goals to those working on the following planning cycles and there are times when the goal of a current planning cycle is taken directly from the liens list.

Role Collaborations

In order to capture the sharing of information and expertise that occurs throughout rover activity planning, participants were asked about various roles with which they collaborated in order to perform their role or meet their goals.

In order to visually represent these relationships, the described collaborations were imported into the network analysis software Gephi© to create a communication web, shown in Figure 16.

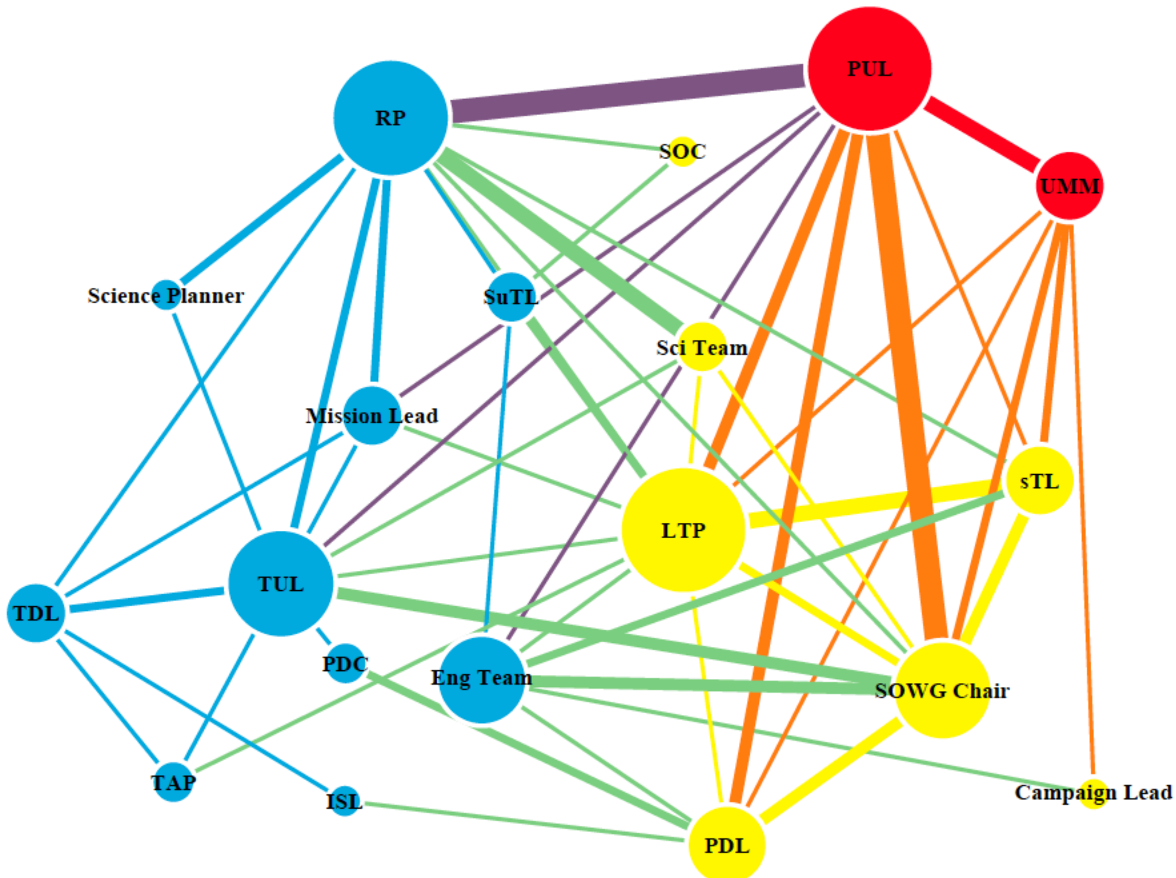


Figure 16: Rover Planning Collaborations

In Figure 16, the nodes (circles) represent different roles. The size of the node is proportional to how many edges (the lines connecting the nodes) are connected to the node (the number of other roles that mentioned each role) and the color of the node reflect whether the participants interviewed in this role were a part of the science team (yellow), engineering team (blue), or both (red). The edges are colored as a combination of the colors of the nodes the edge is connecting. This allows for easy identification of when engineers collaborate with scientists (green lines) or with roles that represent both groups (purple lines). The sizes of the edges are proportional to the number of participants who mentioned each collaboration. It is important to note that the number of participants interviewed in each role is not balanced (e.g. far more Payload Uplink Leads were interviewed than Long-Term Planners), which means that the thickness of the lines are not necessarily representative of the most important collaborations or the ones that occur most frequently; it is representative of the collaborations most discussed by participants.

The edges in this collaboration map are non-directional. This is because participants often talked about the collaborative nature of many of these communications (not simply one role providing information to another in one direction) and adding a second set of lines would make the collaborations that occur more difficult to distinguish in the image. In addition, participants mentioned collaborations with roles that were not interviewed in the study. Those roles are summarized in Table 20. Some participants also talked about collaborations with the “science team” or “engineers” in general, without mentioning specific role. For that reason, there are nodes that represent the general science and engineering teams to account for the collaboration that occurs despite not having specific roles mentioned.

Table 20: Relevant Roles not Interviewed in Study

Role	**Acronym**	**Description**
Science Operations Coordinator	SOC	Remains in contact with the science and engineering teams and conveys the tactical/strategic goals between teams.
Upper Mission Management	UMM	Project scientists, PIs, etc. Personnel who are in major leadership positions in the mission.

Table 21 describes the collaborations (as described by participants) shown in Figure 16, as well as the number of participants who mentioned that collaboration. It is important to note that this is not a complete picture of all the collaborations that occur during rover planning as not all rover operations roles were interviewed in the study and it is possible the participants that were interviewed did not mention all the individuals with whom they collaborate.

Table 21: Role Collaborations

1st Role	2nd Role	Number of Mentions	Description
Campaign Lead	Eng Team	1	Work together to determine the strategic route for a campaign; the campaign lead suggests waypoints of scientific interest and the engineering team determines possible traverse paths to those points, time estimates, and distances.
Campaign Lead	UMM	1	Upper mission management can inform the campaign lead of changes to the goals/timeline of the planned campaign, causing a need to re-plan certain aspects.
LTP	Eng Team	1	Work together to balance science priorities and engineering constraints when developing a strategic plan.
LTP	Mission Lead	1	LTP presents the strategic goals to the Mission Lead.
LTP	PDL	1	LTP presents the strategic goals to the PDL.
LTP	PUL	3	
LTP	RP	1	LTP presents the strategic goals to the RP.
LTP	Science Team	1	LTP presents the strategic goals to the Science Team and ensures they keep them in mind during tactical planning. The Science Team informs the LTP about recent discoveries and status of instruments which affect the long-term plan.
LTP	SOWG Chair	2	LTP presents the strategic goals to the SOWG chair. LTP ensures SOWG Chair stays on track with strategic goals during planning.
LTP	sTL	4	LTP presents the strategic goals the sTL. LTP follows sTL discussions to ensure they remain on track during planning.
LTP	SuTL	2	Work together to balance engineering and science supratactical/strategic goals and constraints.
LTP	TAP	1	LTP presents the strategic goals to the TAP.
LTP	TUL	1	LTP presents the strategic goals to the TUL.
LTP	UMM	1	LTP takes some direction from upper mission management as to the direction the strategic plan should take.
PDC	PDL	2	PDL reports the status of rover subsystems to the PDC.
PDC	TUL	1	PDC provides instrument status information to the TUL.
PDL	Eng Team	1	PDL may check on the status of a piece of downlinked data with the engineering team and let the engineering team know whether a piece of data was not properly downlinked.
PDL	ISL	1	PDL reports status of instruments to the ISL and what kinds of anomalies, if any, occurred.

Table 21 continued

PDL	PUL	3	PDL provides status of instrument to PUL. PUL informs PDL of the activities selected for the rover and what data to expect to be downlinked.
PDL	SOWG Chair	3	SOWG Chair can communicate to PDL when there is something that requires the current plan to change. PDL provides information to the SOWG Chair on the status of instruments as well as the results of activities performed with various instruments.
PDL	UMM	1	Upper mission management may inform PDL of reasons why downlink is affected.
PUL	Eng Team	1	Work together to ensure instruments are safe, positioned properly, and collecting desired science.
PUL	Mission Lead	1	Mission Lead remains aware of what is being planned by the PULs to ensure no commands will damage the rover.
PUL	RP	6	Work together to ensure that desired rover activities are done safely and meet required conditions in order to generate good science.
PUL	SOWG Chair	6	SOWG Chair provides PULs with desired activities for that cycle. PULs inform SOWG Chair whether or not the instruments can perform that particular task or the best conditions with which to use the instrument.
PUL	sTL	1	sTL can inform the PUL if there is an anomaly that requires a re-evaluation of the current plan.
PUL	TUL	1	PUL will check with the TUL to ensure proper commanding of an instrument.
PUL	UMM	4	Upper mission management can inform PULs if there is a major shift in the current plan and the status of anomalies.
RP	Mission Lead	2	Mission Lead follows commands developed by RPs to ensure rover is being operated safely.
RP	Sci Team	4	Science team informs RPs as to what the desired scientific targets/activities are. RPs gives feedback to the science team about whether or not their goals are attainable.
RP	Science Planner	2	RP provides rover travel estimates to the Science Planner. The Science Planner provides a schedule of the planned activities to the RPs to ensure activities are completed at the right time of day, in the correct order, etc.
RP	SOC	1	The SOC keeps in contact with the science team to relay the science goals to the RPs.
RP	SOWG Chair	1	SOWG Chair can communicate science goals to the RPs.

Table 21 continued

RP	sTL	1	RPs provide information to the sTLs about the current state of the rover, and whether its performance is deviating from what is expected.
RP	SuTL	1	RP may clarify the required priority of activities to the SuTL if there is a conflict with supratactical planning.
RP	TDL	1	TDL provides information on the current status of all vehicle subsystems.
RP	TUL	2	RPs provide information to the TUL on the feasibility of planned activities. The TUL provides the skeleton plan to the RPs and inform RPs whether the plan needs to change.
SOWG Chair	Eng Team	3	Work together to balance scientific priorities with engineering constraints.
SOWG Chair	Sci Team	1	SOWG Chair leads the science team to a consensus on the desired activities for the planning cycle.
SOWG Chair	sTL	3	SOWG Chair can communicate to PDL when there is something that requires the current plan to change. The sTLs relay the desires (in terms of activities with the rover) of their respective theme group. The SOWG Chair balances the desires of the different sTLs.
SOWG Chair	TUL	3	SOWG Chair communicates science priorities to the TUL. The TUL generates the skeleton plan that outlines allotted time/resources for science activities. The TUL ensures any changes to the plan requested by the SOWG Chair do not impact vehicle health and safety.
SOWG Chair	UMM	2	Upper mission management can communicate to the SOWG Chair when there is something that requires the current plan to change. If activities are complex, the SOWG Chair may discuss the plan with upper mission management.
sTL	Eng Team	2	The engineering team informs the sTL as to the status of the vehicle and the resources available for planning.
sTL	UMM	2	Upper mission management can communicate to the sTLs when there is something that requires the current plan to change.
SuTL	Eng Team	1	Engineering team may inform the SuTL if there are any required engineering activities to be fit into the supratactical plan, the priority of those activities, and the resources required to complete those activities.
SuTL	SOC	1	The SOC is involved in communicating the desired long-term science goals to the SuTL.
TAP	TDL	1	TDL provides information to the TAP on the health status of the rover and the resources available for planning.

Table 21 continued

TAP	TUL	1	TUL informs the TAP as to whether the current plan needs to change.
TDL	ISL	1	ISL provides instrument status information to TDL. TDL can provide context to ISL as to why something failed or how that anomaly affects other vehicle subsystems.
TDL	Mission Lead	1	TDL provides current health status of rover to Mission Lead.
TDL	TUL	2	TDL provides current health status of rover to TUL.
TUL	Mission Lead	1	Work together to ensure changes to the current plan won't affect the larger strategic plan. TUL provides current skeleton plan to Mission Lead. Mission Lead provides some input into planning future skeleton plans.
TUL	Science Planner	1	Science Planner provides information to the TUL as to the feasibility of the currently planned activities.
TUL	Sci Team	1	TUL receives science priorities from the science team. TUL provides the skeleton plan to the science team.

Human-Rover Similarities

Participants were asked to describe what they thought would be similar between rover operations and human operations on Mars. Figure 17 and Figure 18 show what participants identified as likely similarities. A short description of each identified similarity is provided below.

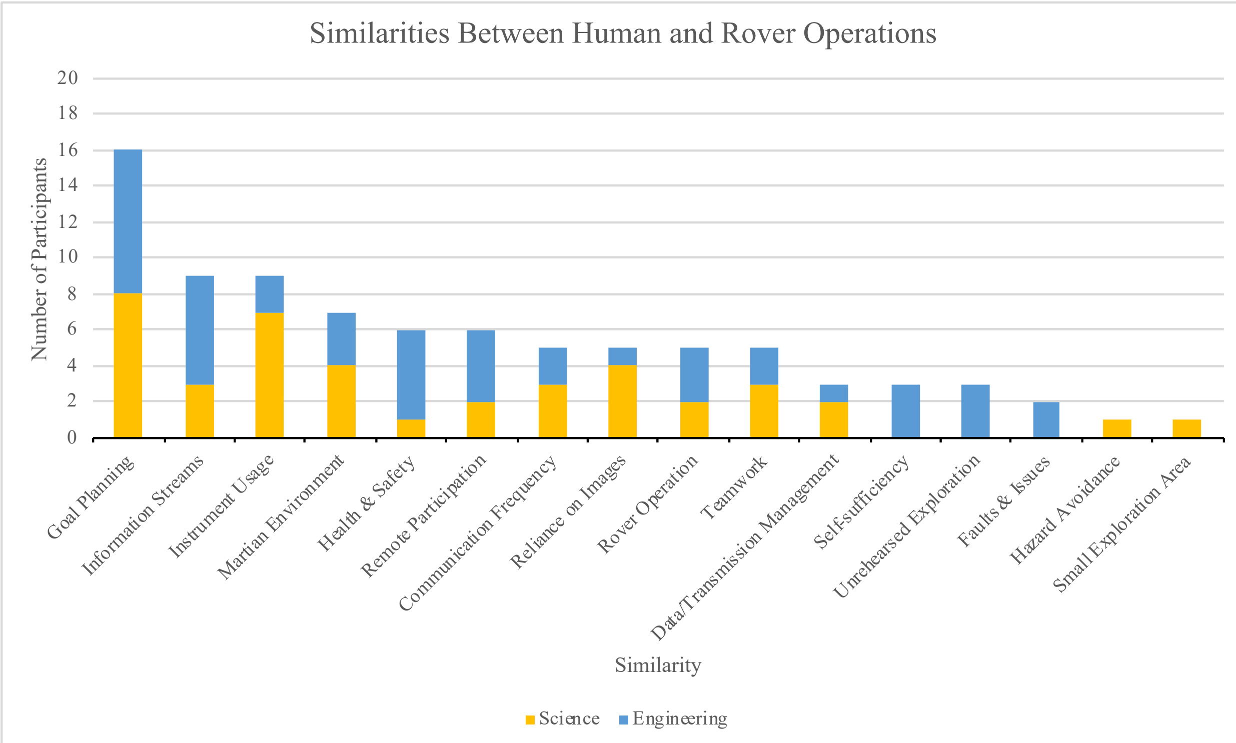


Figure 17: Similarities Between Human and Rover Operations (Participant Numbers)

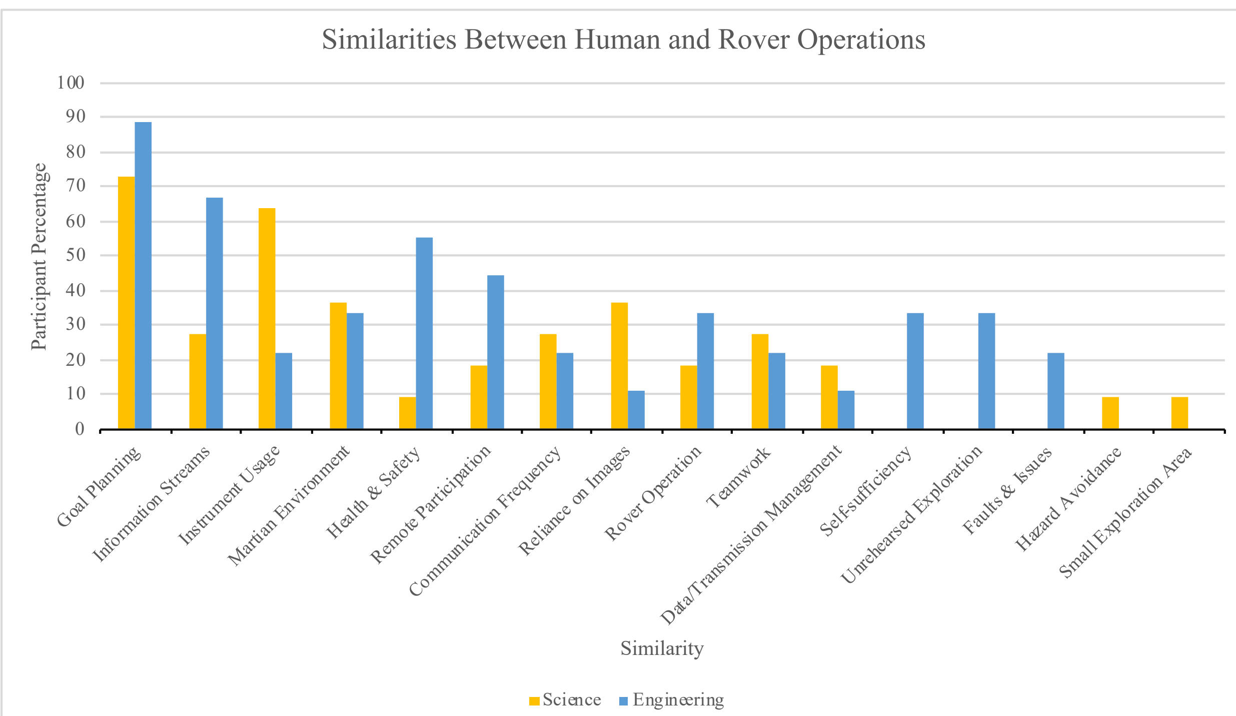


Figure 18: Similarities Between Human and Rover Operations (Participant Percentage)

Goal Planning

This was the most commonly mentioned similarity between rover operations and an imagined human mission to Mars. It was the most commonly mentioned similarity among engineers (88.9%) and scientists (72.7%).

Participants described how planning a spacewalk can be very similar to how rover activities are planned—on all timescales. Strategically, many participants stated that they believed the current strategies adopted by rover operators for strategic planning could be adopted with little to no modifications; personnel on Earth could provide long-term goals, traverse routes and timelines to astronauts on Mars. Supratactically, plans could be created for future spacewalks based on the results obtained during a previous spacewalk (much like a skeleton plan created for planning cycle n+1). These plans could balance science goals and engineering constraints, much like rover operations planning does. Even the tactical planning process has some applicability to human exploration with astronauts responding to the newest information collecting during their spacewalk (though this information collection will occur at a much higher rate). Ultimately, participants agree that astronauts will still be provided with a longer-term plan that outlines their goals and broadly assigns their activities.

One participant also discussed how rover operators are able to accurately simulate different rover activities and sequences and how that could be adapted and applicable to EVA planning.

Information Streams

As part of asking what similarities and differences would exist between rover operations and human Mars exploration, participants were also asked whether or not they thought the type of information relevant to planning would be similar in both mission types. Many stated that there would be multiple information streams that would overlap. Prominent among those overlapping information streams were power data, spacecraft subsystem status data, terrain traverse-ability, image processing/interpretation, and many science-relevant data streams (e.g. chemistry/mineralogy of rocks). Because the rover is a complete spacecraft, many of the data streams that are monitored when planning rover activities will apply to the spacecraft and habitat systems used by astronauts on Mars.

Along with data that are directly comparable, many participants talked about rover information streams that assess vehicle health as being homologous to human health data used to ensure the well-being of astronauts on Mars. Though the content of the data transmissions will be different, multiple participants categorized the information stream as the “same” due to the fact that it assesses the health of the astronaut, just as rover telemetry indicates rover health.

One participant also talked about how the data will be used during human missions as being similar to how various information streams are used in rover operations. In both mission types information from multiple information sources needs to be synthesized and used to update current scientific models and operations procedures.

Instrument Usage

This information stream was the second most mentioned similarity amongst scientists (63.6%). Many participants believe that, like rover, astronauts will use handheld instruments in order to assess more scientific properties of the Martian surface (scientific properties that are not observable with human vision). The rovers from the MER and MSL missions were designed to be mobile laboratories and therefore the instruments chosen for inclusion on each vehicle was chosen to meet the goals of the rover (e.g. geologically characterize the planet, determine the chemical composition of Mars). Similarly, humans will use handheld instruments during their EVAs (as field geologists often do) in order to gain more information on their surroundings.

In addition to rover and human missions being similar in their use of instruments, many participants stated that there will be significant overlap in the instruments used by the rover and the instruments that will likely be used by astronauts. There are rover instruments that produce spectral signatures and those will continue to be relevant to astronauts as humans are not able to visually assess chemical composition. In addition, high resolution cameras will likely be used to document what humans are able to assess visually (just like many of the high resolution cameras on Mars rovers).

Martian Environment

Some participants discussed how the familiarity with the Martian environment gained through rover operations will be directly applicable to human operations on Mars. Humans will have to operate on the surface of another planet and, even if the location in which humans are exploring is different than any rover exploration site, there will be similarities in the Martian environment that will inform how operations are planned and executed.

Health & Safety

Similar to human space exploration, health and safety of vehicle hardware and software is of the utmost importance during rover operations. Participants described how rover hardware and software health considerations could be comparable to the care that will be taken to ensure astronaut physical and mental health. Like rover operations, there will be data that is analyzed to ensure all systems and subsystems are working nominally (including human biological systems) and humans will be able to provide feedback to Earth if they are feeling unwell (just as the rover can specify what subsystems are "sick" and which are "safe"). One participant also commented on the amount of autonomy that astronauts are going to be expected to have in terms of their health and safety and compared that to rover operations saying, "…we try to make our rover smart enough that it can keep itself out of trouble if something unexpected happens and know when to call for help."

Remote Participation

Some participants discussed how the scientific and engineering community at large on Earth will still have a role for participation during a human mission, much like the community is involved in the activities of the Mars rover. Though the community may have less influence over the tactical activities performed by the astronauts, they would be able to influence the strategic and supratactical plans. And while they would not have access to the data in real-time, it is likely that the collected data will eventually be transferred back to Earth, and it is possible that this could occur on a fast enough timescale to allow the larger scientific community to weigh in on the results of a previous EVA while the next is being planned. Some scientific participants stressed the importance of having many scientific opinions and the input of many experts in terms of addressing scientific questions, and it is desirable to be able to incorporate that in future human missions.

Communication Frequency

Participants who mentioned this similarity discussed the fact that ground controllers coordinating with human crews on Mars will need to become habituated to receiving communications and transmissions from Mars about as frequently as rover operators receive transmissions from the rover. This is due not only to the time-delay on communications making it impossible for real-time, interactive communication, but that the current communication infrastructure in place would not allow for communications at a significantly higher frequency than what is already being used for rover operations. One participant also mentioned communications blackouts that occur based on the positions of Earth and Mars and how that is not something that's ever needed to be considered for past human space exploration.

Reliance on Images

There are participants who stated that image data will still be critical when it comes to certain aspects of mission planning. When it comes to path planning, images are still critical when it comes to hazard avoidance. Orbital images are still likely to be used in order to plan astronaut traverse routes. However, depending on whether or not a robotic aid (like a rover) is used to "scout" the path ahead of astronauts, images collected by that robot may remain a critical information stream when it comes to path planning. Different participants discussed different mission architectures, including those with "fetch" rovers (rovers that go ahead of astronauts or perform certain activities in the place of astronauts) which may be tele-operated by astronauts on Mars. The operation of these robotic aids will be reliant on video streams (which participants considered homologous to images taken from a current Mars rover).

In order to keep Earth in-the-loop with respect to the activities performed by astronauts on Mars, images and video streams will also remain important. Though these images and videos will not be received in real-time, it will allow Mission Support to stay informed as to current astronaut activities and scientific discoveries.

Rover Operation

Depending on the assumed architecture of a human mission to Mars, it is possible that astronauts will be supported by rover activities while on the surface. Some participants assumed that astronauts would be tele-operating a rover from their habitat. In that case, there would be similarities in terms of the information required in order to allow that tele-operation (e.g. images of terrain, system status reports, etc.). If that rover is performing scientific activities with instruments or taking samples, then that increases the similarities in how astronauts would approach features of interest with the rover.

One participant discussed the possibility of having rover operations occurring while the astronauts are asleep or performing other activities, and that those rover activities would be controlled by operators on Earth in a very similar—if not identical—way as the method used for rover exploration currently.

Teamwork

Some participants discussed working in a spatially distributed, multi-disciplinary team, and how the experience of coordinating all of that expertise will be relevant to human missions to Mars. Not only will people from all over the world be interested and want to have input in the planning of human missions (just as they are with rover missions), but these individuals will also need to coordinate with astronauts on Mars, who are not only spatially distributed, but also temporally distributed due to the time-delayed communications. Personnel involved in both human and rover missions to Mars need to be open to the opinions of those in other fields in order to gain a better understanding of the planet.

Data/Transmission Management

Similar to the previously mentioned similarity, the current communication infrastructure in place limits not only the frequency with which transmissions can be sent between Earth and Mars, but the amount of data that can be included in those transmissions. While participants agree that the amount of transmission bandwidth will likely increase before humans are sent to Mars, they also stipulate that it will not increase by so much that it will allow for the current levels of crew-to-

Mission Control communications that have occurred during other human missions in space. In addition to this, there are long periods of time when there are losses in communications between Earth and Mars (e.g. when the Sun is between the two planets), which may not be possible to overcome. The amount of information transfer that can occur will be more comparable to current rover transmissions levels than the transmission bandwidths currently available for ISS missions.

One participant also brought up another similarity between data management in rover missions and human missions: the importance of data storage and archiving. As with rover operators, astronauts will need to ensure they have enough onboard storage to properly store and archive the results of the activities they are performing.

Self-sufficiency

Much like Mission Control is beginning to be thought of as Mission Support Center for human operations on Mars, the rover control center is referred to as the "Mission Support Area". This similarity in nomenclature demonstrates the similarity in how rover operations and human operations on Mars need to be self-contained and relatively self-sufficient. Largely due to the time-delay on communications, rovers have a certain amount of decision-making and autonomy programmed into their software to ensure the vehicles remain safe when there are unexpected occurrences. Similarly, humans are going to have to act with a level of autonomy and respond to unexpected occurrences without direct input from Earth. Astronauts are going to need to solve problems and, due to the distance between Earth and Mars, crewmembers in space cannot rely on system repairs from Earth if something goes wrong. Similarly, if a system onboard the rover is not working nominally, workarounds have to be developed using existing nominal systems, as there is no way to make repairs onboard the rover.

Unrehearsed Exploration

Two participants discussed how EVAs on Mars will not be as rehearsed as EVAs currently are in low-Earth orbit. Astronauts on Mars are going to respond to the latest information collected on the surface and adjust their activities accordingly. Discoveries will have a major impact on their activities in a way that is not found in the current EVA architecture. Similarly, rover operations (especially on the tactical timeline) is highly reactive to the results of the previous planning cycle's activities. So, like rover operations, human exploration on Mars is not going to be heavily rehearsed in advance due to the fact that it is much more reactionary.

Faults & Issues

Two engineering participants pointed out the similarity between the rover experiencing a fault (e.g. a drive not completing due to an unforeseen hazard) and an astronaut experiencing an issue during an EVA (e.g. not being able to follow the originally planned route due to an unforeseen hazard). The rover will report various reasons why it was unable to complete an activity (to help rover operators quickly identify the cause of the fault and adjust accordingly), which participants saw as similar to when astronauts alter a plan and provide feedback on the reasons behind the change.

Hazard Avoidance

One participant described the stereo-image analysis software on board the rover that allows the vehicle to identify hazardous terrain and avoid it. This participant described how that was similar to how humans would react to terrain on Mars and may result in route re-plans (which also can occur with rover operations).

Small Exploration Area

One participant discussed the limitations that exist in terms of distance for both humans and rovers on Mars. Martian rovers move very slowly and are therefore limited in terms of the area that they can explore. Humans are able to move more efficiently, however they are limited in terms of resources and how far they can traverse in a single EVA, since they need to return to a habitat (assumed to be stationary) in order to replenish consumables. This participant stated that despite sending humans to Mars (and the fact they can do things and go places rovers cannot), only a small part of the planet will be explored.

Human-Rover Differences

While participants were asked about the similarities between human and rover scientific exploration of Mars, they were also asked to describe what they thought would differ. Figure 19 and Figure 20 show what participants identified as likely differences. A short description of each identified difference is provided below.

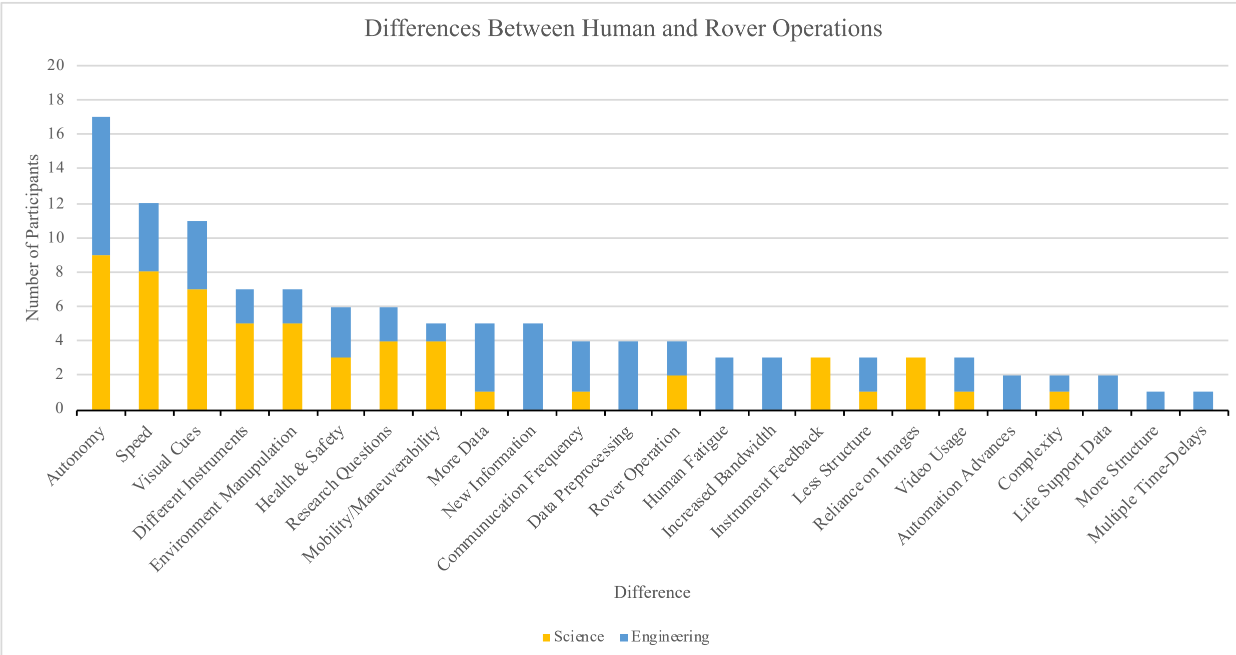


Figure 19: Differences Between Human and Rover Operations (Participant Numbers)

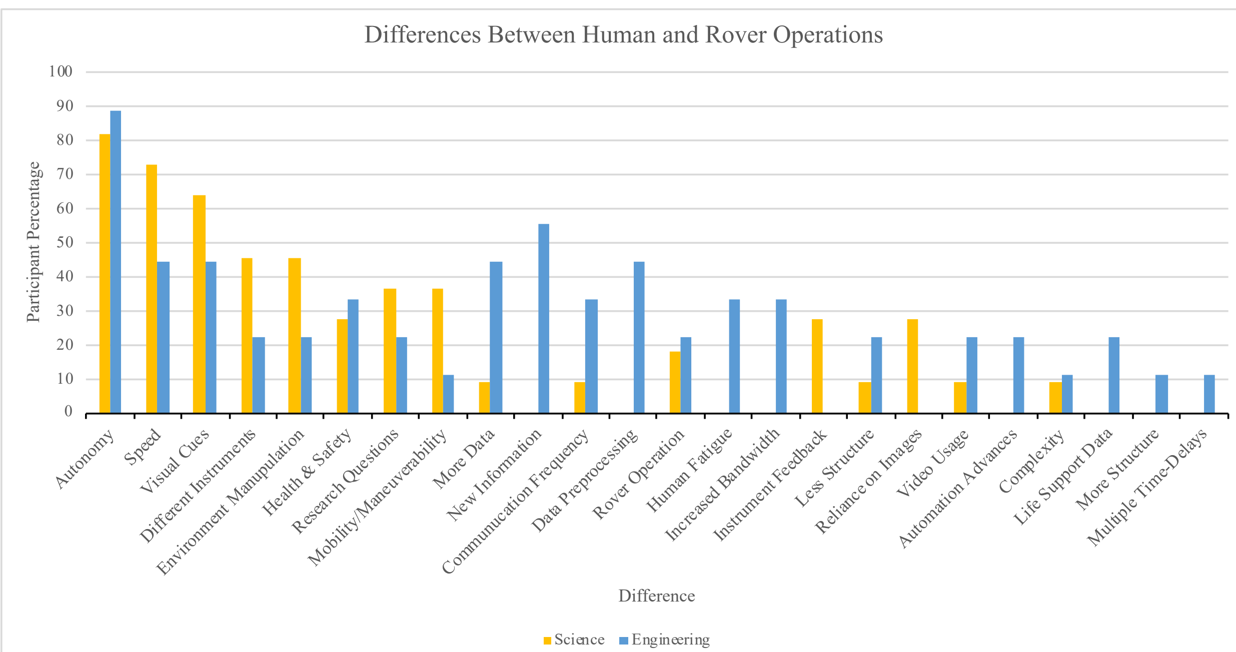


Figure 20: Differences Between Human and Rover Operations (Participant Percentage)

Autonomy

The most commonly mentioned difference between rover and human Martian operations (88.9% of engineering participants and 81.8% of scientific participants) was the increased autonomy of astronauts: their abilities to act without input from Mission Control, notice things on their own, react to changing situations, and have their own insights based on what they see on the surface.

Rovers only provide images to Earth when the vehicle is stopped in an area and only in the direction in which it is directed to take an image. Many participants discussed the fact that humans take in and process large amounts of information as they move from place to place, which provides a significant amount of context and informs their perception of the area. The ability of a human to take in and synthesize that much information differs significantly from rover operations. The ability of humans to synthesize and understand information also allows them to make on-the-spot decisions and respond quickly to discoveries, which a rover cannot do.

The increased autonomy of astronauts also alleviates a lot of the commanding required from Mission Control. Rover operators create sequences of commands for a rover to complete over 24 hours and they need to specify all the actions the rover takes. Astronauts can be given much broader goals and directives which they can complete in the most effective way based on what they see on the surface. In addition to this, scientific exploration with humans can continue when communications between Earth and Mars are unavailable, which is not possible for rover operations.

Speed

The speed at which exploration will occur was the second most mentioned difference between rover and human operations and mentioned by the second largest percentage of scientists (72.7%). Multiple participants mentioned a quote they attributed to MER principal investigator Steve Squyres which was (as expressed by one participant): “These are the best robots we’ve ever sent to the surface of Mars. I could have done everything that Opportunity did [over its mission life to that date] in a weekend with a graduate student and a car.” This highlights the understanding that many participants have that field science and exploration done by humans on the surface of Mars will happen at a much faster rate than exploration done by rovers. Participants attribute this speed to human processing power, mobility, and ability to react to unexpected circumstances without ending an EVA. The ability of humans to perceive and process more information and respond to changing situations means that scientific exploration can occur at a much faster rate.

Visual Cues

Many participants discussed the benefits to have a human on the surface over a rover through the visual cues that humans interpret. Humans in the field perceive and process large amounts of data from looking at the terrain around them as they traverse. Rovers only take images once they have reached a destination, and only in the direction in which their cameras are pointed. This makes it more likely that humans on the surface will perceive features on interest that rovers may have missed as they passed it on a traverse. Human visual cues are also invaluable when it comes to path planning. Many participants identified these visual cues and the accompanying increase in information as a significant difference between rover and human operations.

Different Instruments

While one of the similarities identified between rover and human missions is the continued reliance on different scientific instruments, some participants discussed how the instruments used may differ in some ways. Some participants discussed the technological advances that may occur between now and the time that humans are sent to Mars, meaning that higher quality or more sophisticated instruments may be available to astronauts. Also, having a human operator on the surface may also change some of the instruments that may be used; some participants mentioned the possibility of a laboratory situation in the habitat which would allow for analyses that are not currently possible with the technology that can be put on a mobile rover. Other participants also stated that humans could use a larger variety of instruments due to the fact that there would likely be fewer limitations on power, data storage, or space on a mobile vehicle.

Environment Manipulation

Some participants discussed the benefits of having a human in the field due to the ease with which an astronaut can manipulate the environment. There were discussions about the value of being able to turn a rock over, touch the surface of a sample, or break open a rock with a hammer, which a rover is not able to do. Especially participants who also had significant field geology experience discussed the value added to field geology and analyses by being able to tactically manipulate a possible sample.

Health & Safety

While rover operators prioritize the health and safety of the vehicle, some participants discussed how the operations with astronauts will be even more risk-averse. Ensuring that a rover is functioning nominally on Mars is easier when compared to keeping a human alive and in good physical health while on Mars. Humans need to eat, sleep, and can require medical attention. Health and safety, while a significant concern with rover operations, will be prioritized even more during human missions.

Research Questions

The ability of astronauts to perform different types of experiments and use different types of instruments on Mars changes the possible research questions that can be explored. Having humans on the surface would aid in the search for potential past life on Mars and multiple participants mentioned the possibility of absolutely aging rocks on Mars (something that has not previously been possible without a lab on the surface or a sample-return mission). It is also possible that humans will be able to visit areas on the surface previously inaccessible to rovers, which allows for the exploration of different locations on Mars.

Mobility/Maneuverability

Some participants discussed the mobility and maneuverability constraints of Mars rovers. One participant who is a Rover Planner discussed how each detailed movement the rover makes needs to be commanded, which is not necessary for a human (a human can see how high a leg needs to be raised to step over a rock). Other participants discussed how much easier it would be to have a human turn around and revisit a site they had previously examined, something that is extremely difficult for a rover. Humans also traverse terrain far quicker than a rover does.

More Data

It is likely that there will be more data generated during human missions to Mars, which will necessitate increasing the amount of data processing power and storage onboard spacecraft supporting astronauts. Rovers have very little onboard data storage (which is why data processing occurs on Earth) and their data sampling rate is low (e.g. once per 5 minutes for most telemetry channels). There are many data streams relevant to human exploration (e.g. life support system status) that will need to be sampled more frequently, producing more data that will need to be stored.

In addition to this, the possibility of incorporating more instruments in scientific exploration also means that more data will need to be stored onboard. Because there are assumptions that instrument results will impact astronaut activities, there will also need to be capabilities for in situ data analysis and processing that do not exist onboard rovers.

New Information

Some participants stated that there would likely be different information streams generated during human missions to Mars. Many of those participants specifically mentioned more qualitative or subjective data (e.g. reports on the insights of the astronauts) which are not relevant to rover operations. The differences in relevant information streams was the second most commonly mentioned difference among engineering participants (55.6%).

Communication Frequency

While still constrained by the one-way light-time delays on communications, some participants discussed the likelihood that personnel on Earth will want more than one (occasionally two) transmissions from Mars every day. Participants stated that flight controllers on Earth will almost certainly be working on Mars-time at all times (no matter the time of day in Houston) and will want to receive updates in as close to real-time as possible (taking into account the time-delay). This will likely require updates to the current orbiter/DSN architectures.

Data Preprocessing

When rovers collect data, that data is not pre-processed or screened for saliency before being sent back to Earth. With humans on Mars, it may make more sense to have onboard processing capabilities and that astronauts will only return the results of data analyses of relevant data back to Earth. This would make better use of the limited communication channels and would allow the astronauts to send back their own reports and scientific observations. One participant also mentioned that this could work in reverse as well: some data products could be generated back on Earth and sent to astronauts on Mars.

Rover Operation

Participants who considered human mission architectures supported by rovers also discussed how the operation of these rovers would differ from current rover operations. Many of these participants discussed how it was likely that astronauts would teleoperate the rovers from their habitat on the surface, as commanding the rover from Earth would be incompatible with the rover supporting astronaut activities in real-time. One participant also discussed the automation advances that would need to occur to allow rover to autonomously respond to human activities and support real-time exploration activities.

Human Fatigue

Similar to human health and safety considerations, humans also experience fatigue and it will important to ensure their mental health when they are isolated and away from Earth for long periods of time. As one participant stated, “We tell the rover to drive seven sols in a row and the rover will dutifully go off and drive seven sols in a row.” However, human astronauts will experience fatigue, boredom, psychological illness, and may push back against some of the commands given to them. These considerations do not exist when planning rover activities.

Increased Bandwidth

Three engineering participants discussed the need to increase the amount of data that can be relayed between Earth and Mars with each transmission. Currently, rover operations have access to hundreds of megabits per sol and it is unlikely that that will suffice for human operations. If

Mission Control wants to have access to all the data collected by astronauts (scientific, spacecraft, and life support data) in as close to real-time as possible, then there will be a need to update the current communication architecture to allow increased transmission bandwidths.

Instrument Feedback

Rover instruments collect raw data, send that data back to Earth, and scientists on Earth perform analyses on that data and produce derived products that are meaningful to the majority of the scientific community. While this is functional due to the fact that the rover operates slowly enough to allow time for these analyses to take place to inform the future actions of the rover, humans will operate at a much quicker pace. If the results of instrument readings are going to have any bearing on the activities performed by astronauts within a single EVA, they are going to have to provide immediate or near-immediate feedback that is understandable by those astronauts (e.g. instead of producing a spectrum, it informs the astronaut of the chemical composition of the rock in percentages). This will allow astronauts to use the information provided by instruments in the selection of potential scientific sampling locations.

Less Structure

Three participants discussed how human operations on Mars will be less structured than current rover operations. If astronauts are receiving near-instantaneous feedback on instrument data, then there is less reliance on the uplink/downlink time windows. This makes it likely that astronauts will be given broader goals that they are to meet using the strategies they find the most effective and will be less “micro-managed” than a rover. One participant stated:

> *The reason you send the astronaut in the first place is because they can do things the robots can’t. They can make analyses that the robots can’t. They can make decisions on short-term basis that the robots can’t. So, there’s no point in sending humans if it’s not going to be somewhat willy nilly.*

It is interesting to note that one participant who identified this difference, also discussed how, depending on the mission architecture chosen, operations may be *more* structured (discussed in a proceeding section).

Reliance on Images

Certain rover images are taken in stereo pairs in order to closely replicate how humans would see the surface if they were there and rover planning is heavily reliant on those images. With humans on the surface, some participants discussed how images would play less of a role in scientific exploration than they currently do with rover operations. Astronauts will be able to see the surface first-hand and do not have to rely on images to gain insight into their surroundings.

Video Usage

Some participants discussed the use of video streams and clips as being more useful during a human Mars mission than images. While there is the possibility of shooting short videos with the cameras on the Curiosity rover, it is rarely used to due to the transmission bandwidth limitations. Not only would personnel on Earth want to see video transmissions from Mars, but video streaming may be a useful information stream for IV crewmembers monitoring fellow astronauts on a spacewalk, or for astronauts tele-operating a rover on the surface.

Automation Advances

Two engineering participants discussed the automation advances that will need to occur within the design of robotic aids that support human exploration on Mars. Any robots that directly assist human operations will not be able to be commanded the way they are now (sequences developed for 24 hours of activities with limited sensitivity to their environments) and will need to be far more responsive to crew activities. A participant also identified the need for automated support systems to offload data processing and monitoring requirements for astronauts on Mars, which do not exist for current rover operations. This participant stated the need to shield the astronauts from some of the system complexity and have "enough autonomous performance capability to handle the more mundane aspects."

Complexity

Two participants discussed the added complexity of supporting human operations on Mars (keeping them alive, healthy, sane) and how this will increase the complexity of the systems involved in the mission. This complexity extends beyond the stay of humans on the surface to include astronaut training and long-duration cruise phases of the mission.

Life Support Data

Two participants specifically mentioned life support and astronaut biological data that will be monitored during human missions to Mars as a different information stream from those used in rover operations.

More Structure

One participant discussed the possibility of adopting the current model of EVA and applying it to human Mars missions. This would require all activities performed on Mars to be highly rehearsed and structured—more so than rover operations.

Multiple Time-Delays

One participant discussed the challenges that accompany robotic systems being operated by different operators in different locations under different time-delay regimes. This participant used the example of robotic assets being commanded at different times from crews on Mars, personnel on Earth, and potentially crews on other planetary bodies (like the Moon or a Martian moon), depending on the mission architecture chosen. This is not something that needs to be considered for rover operations as rovers are operated only by individuals at NASA JPL. It is possible that robotic assets supporting astronauts on Mars will be operated by a combination of different astronaut crews or personnel on Earth and there will be challenges in coordinating those different groups of individuals.

Ancillary Topics

Through interviews with participants, discussions occurred that were not directly relevant to the research questions being investigated in this study, but were either interesting, provided areas for future investigation, or provided important context to some of the responses to the research questions. In an effort to present as complete a picture as possible of participant responses during the interviews, those supplemental topics are provided below.

Adapting Operations

One participant discussed how Curiosity operations were built from the operations of Spirit and Opportunity and how the model of Curiosity operations will play a large part in informing the operations of the Mars 2020 rover. This participant stated that usually new missions do adopt the models and operational styles of previous missions and adapt them to changing goals and situations of the new mission. Therefore, it was logical that a new human mission to Mars would adopt some of the operational models of rover missions.

Argument Against Human Missions

One participant expressed their opinion against sending humans to Mars at all. This participant discussed how robotic technology is advanced and is only improving, and how it is much cheaper to send a rover to Mars than a human mission. Another consideration for this participant was that the risk that it posed to astronauts that may eventually go on this mission and that he/she did not think this risk was worth the benefits of sending a human to Mars.

This participant also stated their preference for performing scientific exploration through the use of robotic assets, even asserting:

> *I think working on Mars on a robot has made me a better scientist…it has pulled me back to first principles, it makes you realize all of the assumptions that you put into observations. You know, all of that data your brain collects when you're walking from point A to B. Because, when you're doing that, you're not cognizant of you doing that. You know, the rover makes you…you know, this looking at it through a straw makes you abundantly aware of assumptions and the types of data that you're picking up from the outside world. And I think that's made me a better scientist here on Earth because it's made me be able to articulate some of those issues.*

No other participant expressed an opinion against sending a human mission to Mars, which makes this statement particularly interesting.

Field Geology

Three scientific participants expressed that they believed that apart from current rover operations, future human missions to Mars would be heavily informed by how field geologists currently do science in the field. Rover operations were, at least partially, informed by how humans perform geology in the field and these participants discussed how human operations would be even more informed by field geology. One participant stated that they believed the lessons learned from field geology would be more useful than the lessons learned from rover operations.

General vs. Specific Applicability

One participant stated that the closer you look at specific details of how operations will be performed, the less comparable human operations will likely be to rover operations. For example, a human does not need to be told how to avoid stepping on a specific rock, but a rover does need to be commanded at that level of detail. Therefore, this participant discussed, the further away you move from the specific details of activity planning, the more applicable rover operations are to human operations.

Maintaining Institutional Knowledge

When missions and projects continue for long periods of time, it is inevitable that certain personnel will leave the project. One participant discussed the challenge this situation presents in allowing projects to maintain institutional knowledge. When key personnel leave the project, they take the experiential knowledge they gained by working on the project and it is difficult to transfer all of that knowledge to new personnel who come to work on the project. This is a challenge for rover operations and will also likely be a challenge for human missions to Mars.

Mission Architecture & Design

This topic is the supplemental theme mentioned by the most participants. Five different participants discussed different ways in which human missions could be designed, and how that would have an impact on whether rover operations are applicable, and what aspects of those operational models. Participants discussed aspects of the mission such as how many astronauts would be sent to the surface, the involvement and use of robotic aids, the amount of autonomy given to crew members, the range of crew exploration, the expertise of the astronauts chosen for the mission, and the duration of surface operations. Depending on the decision made on any of these aspects, participant opinions on relevant information streams and the level of applicability of rover operations to human missions would change.

One participant discussed how the architecture of a human mission should be determined: by performing a realistic reliability assessment of the systems being sent to Mars. This participant expressed an opinion that the number of crewmembers should not be determined by how many people can be transported in a specific spacecraft, but how many are necessary to operate, maintain, and repair the systems that are being sent with the astronauts to keep them alive. An integrated mission design that considers both desired system reliability based on crew size, and the number of crew required based on system reliability is needed, as well as a way to accurately assess system reliability.

5. STUDY II RESULTS

This chapter presents the results of Study II, which used physiological data collected from individuals performing field science tasks to determine whether differences exist between physiological responses to those tasks (RQ4.1) and whether the data follows a distribution that would allow for the establishment of individual action limits (RQ4.2).

Participant Demographics

There 3 female and 5 male participants in this study for a total of 8 different participants (N=8). Due to the limited pool of individuals from which the participants were pulled, their ages will not be disclosed. Data was collected from participants over the course of the 3 deployments; data was collected from 2 participants in all three deployments, two individuals participated in two deployments, and the remaining four participants participated in only one of the three deployments.

Data Processing and Combination

After associating a timestamp with collected data points, any data points that were not associated with a specific EVA task were removed from the data set. The BioHarness™ calculates a confidence value to each reading, those values less than 50% were filtered out of the data sets and the mean responses to each occurrence of each task were calculated (a mean was taken from the parameter readings over the time during which a participant performed a specific task). This resulted in 1816 data points (one data point being the mean response to one occurrence of a task) used in the heart rate and respiration rate analyses. The BioHarness™ calculates heart rate variability using the 300 previous high confidence heart rate data points. The duration of some tasks was too short to produce a heart rate variability measurement and there were therefore a total of 1690 heart rate variability data points used in the analyses. The data sets composed of the mean responses to each occurrence of each task (and are therefore more independent than the raw time series data) were the data sets that were used for all proceeding analyses. All proceeding analyses used the data sets composed of the mean responses, not the raw data, as the raw data is a dependent time series data set.

Of the participants that participated in more than one deployment, a Kolmogorov-Smirnov (K-S) test was used to determine whether or not data sets from the same participant but during different deployments could be combined to increase the number of data points in each data set. In certain cases, participant data sets could be combined but not in others. The ability to combine data sets was also inconsistent when considering different physiological parameters. This resulted in different "cases" that were used in the analyses, shown in Table 22, Table 23, and Table 24. The number of total data points in each case varies from 91 to 410 depending on the number of EVAs in which the participant took part, whether those data sets could be combined, and which parameter was being considered. In the following tables, "ID" refers to the first project deployment in Idaho, "HI1" to the first deployment in Hawai'i (the second project deployment) and "HI2" to the final project deployment in Hawai'i.

Table 22: Heart Rate Cases

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Participant	1	2	3	3	4	4	5	6	7	8
Location	ID/HI1	ID/HI1/HI2	HI2	ID/HI1	HI1	ID	HI1	HI1	HI2	HI2

Table 23: Respiration Rate Cases

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Participant	1	2	3	4	5	6	7	8
Location	ID/HI1	ID/HI1/HI2	ID/HI1/HI2	ID/HI1	HI1	HI1	HI2	HI2

Table 24: Heart Rate Variability Cases

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Participant	1	1	2	3	4	4	5	6	7	8
Location	HI1	ID	ID/HI1/HI2	ID/HI1/HI2	HI1	ID	HI1	HI1	HI2	HI2

The author had no control over how many times participants performed each task and for how long. This resulted in unbalanced data sets where tasks that occur frequently (e.g. traversing or observation tasks) could have as many as 174 data points in a specific case, while infrequent tasks (e.g. breaking rocks or bagging samples) could have as few as 3 data points in a specific case. Table 25, Table 26, and Table 27 break down the number of data points associated with each task that were used in the analysis for each case, with the total number of data points in the case listed in the bottom row. It is important to note that one participant never performed the instrument use (EI) task.

Table 25: Occurrences of tasks for each heart rate case

	Heart Rate Case									
Task	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
BA	10	17	6	8	4	4	5	8	6	8
BR	13	22	18	13	4	10	4	8	14	17
BS	23	29	4	23	6	21	7	12	6	3
EI	23	32	4	17	6	12	5	8	13	0
EO	85	174	68	77	41	49	40	59	80	86
ET	75	136	52	63	32	39	33	51	55	68
Total	**229**	**410**	**152**	**201**	**93**	**135**	**94**	**146**	**174**	**182**

Table 26: Occurrences of tasks for each respiration rate case

	Respiration Rate Cases							
Task	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
BA	10	17	14	8	5	8	6	8
BR	13	22	31	14	4	8	14	17
BS	23	29	27	27	7	12	6	3
EI	23	32	21	18	5	8	13	0
EO	85	174	145	90	40	59	80	86
ET	75	136	115	71	33	51	55	68
Total	**229**	**410**	**353**	**228**	**94**	**146**	**174**	**182**

Table 27: Occurrences of tasks for each heart rate variability case

	Heart Rate Variability Cases									
Task	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
BA	3	5	15	12	3	4	5	8	6	8
BR	4	9	19	31	4	10	4	8	10	17
BS	7	13	27	27	6	21	7	10	6	3
EI	5	14	29	21	6	12	4	6	12	0
EO	44	30	155	142	41	49	39	54	73	81
ET	39	28	127	110	32	39	32	42	51	61
Total	**102**	**99**	**372**	**343**	**92**	**135**	**91**	**128**	**158**	**170**

Data Distribution

A distribution for each case was generated and compared to a normal distribution using Goodness of Fit tests. Some distributions were found to be approximately normally distributed (as shown in Figure 21), but others were not (as shown in Figure 22). The majority of the respiration rate cases were found to be approximately normally distributed but the majority of the heart rate and heart rate variability cases were not. The fact that not all of the data sets were normally distributed indicated a need for a non-parametric analysis method. The distributions of all cases can be found in **Appendix D**.

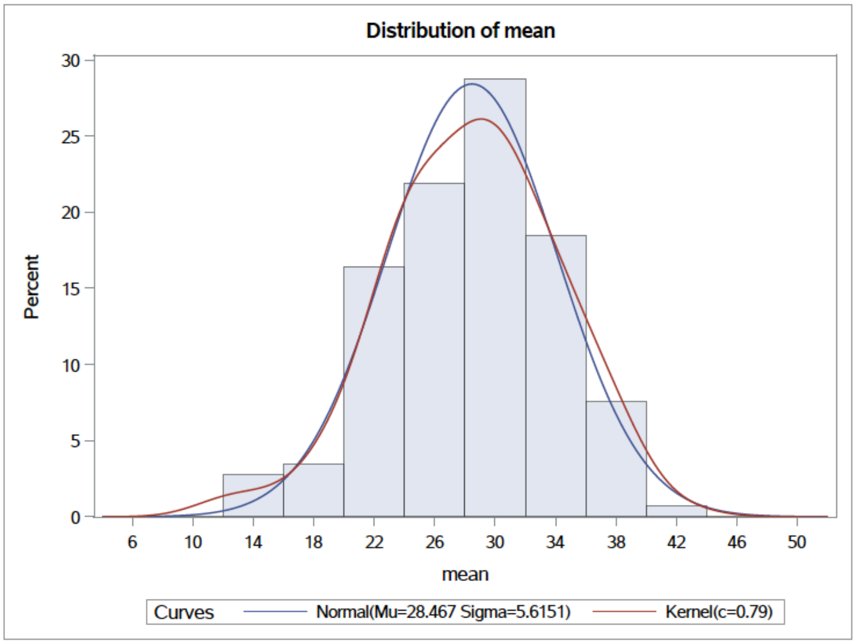


Figure 21: Normal Distribution (Respiration Rate Case #6)

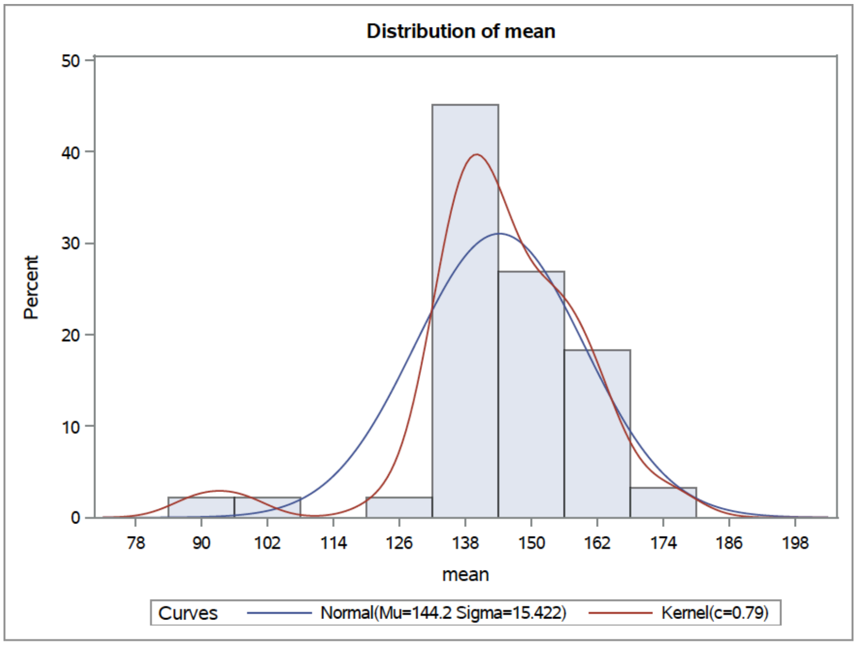


Figure 22: Non-normal distribution (Heart Rate Case #5)

Heart Rate

The mean heart rate responses for each case to different EVA-like tasks is shown in Figure 23. Each case is represented in a separate panel and those cases representing the same participant (during a different deployment) are the same color. The 10^{th} case is missing a bar as that participant never performed any instrument analyses during the simulated-EVAs in which they took part.

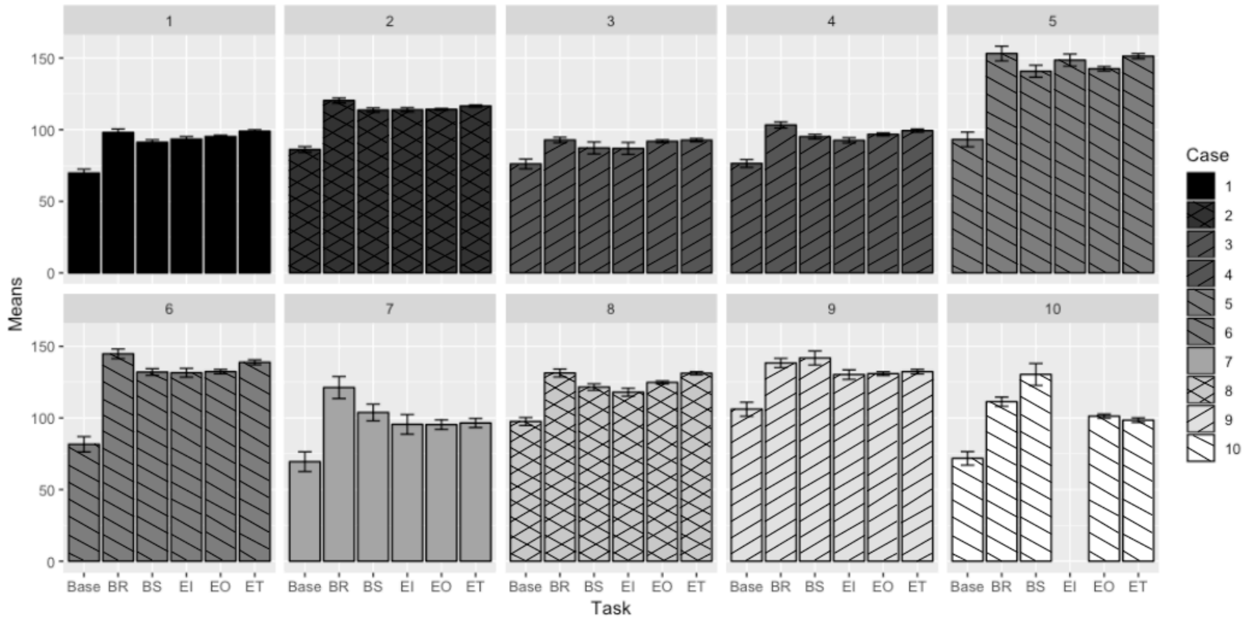


Figure 23: Case mean heart rate responses to EVA-like tasks

Table 28 contains the pairwise comparisons that were performed between the responses to each task. Each cell contains the least square mean difference (LSD) in the responses between the two tasks shown. If the 99.98% confidence interval (generated from the bootstrap analysis) associated with that pairwise comparison contained zero (meaning the difference was not statistically significant), then that cell was shaded. If the LSD shown is negative, this indicates the direction of the difference and means the second listed task elicits a larger response than the first task (e.g. if the LSD is negative for the Base-BR comparison, then the heart rate response to the breaking rocks tasks is larger than the baseline measurement).

Table 28: Differences in mean heart rate responses to EVA-like tasks

Participant	1	2	3		4		5	6	7	8
Difference	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**	**Case 10**
Base-BR	-28.29	-34.13	-16.59	-26.86	-59.79	-63.18	-51.82	-33.82	-32.07	-39.69
Base-BS	-21.26	-27.48	-11.09	-18.71	-47.69	-50.41	-34.34	-24.12	-35.61	-58.74
Base-EI	-23.64	-27.74	-10.68	-16.09	-55.27	-50.01	-26.36	-20.48	-24.07	
Base-EO	-25.34	-28.00	-15.74	-20.37	-49.42	-50.69	-25.70	-27.25	-24.60	-29.60
Base-ET	-29.15	-30.35	-16.57	-22.90	-58.14	-57.14	-26.97	-33.63	-26.06	-26.68
BR-BS	7.03	6.65	5.50	8.15	12.10	12.77	17.48	9.70	-3.54	-19.05
BR-EI	4.64	6.39	5.91	10.77	4.52	13.17	25.45	13.34	8.00	
BR-EO	2.95	6.13	0.85	6.49	10.36	12.50	26.11	6.57	7.47	10.09
BR-ET	-0.86	3.79	0.02	3.96	1.64	6.04	24.85	0.19	6.01	13.01
BS-EI	-2.38	-0.26	0.41	2.62	-7.58	0.40	7.97	3.64	11.55	
BS-EO	-4.08	-0.52	-4.65	-1.66	-1.74	-0.27	8.63	-3.13	11.02	29.14
BS-ET	-7.89	-2.87	-5.48	-4.19	-10.46	-6.73	7.37	-9.51	9.55	32.06
EI-EO	-1.70	-0.26	-5.06	-4.28	5.85	-0.68	0.66	-6.77	-0.53	
EI-ET	-5.51	-2.61	-5.89	-6.81	-2.87	-7.14	-0.60	-13.15	-1.99	
EO-ET	-3.81	-2.34	-0.84	-2.53	-8.72	-6.46	-1.26	-6.38	-1.46	2.92

Respiration Rate

Figure 24 demonstrates the mean respiration rate response to each task for each case.

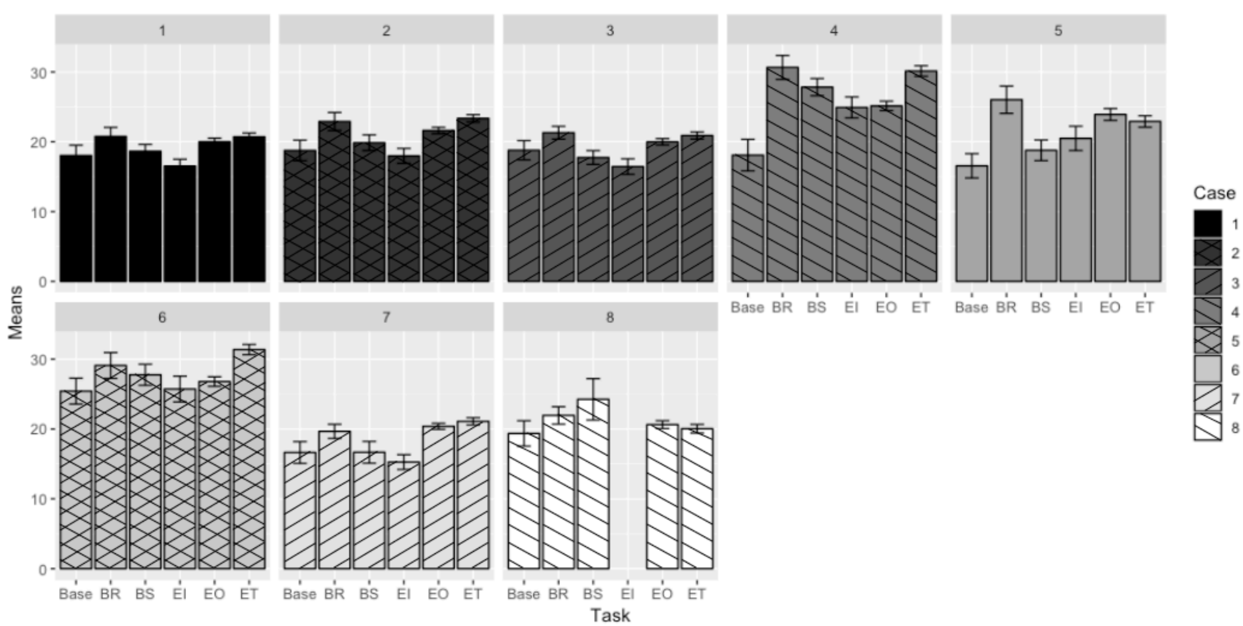


Figure 24: Case mean respiration rate responses to EVA-like tasks

Pairwise comparisons were also calculated for respiration rate responses to different tasks using the same method described for heart rate responses. These pairwise comparisons are presented in Table 29 and those differences that are not statistically significant are shaded.

Table 29: Differences in mean respiration rate responses to EVA-like tasks

Participant	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Difference	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
Base-BR	-2.78	-4.22	-2.49	-12.52	-9.45	-3.58	-3.10	-2.58
Base-BS	-0.65	-1.17	1.07	-9.69	-2.15	-2.39	-0.06	-4.91
Base-EI	1.46	0.74	2.35	-6.73	-3.96	-0.26	1.33	
Base-EO	-2.01	-2.88	-1.18	-7.01	-7.33	-1.31	-3.75	-1.26
Base-ET	-2.74	-4.64	-2.10	-11.92	-6.36	-5.91	-4.49	-0.65
BR-BS	2.13	3.05	3.56	2.83	7.30	1.19	3.04	-2.33
BR-EI	4.24	4.95	4.84	5.79	5.49	3.32	4.43	
BR-EO	0.77	1.34	1.31	5.51	2.12	2.27	-0.65	1.32
BR-ET	0.03	-0.42	0.39	0.60	3.09	-2.33	-1.39	1.93
BS-EI	2.11	1.91	1.28	2.95	-1.81	2.13	1.39	
BS-EO	-1.36	-1.71	-2.24	2.67	-5.18	1.08	-3.69	3.65
BS-ET	-2.09	-3.47	-3.16	-2.23	-4.21	-3.52	-4.43	4.26
EI-EO	-3.47	-3.61	-3.53	-0.28	-3.37	-1.05	-5.08	
EI-ET	-4.21	-5.37	-4.45	-5.19	-2.40	-5.65	-5.82	
EO-ET	-0.73	-1.76	-0.92	-4.90	0.98	-4.60	-0.73	0.61

Heart Rate Variability

Figure 25 demonstrates the mean heart rate variability responses to each task for each case.

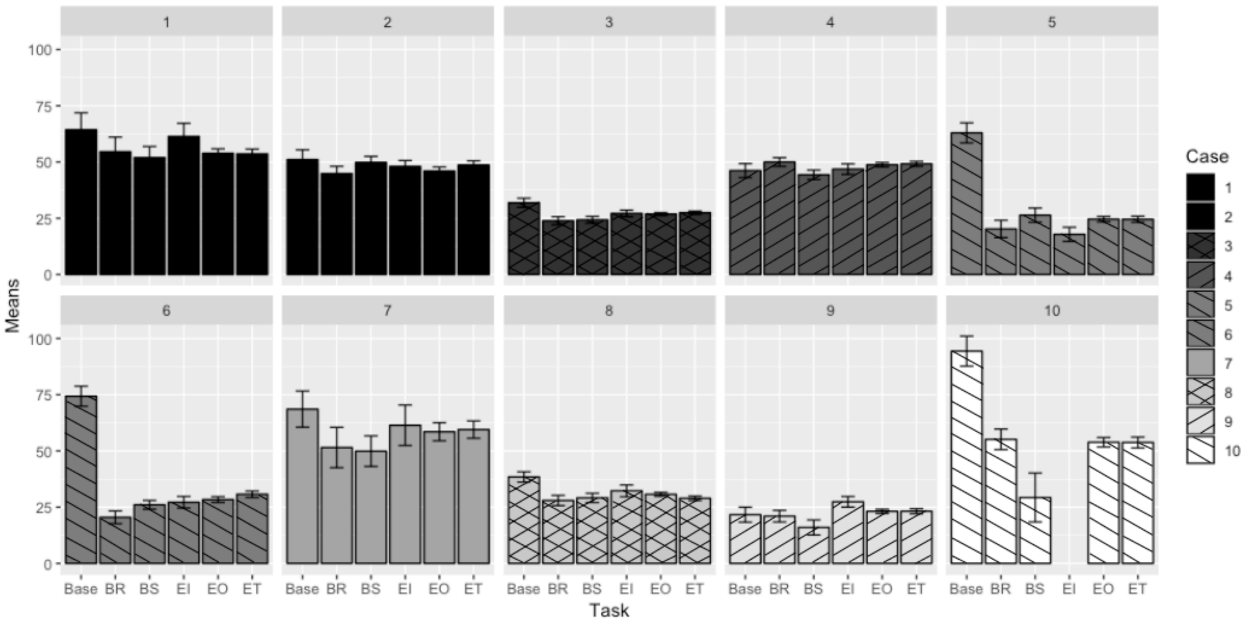


Figure 25: Case mean heart rate variability responses to EVA-like tasks

Using the same method described for heart rate and respiration rate responses, pairwise comparisons were made between heart rate variability responses to different tasks. These pairwise comparisons are shown in Table 30 and non-significant differences are shaded.

Table 30: Differences in mean heart rate variability responses to EVA-like tasks

Participant	1		2	3	4		5	6	7	8
Difference	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**	**Case 10**
Base-BR	9.71	6.25	8.11	-3.79	42.42	53.94	16.54	10.38	0.55	38.63
Base-BS	12.46	1.21	7.53	1.80	36.31	48.30	18.22	9.20	5.56	64.49
Base-EI	2.64	3.08	4.87	-0.57	44.85	47.31	6.82	6.07	-5.76	
Base-EO	10.49	5.14	5.12	-2.57	38.19	46.01	9.48	7.63	-1.63	39.80
Base-ET	10.72	2.32	4.48	-3.05	38.18	43.65	8.54	9.37	-1.70	39.90
BR-BS	2.74	-5.03	-0.57	5.59	-6.11	-5.64	1.68	-1.18	5.01	25.86
BR-EI	-7.07	-3.17	-3.24	3.22	2.43	-6.63	-9.71	-4.31	-6.31	
BR-EO	0.77	-1.11	-2.99	1.21	-4.23	-7.93	-7.05	-2.75	-2.18	1.17
BR-ET	1.00	-3.93	-3.62	0.73	-4.24	-10.30	-8.00	-1.01	-2.25	1.28
BS-EI	-9.81	1.86	-2.67	-2.37	8.54	-0.99	-11.39	-3.13	-11.32	
BS-EO	-1.97	3.92	-2.42	-4.38	1.88	-2.29	-8.73	-1.57	-7.20	-24.69
BS-ET	-1.74	1.11	-3.05	-4.86	1.86	-4.66	-9.68	0.17	-7.26	-24.59
EI-EO	7.84	2.06	0.25	-2.00	-6.66	-1.30	2.66	1.56	4.13	
EI-ET	8.07	-0.76	-0.38	-2.48	-6.67	-3.66	1.72	3.30	4.06	
EO-ET	0.23	-2.82	-0.63	-0.48	-0.01	-2.36	-0.95	1.74	-0.06	0.10

Parameter Responsiveness to Tasks

Table 31 summarizes the number of cases that demonstrate statistically significant differences in responses to pairs of tasks (presented out of the total number of cases considered in the analysis). This is also presented as a percentage due to the fact that one participant did not perform one of the tasks and therefore the totally number of cases considered for each pairwise comparison differs. The final column sums the differences detected and can give an indication as to which pairs of tasks are more likely to demonstrate differences in physiological responses across parameters. The final row sums the total number of differences detected in each parameter and gives an indication as to which parameter is the most responsive to changes in task.

Table 31: Number of Statistically Significant Differences Detected per Parameter

Difference	**HR**	**RR**	**HRV**	**Total**
Base-BR	10/10 (100%)	2/8 (25%)	7/10 (58%)	19/28 (68%)
Base-BS	10/10 (100%)	1/8 (13%)	8/10 (67%)	19/28 (68%)
Base-EI	9/9 (100%)	2/7 (29%)	4/9 (36%)	15/25 (60%)
Base-EO	10/10 (100%)	4/8 (50%)	6/10 (50%)	20/28 (71%)
Base-ET	10/10 (100%)	5/8 (63%)	6/10 (50%)	21/28 (75%)
BR-BS	2/10 (20%)	2/8 (25%)	3/10 (25%)	7/28 (25%)
BR-EI	3/9 (33%)	3/7 (43%)	1/9 (9%)	7/25 (28%)
BR-EO	3/10 (30%)	0/8 (0%)	2/10 (17%)	5/28 (18%)
BR-ET	2/10 (20%)	0/8 (0%)	3/10 (25%)	5/28 (18%)
BS-EI	0/9 (0%)	0/7 (0%)	4/9 (36%)	4/25 (16%)
BS-EO	2/10 (20%)	1/8 (13%)	3/10 (25%)	6/28 (21%)
BS-ET	5/10 (50%)	1/8 (13%)	3/10 (25%)	9/28 (32%)
EI-EO	1/9 (11%)	4/7 (57%)	2/9 (18%)	7/25 (28%)
EI-ET	3/9 (33%)	6/7 (86%)	3/9 (27%)	12/25 (48%)
EO-ET	1/10 (10%)	2/8 (25%)	0/10 (0%)	3/28 (11%)
Total	**71/145 (49%)**	**33/115 (29%)**	**30/145 (21%)**	**134/405 (33%)**

6. DISCUSSION

The previous chapter presented the results obtained from the studies included in this dissertation. This chapter will provide a discussion of these results including how they respond to the research questions, the significant findings and limitations of each study, and opportunities for future work that stems from the results obtained in this dissertation.

Study I Discussion

Information Streams and Relevant Timescales

Chapter 4 provided insights on what information streams are used to enable robotic scientific exploration on Mars; this includes both scientifically-relevant data streams and vehicle safety-relevant data streams. Though there are some differences between strategic and supratactical/tactical information streams, there is also significant overlap. Even information streams that were given different labels based on what participants were discussing on various timescales, a higher-level information stream could be conceived that encompasses multiple relevant strategic and supratactical/tactical information streams.

Though there was some mention from participants about similarities between the information relevant for rover operations and an imagined human mission to Mars, participants did not always go in-depth into exploring how different rover information streams were homologous to possible information streams to enable human Mars missions.

To explore homologous (as defined in Chapter 2 of this dissertation) information streams, the author created Table 32 by considering how the information streams mentioned by rover operations personnel would relate to human missions to Mars (using both the information given by study participants and the author's understanding of both rover and human space exploration). In some cases, information streams change little from rover operations to human operations (e.g. power). In other information streams (such as Astronaut Status), rovers are used as homologous systems to astronauts or other spacecraft that may be involved in the mission.

The first column in Table 32 denotes the information stream relevant to human exploration. The second column provides a description of the information stream. The third column provides the related rover information stream(s) (presented in Chapter 4) and the fourth column indicates for which timescale(s) the rover information stream(s) was(were) mentioned (with “S” representing strategic, “SuT” representing supratactical, and “T” representing tactical).

This table was constructed focusing on the performance of scientific EVA specifically. Though many of these information streams would be applicable to different types of EVA (or activities where astronauts do not leave the spacecraft), it was not the purpose of this table to be an exhaustive list of possible information streams for all potential astronaut activities. In fact, due to the fact that this list is derived from the insights of rover operations personnel, it is unlikely that this list is exhaustive even when considering scientific EVA.

Table 32: Human Mission Information Streams

Information Stream	**Description**	**Rover Homology**	**Rover Timescale**
Activity Duration	Time required in order to complete an activity/set of activities and the amount of time available to perform those activities.	Activity Duration	All
Activity Priority	The priority of planned activities.	Activity Priority	SuT/T
Astronaut Location	The locations/positions of astronauts on the surface.	Rover Location; Rover Position	All
Astronaut Status	Physiological, mental, and emotional health of astronauts. Includes in the short- and long-term.	Rover Status	All
Astronaut System Status	Status of systems meant to ensure the physical health of astronauts (e.g. life support systems).	Rover Status	All
Data Management	Considerations surrounding data storage and transmission management. Includes long-term planning of transmission windows and bandwidths.	Data; Orbiter & DSN	All
Decision Priority	The priority of each decision that needs to be made or piece of information that should be addressed.	Decision Priority	T
Drive/Traverse Path	Planned traverse maps/routes to be taken.	Drive Path	All
Experimental Conditions	The conditions (light, temperature, pressure, etc.) under which experiments/tests are run.	Experiment Conditions; Light Conditions	SuT/T

Table 32 continued

Flight Rules	Rules that govern and constrain how operations (including EVAs) can be run.	Flight Rules	S
In Situ Context	Details and contextual information of a location gleaned from in situ exploration of that location.	In Situ Context; Location Context; Surface Properties	S/T
Instrument Capability	The ability of an instrument/piece of equipment to perform a prescribed task.	Instrument Capability	T
Interest of Location	The scientific interest of current location. Includes the type of scientific interest and whether or not an area is scientifically interesting at all.	Interest of Location	S
Interesting Scientific Locations	The location of scientifically interesting areas on the surface of Mars.	Interesting Scientific Locations	S
Liens	Desired tasks to be completed.	Liens	SuT/T
Mission Elements	Coordination among mission elements (rovers, humans, etc.).	Rover Elements	T
Mission Goals	Overarching goals for the entire mission.	Mission Goals	All
New Capabilities	Strategic development efforts to enhance capabilities of personnel/equipment or to recover lost capabilities.	New Capabilities	S
Orbital Context	Details and contextual information gleaned from orbital imaging/data.	Orbital Context	S
Past Activities/Performance	Past activities performed and the performance of astronauts/robotic aids/etc. on the performance of those activities.	Past Activities/Performance	All
Power	Power availability, activity power requirements, and factors that affect power generation/usage.	Power	All
Recent Results/Findings	Results of recent tests/experiments/observations. Discoveries.	Recent Results/Findings	All
Required Activities	Activities that need to be performed to enable other activities, or to ensure crew/equipment health & safety.	Required Activities	SuT/T
Scientific Hypotheses	Asked research questions, hypotheses being tested, and priorities given to each research objective. Includes how activities relate to addressing these hypotheses.	Scientific Hypotheses	All
Scientific Targets	Specific activities to be performed on specific scientific samples/targets. Includes potential targets in the area.	Scientific Targets; Workspace	SuT/T

Table 32 continued

Spacecraft/Robot Location	Location of the spacecraft/habitat and any robotic assets.	Rover Location; Rover Position	All
Spacecraft/Robot Status	Health and nominal operations of spacecraft/habitat subsystems and any robotic aids.	Rover Status	All
Strategic Goals/Plans	Long-term plans. Includes desired observations, investigation locations, and activities.	Strategic Goals/Plans; Planned Activities	All
Tactical/Supratactical Plans	Short-term plans that heavily influence the specific activities performed by astronauts/robotic aids/etc.	Tactical/Supratactical Plans	SuT/T
Task Ordering	The constraints on the order in which certain activities/sets of activities need to be completed.	Task Ordering	SuT/T
Terrain	Terrain surrounding astronauts/robotic aids/etc. and whether that terrain can be traversed.	Terrain	All
Unexpected Occurrences	Unexpected events or conditions which can significantly impact current planned activities.	Unexpected Occurrences	All

As stated by a significant number of participants, human exploration will take place at a significantly quicker pace. That implies that many of the timescales described as relevant to rover operations will be compressed when considering human exploration. So, now that homologous information streams have been identified, it is important to identify on which timescales they will operate as they relate to *human* exploration (instead of rover exploration timescales, which is what is included in Table 32).

For rover operations, in addition to tasks being performed at a much slower rate, the quickest rover operations personnel can receive updates from the rover is once or twice a day (making that the shortest timescale). However, there are many information streams listed that, if it were possible to perform tasks at a quicker tempo, would update much more frequently than once or twice a day. For example, rovers perform a select few scientific instrument activities each day. A human performing these same observations on Mars could take multiple measurements every hour. If decisions are going to be made within an EVA based on the results of those instrument readings, then astronauts are going to need to be responsible for the processing and decision-making based on this information stream; the restrictions on bandwidth, transmission windows, and time-delayed communications would make it essentially impossible for Earth-based personnel to make decisions relevant to the EVA being performed. This serves as an important illustration of the increased levels of autonomy with which astronauts are going to have to operate on Mars; far more autonomy than rovers and even humans performing EVA in low-Earth orbit.

It is important to note that the idea of astronauts using instruments to inform decisions made within the same EVA is an assumption made about the architecture of a future mission to Mars. It assumes that scientific EVAs will resemble traditional field science on Earth. There are other architecture possibilities—all of which will still have a much quicker tempo than current rover operations—that involve reconnaissance EVAs or using rovers to survey areas/take instrument readings. In order to more specifically determine on what timescales information streams operate during human Mars missions, an architecture needed to be chosen. For the purposes of this discussion, the traditional field science model of scientific EVA was be adopted.

Using information gleaned from study participants and the author's understanding of human exploration, relevant timescales were given to each of the information streams identified in Table 32. It is important to note that this analysis represents the author's opinion and is based on the author's assumptions; others may deem different timescales as relevant to particular information streams.

The information streams identified were relevant across multiple different timescales, as shown in Table 33. Table 33 has a red line separating the "hours" and "days" timescale as the author determined that if an information stream is relevant on an hours-or-less timescale, that the time-delay on communications and constraints on transmissions between Earth and Mars would make it impossible or infeasible to have Earth-based personnel completely responsible for monitoring/processing that information or making time-sensitive decisions based on that information.

Table 33: Human Mission Information Timescales

	Relevant Timescale						
Information	**Seconds**	**Minutes**	**Hours**	**Days**	**Weeks**	**Months**	**Years**
Activity Duration							
Activity Priority							
Astronaut Location							
Astronaut Status							
Astronaut System Status							
Data Management							
Decision Priority							
Drive/Traverse Path							
Experimental Conditions							
Flight Rules							
In Situ Context							
Instrument Capability							
Interest of Location							
Interesting Scientific Locations							
Liens							
Mission Elements							
Mission Goals							
New Capabilities							
Orbital Context							
Past Activities/Performance							
Power							
Recent Results/Findings							
Required Activities							
Scientific Hypotheses							
Scientific Targets							
Spacecraft/Robot Location							
Spacecraft/Robot Status							
Strategic Goals/Plans							
Tactical/Supratactical Plans							
Task Ordering							
Terrain							
Unexpected Occurrences							

Rationale behind the timescales allotted to the various information streams is provided below. The information streams are grouped by timescale (those streams operating on the fastest timescales first). Information with related explanations are explained together.

Astronaut Location & Spacecraft/Robot Location

When astronauts perform EVA, IV crewmembers will want to be able to track their location in real-time. In fact, if possible, Mission Control/Support will want to track EV crewmember position in as close to real-time as possible (subjected to delayed communications). Having real-time updates on crewmember location (by GPS, for example) would allow IV crewmembers to guide EV crewmembers to specific locations or warn them of hazards that may be along the route. Similar reasons exist for wanting to know the location of robotic assets (such as rovers). If astronauts are tele-operating rovers on the surface, it would be useful to be able to determine their position with respect to areas of interest. It would also be critical to keeping track of those robotic assets.

There are also long-term interests in tracking astronaut and spacecraft/robot location. This would provide details on exactly what areas were explored on the surface. Also, if astronauts have access to a mobile habitat/spacecraft, then its location may change on a monthly basis. Astronaut and spacecraft/robot locations would ideally be tracked throughout the duration of the mission (which the author assumes would be many months), so timescales from “seconds” to “months” are relevant for these information streams.

Astronaut Status, Astronaut System Status, & Spacecraft/Robot Status

Astronaut health and safety considerations are going to be the highest priority of any mission to Mars. For that reason, information about the physiological, mental, and emotional health of astronauts is going to be collected and monitored at varying timescales throughout the mission. Physical health is going to need to be continuously monitored throughout the performance of EVA, as will the status of the systems that keep astronauts alive during these activities (life-support systems) and the status of the habitat/spacecraft. Similarly, if any robotic assets are going to be used, their status will need to be monitored as well. Something adverse could happen to either the astronaut, the life support systems, or the spacecraft very quickly, and it would require immediate action.

The status of all these systems (including the astronaut) will also be monitored long-term throughout the mission to ensure astronauts maintain their physical health, astronauts are psychologically healthy, and that there is no long-term degradation to any system (or if there is, it is documented, planned, and actions are taken to compensate for the degradation).

Data Management

Though there will likely be more onboard storage aboard the spacecraft housing humans than that aboard current Mars rovers, there may still be limits on data storage. This may be in the form of limits to storage availability in the field (e.g. local storage on instruments). There will also be considerations regarding how much data can be transmitted to Earth, and when those transmissions can occur.

Each time an astronaut collects data, it will be important to ensure that there is enough available storage for that newly acquired data (at least until it can be transmitted to Earth or offloaded to a larger onboard data storage repository). Once that data is collected, it will be important to plan when to send what data to Earth. Collection of new data can happen on a "seconds" timescale (if trends in continuous updating data—e.g. physiological data—is stored for later processing) and the transmission windows could potentially be determined on a "months" timescale.

Decision Priority

This is the only information stream that the author allocated entirely to in-space crewmembers. Because this information stream deals with prioritizing decisions that need to be made or information that needs to be addressed, it assumes that there is a limited amount of time to process information or make decisions. If a decision needs to be made over the course of multiple days, then there is likely enough time to make all required decisions or process all relevant information (especially if that information can be processed by Earth-based personnel). For that reason, this information stream was deemed relevant over "seconds" to "hours" timescales.

Drive/Traverse Path

The drive or traverse path is relevant to all timescales. Once the landing site has been chosen, preliminary traverse plans can begin to be developed to plan EVAs or, if the spacecraft is mobile, where different habitat waypoints may be established. Once astronauts are on the surface, more specific traverse plans can be developed as the planned EVA approaches.

While the EVA is being performed, the astronauts are going to need to keep track of their positions (which may update second-to-second) with respect to the planned traverse. Depending on hazards that may not have been visible from orbital maps, the traverse plan may have to change during the performance of the EVA.

Mission Elements

In order to ensure the success of a human mission to Mars, there will be many mission elements (such as astronauts, rovers, robotic aids, automation, satellites, etc.) that need to be coordinated to work together effectively and to not interfere with the proper performance of other mission elements. The coordination of these various elements can take place over a variety of timescales. When considering the coordination of robotic aids or rovers with astronauts while performing EVA, it will be important to consider how these elements work together to avoid interference on a second-by-second or minute-by-minute basis. When considering communication windows between satellites or with satellites and Earth or Mars, some of the coordination surrounding which elements transmit to which satellites and during which times can occur months in advance of those transmissions taking place. Other element coordination may be detailed in specific EVA plans developed on days to weeks timescales.

Power

Much like life support resources (e.g. oxygen), it is going to be critical that electrical power availability is monitored to ensure that there is enough to keep the astronauts alive and all the instruments/equipment working throughout the duration of the EVA. Power availability changes continuously and should therefore be continuously monitored during EVA (and during the entire mission) as the majority—if not all—of the systems responsible for keeping humans alive on the surface will required electrical power.

Understanding the power requirements of various activities and the total available power that can be used/generated/stored will be important for planning EVAs to ensure that power requirements do not exceed availability. If electricity is generated through solar power, it may also be necessary to adjust power generation values depending on seasonal changes in sunlight availability or intensity, or other factors that may influence generation capabilities. Power generation trends can also be tracked throughout the mission duration to determine if there is any degradation in the power systems.

Unexpected Occurrences

Unexpected occurrences can occur quickly (e.g. if an airlock breaks). The results of an unexpected occurrence can also demand immediate action and/or can have lasting impacts on the capabilities of the crew/equipment to be able to perform certain activities or meet certain goals. In some cases, unexpected anomalies can threaten the entire mission. For that reason, this information stream stretches across all timescales relevant duration of the entire mission (all but the "years" timescale).

Activity Duration & Activity Priority

Due to resource limitations (e.g. oxygen levels) it is going to be important that EVAs are planned while keeping resource usage in mind. A key component of EVA planning is the time it takes to perform certain activities. While performing EVA, it will also be important to know how long a task will take to complete and whether there is enough time or enough available resources to complete the task.

Similarly, different tasks will have different priorities based on various factors (e.g. scientific findings, health & safety considerations, etc.). This will inform the planning of EVAs and how to choose between different activities if there are limitations that influence whether or not all desired activities can be completed.

The author assumed that detailed EVA plans would be developed weeks before they are scheduled to be performed; this would give EVA planners the opportunity to respond to recent discoveries while still being able to generate and review a detailed plan. In addition to this, astronauts are going to need to follow a timeline and keep track of the duration of planned activities on a minute-by-minute timescale. For these reasons, both these information streams stretch from a "minutes" to "weeks" timescale.

Experimental Conditions

It will be important that astronauts document and are aware of the conditions under which they run tests or experiments. Certain experiments may have prescribed conditions that need to be met or the results may be affected by changing conditions. It is possible that these experiments will take a few minutes, or multiple hours, depending on the instruments or equipment sent to the surface.

The documented experimental conditions will also be relevant to those looking at the results over the longer-term, especially if the interpretation of those results is significantly affected by the conditions under which the experiment took place. It is likely that scientists interpreting the results of these experiments weeks or months after they were performed will need to know the conditions under which they were performed.

In Situ Context & Orbital Context

As stated by multiple study participants, features can appear very different when comparing orbital and in situ perspectives. Orbital information about different areas on the surface can be collected years before humans visit that particular location. In situ data can only be collected when a human or robotic aid goes to the location to explore. These information streams are closely related because, as expressed by multiple participants, interesting sites that have been identified through orbital imaging have to be explored in situ to gain the full context of the feature of interest. Contrarily, observations made in situ are often compared to orbital data on the same location.

In situ context can change on a "minutes" timescale as astronauts explore different locations on the surface, and the synthesis of all the collected information in situ can occur throughout the mission duration. Similarly, because of the speed at which in situ data can be collected with human exploration, comparisons with orbital data can occur on a similar timeline (e.g. placing a feature identified in situ in the context of an orbital image). Orbital context can be collected before the mission occurrence which is why it is also relevant on a "years" timeline, whereas in situ context is not.

Instrument Capability

When planning and executing an EVA, it is important that the capabilities of the instruments and equipment available on the surface are well known. During the EVA, the astronauts will need to understand the field of view, precision, and other aspects of instrument performance. This will affect what can and cannot be accomplished with which piece of equipment. This will also need to be considered when creating specific EVA timelines and scheduling certain activities—if the activity cannot be performed with the available equipment, then that activity cannot be implemented into a plan. It is assumed that detailed EVA plans will be generated up to a few weeks in advance of the performance of the EVA.

Past Activities/Performance

Especially during the first human mission to Mars, experiential knowledge will be gained on what activities are possible in which conditions/environments, and how various crewmembers or robotic aids perform in those conditions. The knowledge can then be used to inform astronaut approaches to certain tasks, or the plans created for EVAs. In some ways, astronauts will learn from their own activities during an EVA (i.e. they try to perform a specific activity which was unsuccessful due to some change in environmental conditions) which will inform their approaches to activities in that same EVA (i.e. they take a different approach to that failed activity) as well as future EVAs. Over the long-term, astronaut or robotic aid performance on certain tasks may affect how future EVAs/missions are planned and may be tracked to give an indication of robot system deterioration.

Recent Results/Findings

By collecting information with various different instruments and through different experiments, it is possible that the results of a test conducted generate some surprising or breakthrough scientific discovery/result that may affect the plans for future EVAs or tests to be run. This could happen within an EVA (e.g. a surprising instrument reading) affecting how much time is spent in an area or what kinds of further tasks are performed. It can also happen outside of an EVA with tests that are run in the habitat, or analyses that are conducted by personnel on Earth. Recent findings have the possibility of changing scientific hypotheses or changing the priority of research questions being investigated. This could have a significant change on the activities that are performed throughout the mission.

Scientific Targets

Potential areas for investigation and points of interest can be identified weeks in advance of an EVA taking place. However, once astronauts arrive at the specified location, in situ context may change the scientific value of the proposed sites. In addition to this, even if a specific exploration site is scientifically interesting, astronauts will need to decide which specific rocks/locations are best suited to take instrument readings, perform tests, or sample. Astronauts will need to select targets that are accessible and address specified scientific hypotheses or research questions. Should such targets be available in the exploration area, they will also need to decide which instrument readings to take or tests to perform on which targets. There may be multiple targets that would be appropriate for further investigation so those targets will also need to be prioritized.

Strategic Goals/Plans & Tactical/Supratactical Plans

Strategic goals and plans will influence the locations astronauts explore, the types of EVA that will be performed, and the paths they take to reach different locations on the surface. They will also inform short-term (tactical/supratactical) plans, including detailed EVA timelines. Setting these long-term plans and goals will occur on a long enough timescale that it can remain under the purview of Mission Control/Support. Though astronauts should be aware of the strategic plans, there is no processing or monitoring of that particular information stream that they will need to do.

Short-term plans will be one of the most significant information streams during the performance of EVA as it will inform the tasks and activities that astronauts will need to perform on Mars. Tracking astronaut progress as compared to the plan and documenting which activities were and were not accomplished will be very important to ensure that astronauts are performing the desired activities in order to maximize scientific output. Tactical plans could be created by personnel on Earth before the EVA occurs and astronauts would be able to provide feedback on those plans if necessary. Tracking progress through the planned timeline would likely be on a minute to hours scale (it is unlikely that tasks would be scheduled in increments smaller than minutes).

Task Ordering

When detailed EVA plans are created, it will be important that if there are tasks that must be performed in a certain order, that those tasks are scheduled in that order; this can occur weeks or days before the EVA is performed. During the course of the EVA, astronauts should be aware of scheduled tasks that must progress in a specific order to ensure that any unexpected changes they make to the plan do not have unexpected consequences for a more significant portion of the plan.

Terrain

The terrain around the astronauts during EVA will ultimately determine where they will explore and what route they will take to get there. Terrain can be evaluated in advance to create traverse routes and paths, and astronauts can respond to terrain as they approach potential points of interest. The slope of hills, the softness of the ground or the profile of rocks may affect an astronaut's ability to reach a desired destination. Features of the terrain can provide contextual information that is useful for scientific research. During an EVA, astronauts should remain aware of the terrain and potential hazards around them as they traverse to different locations (likely on a minute-by-minute or hour-by-hour basis). Terrain should also be considered by Earth-based personnel planning EVAs and strategic traverse paths.

Flight Rules

Flight rules are going to be developed before humans set foot on Mars, but they may evolve based on experiences performing EVA on Mars (especially during the first human Mars mission). Astronauts will need to keep flight rules in mind while performing EVA (e.g. if there are time limitations on EVA, that they are not exceeding the allowed time) and if there are any changes that need to be made to the planned activities. The author assumes that flight rules will not dictate EVA time allowances on timescales shorter than "hours" and will therefore have relevance to astronauts on that timescale.

Interest of Location & Interesting Scientific Locations

Much like rover missions, potential landing sites and exploration areas will be identified well before the mission begins. The different potential scientific research questions that can be investigated in various locations will be discussed and decided upon by the scientific community on Earth. So, the overarching interest of particular areas and the locations that astronauts will visit will be determined years before humans are on Mars.

In the shorter-term, there may be smaller areas of interest within the landing site or exploration areas. EVAs can be planned days and weeks in advance with the purpose of investigating particular locations. The specific interest of those locations (e.g. geological vs. astrobiological) would dictate some of the tasks that may be completed. Both of these information streams and the processing and decision-making involved with them were deemed not to be especially relevant on timescales shorter than "days". This is because, aside from being aware of the interest of each location and the purpose of the EVAs, it is likely that the exploration areas will be decided upon well-before the EVA is performed and the astronauts will not be concerned with the selection of exploration areas.

Liens

It is likely that certain EVAs will deviate from plan or will need to be ended early due to unexpected occurrences. This indicates that is it likely that there will be planned or desired tasks that are not completed due to deviations from initial EVA plans or because there were too many tasks to fit into a specific plan. This will create a "to do" list of activities to be integrated into future plans. Since detailed EVA planning can occur days before the EVA is scheduled to be performed (and therefore planned by Earth-based personnel), it was determined that liens could also fall under the purview of Mission Control/Support. It would be unlikely and unadvisable that space-based crew try to fit in more activities than what are outlined in the plan, and therefore they would have less interest in the "to do" list of future tasks, than those planned for the current EVA.

Mission Goals

Mission goals will be established years before humans are on the surface of Mars. Most of these goals will be determined and adjusted by the scientific or engineering community on Earth and communicated to the astronauts on the surface. However, it will be important that astronauts are able to relate the tasks they will be performing during EVA to the overarching mission goals, especially when it comes to selecting scientific targets and collecting science. This may alter the approach that astronauts may take when approaching a point of interest or the types of tests they may run (if those tests aren't specifically outlined in the EVA plan) but will remain constant throughout the EVA.

New Capabilities

As experience is gained having humans perform various tasks on Mars, it is possible that new capabilities are developed for the equipment used on Mars (e.g. new ways to use instruments to measure different things). In addition to this, it is possible that capabilities are lost as instrument systems are damaged or experience errors. There will be efforts of personnel on Earth (and astronauts on Mars as well) to regain those lost capabilities. It is likely that regaining lost capabilities will takes days or longer and the development of new capabilities may take months or years to develop and prepare for implementation in human missions. For this reason, Mission Control/Support will be able to take the lead on new capability development and capability recovery efforts.

Required Activities

If certain activities need to be performed, they will be included in specific EVA with high priority to ensure that they are accomplished. Because EVA plans will likely be generated days before EVAs take place, it is likely that the inclusion of required activities into EVA plans will remain under the purview of Mission Control/Support. It is unlikely (and inadvisable) for required, mission critical activities to be fit around existing plans by in-space crewmembers during the performance of an EVA. Because of this, the information stream was deemed relevant on timescales from "days" to "months", depending on if they are reoccurring and how far in advance they can be planned.

Scientific Hypotheses

Even when surprising scientific results are obtained on the surface, new scientific hypotheses will likely only be generated on a daily (if something especially surprising is found) or longer schedule. It is also likely that these hypotheses will be generated by the scientific community on Earth and then communicated to the astronauts in space. While it is important that the astronauts are aware of the scientific hypotheses being tested or the research questions being asked (and the priorities of each) to ensure that they are performing activities in a way that helps answer those research questions, it is unlikely that they will change over the course of an EVA.

Automation Opportunities/Development

Now that the information streams that astronauts on Mars will be responsible for processing or monitoring have been identified, it is possible to identify the information streams which could be well-suited to automated monitoring.

The author determined which information streams would be best suited to automated monitoring by considering a variety of factors. Current work that has demonstrated the effective automation of some of the information streams was considered. In addition, the types of data associated with the information (e.g. images vs. numerical values) and the simplicity with which computers can process that information (e.g. it is more difficult for a computer to interpret an image than to track trends of a numerical value). Finally, the type of information processing required was also considered. Information streams for which a consistent protocol could not be generated (e.g. unexpected occurrences), that required critical thinking, or that demanded a piece of information be interpreted with respect to contextual information (e.g. whether a particular rock is scientifically interesting) were considered difficult to automate and should remain under the purview of humans on the surface. Information streams for which firm rules could be established (e.g. tasks that must always be performed in the same order), or that involved tracking trends in a numerical value or comparing a numerical value to a threshold (e.g. current power level as compared to a threshold power level requirement) were considered comparably simple to automate and were therefore identified as likely candidates for automation development.

The following sections look at the information streams that operate on timescales too short to leave them under the purview of Mission Control/Support and discuss which are best suited to automation.

Timeline Management

As mentioned in Chapter 2, there has been work done in the development of timeline tracking/activity planning support tools for EVA. Many specific information streams could be automatically processed or monitored using a well-designed timeline management tool. Specific tactical plans that are developed for each EVA could be input into the tool in a way that allows astronauts to track their progress through the plan. Constraints could be put on the creation/editing of those plans that take into account flight rules (e.g. an EVA has a maximum total allowable time limit) or task ordering constraints (e.g. a task cannot be put into the plan unless the required associated tasks are input first). The duration of each activity, the activity priority, and the amount of time available to complete the EVA could also be shown in the tool.

The Playbook timeline tool discussed in the literature review takes many of these specific information streams into account (Marquez et al., 2019). The fact that the same specific information streams or requirements for a useful timeline tracking/planning tool were obtained using different methods is an encouraging indication that the information gained from this study is useful and relevant to human Mars exploration.

Data Management

There are many potential ways that effective data management can be achieved through support tools during a human mission to Mars. Participants in this study discussed the limited onboard storage on a Mars rover, and how ensuring that there is enough storage capacity onboard the rover is an important consideration when planning activities. Though limitations on storage may not be as significant a concern for astronauts in the spacecraft or habitat, it is possible that data collected in the field may be stored in repositories in the field (e.g. instrument data is stored on local instrument hard drives) where there may be more of a concern about onboard storage. If such an architecture is adopted, then it would be advisable to have an automated support system that monitors the available storage "in the field" during an EVA and alert IV crewmembers if space is becoming limited. It would be ideal if that automated tool was integrated with the timeline tracking tool to predict the amount of data generated by specific activities and compare it to the available data storage to alert astronauts if there is a risk of exceeding the available storage.

Transmitting data back to Earth is also going to be a significant consideration during human missions on the surface as the scientific community will want access to the collected data in as close to real-time as possible. Since communication windows can be predicted in advance, it is possible to create an automated support system that keeps track of when communication windows will occur and the amount of data that can be transmitted within that window. If data were tagged with a priority or some other characteristic, the automated system could automatically transmit the data within the communication window; if there is limited onboard storage, the system could automatically delete the data from onboard storage repositories transmitted to Earth once it receives confirmation that the data was successfully received. If human activity is necessary to allow the transmission of data during these communication windows, then this automated system could also interface with the timeline/activity planning tool to inform astronauts when the communication windows will occur, and the activities they need to perform within those windows.

When considering the storage of the data collected, an automated support tool could tag the collected data with relevant information (e.g. date collected, instrument used, location where data was collected, etc.) to allow it to be easily searched. This is a feature that is included in the xGDS software tool discussed in Chapter 2 (Marquez et al., 2019).

Power

Electrical power is an important resource during EVA. It is therefore going to be important to have some power level monitoring function throughout mission activities. Power levels for various systems, instruments or pieces of equipment could be monitored by an automated support system that continuously updates power availability and could present the information as a percentage of total possible power availability (similar to a fuel gauge in an automobile). The system could alert astronauts if the power levels fell below a predetermined level. Another potential feature of a power monitoring system (which is slightly more complex than a simple power percentage display) could be a countdown clock that takes into account power usage rates and estimates the time until power levels reach an unacceptably low level (a level that could be determined prior to the mission). Because power usage would vary depending on the activities being performed, the power monitoring system could potential interface with the timeline tracking tool to estimate power usage during the activities planned for the EVA to generate a more accurate countdown clock.

Astronaut Status

While there are aspects of astronaut status that operate on longer timescales (e.g. psychological well-being) the aspects that indicate short-term health and safety will need to be monitored during EVA such as core body temperature, heart rate, respiration rate, or pulse oximetry. This idea was addressed in the author's previous work (Hill, 2017) and in the second study of this dissertation. More details on how certain physiological parameters may be monitored by an automated system are discussed later in this chapter, but there are likely multiple different methods of automated physiological monitoring. A simple method could be to specify upper and lower bound values for each parameter and have the system alert the astronauts if a physiological measurement is outside the desired operational range. More complex monitoring algorithms could have differing operational ranges depending on the activity being performed and could interface with the timeline tracking tool.

Life Support Status

Monitoring short-term astronaut health and safety will also require the monitoring of the systems required to keep them alive. Aside from monitoring the power levels of the necessary life support system components (already mentioned), there will also be other life support resource levels that can be monitored in similar ways such as oxygen or water levels. Like power monitoring, these resources can also be presented as a percentage of total capacity and/or as a countdown clock displaying the amount of time until the resource levels drop below an acceptable level. As with other resource monitoring, if different consumable usage rates are known for different activities, then the system responsible for monitoring consumable usage could interface with the timeline tracking tool to give a more accurate countdown clock estimate.

Aside from consumable usage, all the subsystems of the life support system should be monitored (similarly to how the subsystems of a rover provide a “safe” or “sick” reading) to ensure that they are working nominally. If a subsystem displays an anomaly, astronauts should be alerted immediately so that the anomaly can be investigated, the problem can be fixed, or (in extreme cases) the EVA can be terminated.

Spacecraft Status

There are various spacecraft that are integral to the success of an EVA. One such spacecraft is the one housing the IV crewmembers. Throughout an entire mission, including the during the performance of an EVA, the habitat subsystems will need to be monitored to ensure that they are operating nominally. Many of these subsystems will be necessary to keeping astronauts alive (e.g. pressurization systems). Because the habitat spacecraft will likely have many complex subsystems, it would be ideal to have them continuously output a “sick” or “safe” measurement (similar to Mars rover subsystems) that can be monitored by an automated system. If one of the subsystems outputs a “sick” reading, then the astronauts can not only be alerted that there is a problem, but there will also be an indication as to which subsystem (and which part of that subsystem) is having the problem. This will likely expedite the diagnosis and treatment of the anomaly.

In addition to spacecraft that house astronauts, there are also mission architectures that will rely on robotic aids during EVA (e.g. rovers). Similar to how an automated system could monitor the subsystems of the habitat, another system could monitor the subsystems of the robotic spacecraft that are assisting during EVA to ensure that they are also operating as intended.

Path Planning & Astronaut/Spacecraft Location

As discussed in Chapter 2, there have been efforts to develop path planning tools that take into account terrain, distance, time, and metabolic expenditure to create the most efficient path between two points (Marquez, 2007; Marquez et al., 2019). This automation could be useful in providing a suggested path for astronauts during EVA. However, as discussed by participants in the study, humans are fairly skilled at finding paths through difficult terrain and therefore may not exactly follow the paths outlined by the tool. In addition to this, one of the motivations behind observing an area in situ is that more information and context is gathered by having an agent on the surface at the location of interest. Therefore, the path outlined may not be followed because something of scientific interest was seen off the outlined path.

However, having a planned path can be a useful guideline for planning EVA traverses and giving EV and IV crewmembers a geospatial plan that they can follow. By having areas of interest on a map and if the locations of astronauts/rovers are shown in real-time on that map (e.g. via GPS), then the path planning tool could alert IV crewmembers if astronauts or rovers are straying too far from the planned path and/or into a hazardous area. It is also possible that if astronauts stray too far from the path that they could contaminate future exploration sites.

Experimental Conditions

Different tests performed could require different experimental conditions depending on what test is being performed and on what target. Having a record of the conditions under which an experiment took place can be important to the future interpretation of the results of that experiment. There are a couple forms of automation that could be developed to ensure that required experimental conditions are reached and documented. First, an automated system could automatically document the experimental conditions of a test or experiment (e.g. time of day, temperature, duration of experiment, etc.) and store that information with the results of the test. This would ensure that all relevant information is associated with the data collected from the test. If different experimental conditions are required for different tests, then it is also possible that presets could be programmed into the instruments or equipment used to run the test. This way, astronauts could select the test that they want to perform, and the test will be run with the required experimental conditions used.

Instrument Results

The results of tests performed by instruments are a major component of identifying interesting scientific trends or surprising readings (recent results/findings, or "discoveries") during rover operations. For current Mars rover operations, the rover sends back the raw data from the instrument tests which then need to be processed and analyzed by scientists on Earth in order to gain scientifically interesting information (e.g. spectra need to be converted into chemical compositions to be useful to the scientific community at large). It is likely that few of the crew will be scientists who are truly able to interpret the raw data from the instruments. It will be critical that instruments used during EVA be able to do this raw data processing and analysis automatically and as quickly as possible in order to allow astronauts to react to scientifically surprising results in real-time. By providing useful information in real-time, EV crewmembers will be able to investigate surprising results further and will likely be able to collect more valuable information to investigate these occurrences.

Mission Element Interference

A human mission to Mars will require the use of many complex systems and there is the possibility that, in certain conditions, those various systems and mission elements could interfere with the nominal operations of other mission elements. Coordinating the actions of various humans, robots, and automated systems will require a significant effort, much of which could be helped with automated support tools.

It is possible that safeguards could be programmed into various systems to alert astronauts if a set of activities is about to be performed that would interfere with another mission element. This automation would likely be complex as would require that various subsystems be aware of what other subsystems are doing and comparing that to planned activities. A more sophisticated automated system could interface with the timeline planning/tracking tool to ensure that tasks which cause interference between mission elements are not planned at the same time (a planning constraint).

Information Streams Poorly Suited to Automation

There are information streams identified that will need to be processed and monitored by astronauts on Mars that are not well-suited to automation. Many of these information streams are related to the synthesis of the collected scientific information in order to determine what is and what is not scientifically interesting. Most of the context collected in situ or through orbital means will need to be processed by a human in order to place that context within the scientific hypothesis being tested or relate that context to current scientific paradigms. Similarly, determining what are scientifically interesting targets is often based on various qualitative information (e.g. color, texture, location, shape) which is not easily assessed by machines. Therefore, astronauts will need to use their own scientific expertise to identify potential scientific targets. In addition to this, while instrument data processing can be automated to provide useful information quickly, determining whether those results are surprising or interesting will likely depend on a lot of this contextual information and astronauts will therefore need to use their own scientific judgement to assess how interesting or surprising a piece of information is.

While the automation of monitoring certain aspects of astronaut/robot/spacecraft location were discussed with a path planning tool, much of this information will need to be processed and monitored by humans. Unless there are specific areas in which astronauts should not traverse, assessing how far is too far to stray from a planned path, and determining where an astronaut or spacecraft is in a given moment is likely contextual information that will need to be assessed by astronauts. Similarly, while terrain maps can be used to develop suggested path plans, much of the details of the terrain surrounding an astronaut or robot will be assessed by astronauts in situ and will feed into some of the scientific assessments made about the area of interest.

While certain activities could suggest methods of use for certain instruments or pieces of equipment, it will be expected that astronauts learn the capabilities of the instruments they will be using for EVA before the mission. It is also possible that astronauts will learn more about instrument/equipment capabilities as they gain experience performing EVA on Mars. Similarly, past activities and the performance on those activities will also give astronauts experiential knowledge that would be difficult to automate. It is possible that trends in activity performance could be used to adjust automation algorithms (e.g. the time duration of certain tasks) but it is likely that astronauts will simply adjust their approaches to tasks and activities as they gain experiential knowledge.

Finally, in order to automate a system to perform a task during a mission to Mars, there needs to be an understanding of the function that that system is performing. By definition, unexpected occurrences are unexpected and therefore cannot be completely prepared for or eliminated. For this reason, it is unlikely that an automated support system could be developed that would account for all possible unexpected occurrences. Astronauts will need to respond to unexpected occurrences using the knowledge and experience they gained through training and their own expertise. Similarly, the priority of certain decisions or pieces of information may change based on the situation in which the decisions present themselves. For the same reason that an automated tool cannot account for all occurrences in an environment this complex, it is unlikely an automated tool could assess the priority of decisions or information in every possible situation.

Personnel Coordination & Mission Architecture

As shown in Chapter 4, there is a significant amount of collaboration that occurs between different roles during rover operations. Participants discussed how important it was to have effective team collaboration and how all rover operations were dependent of effective coordination between scientists and engineers in various roles. Many roles are even given their goals and objectives for the planning cycle by an individual in another role.

Many participants, especially scientific participants, expressed the usefulness of having input from a large group of individuals; when it comes to interpreting scientific data and forming scientific hypotheses, participants expressed an open mind and willingness to listen to those with differing backgrounds as being critical to making good scientific assessments during rover operations. Even engineering participants expressed the value of working in a team with respect to catching mistakes and addressing unexpected situations. While some of this collaboration occurs on a long-term timescale, much of it also occurs on a tactical timeline.

In addition to participants discussing the value of having input from large groups of individuals, most participants also discussed the value that would be added to exploration activities by having a human on the surface being able to think for themselves. Many participants assumed that astronauts would be trained as scientists and therefore would have the ability to notice scientifically relevant or interesting features that may be missed by Earth-based personnel using images. A well-trained human making their own analyses on the surface in a quicker, more efficient way when compared to current rover operations was deemed by most scientific participants in the study as being invaluable and the major motivation behind sending humans to Mars.

With the increased tempo in which humans would perform exploration activities (when compared with a Mars rover), much of the tactical coordination between large groups of individuals on Earth would need to change if the goal was to have that Earth-based coordination affect the tactical results of an EVA. If EVAs on Mars were to progress linearly (i.e. closely mimicking the way field geology is performed on Earth), then it is unlikely that Earth-based personnel would be able to have a significant impact on the activities of the EVA while it is being performed. It is possible that they would be able to view the EVA through video feeds and analyze the results after EVA completion and then provide their opinions to the astronauts at a later time.

If this linear architecture were to be adopted (with the current levels of automation available), then the author believes that there would need to be *at least* 3 or 4 IV crewmembers throughout the performance of an EVA to allow for the effective monitoring of all spacecraft systems, interpreting scientific results, ensuring astronaut safety, managing the timeline, and communicating with Earth. If it is assumed that at least 2 astronauts would be sent out for each EVA, then this reaches the upper limit of the crew size proposed in the current human mission planning (crew sizes of 3-6).

This linear architecture would also indicate that focus needs to be directed to automating the processing of scientific instrument data. Currently, the raw results of instrument readings taken by Mars rovers is analyzed on Earth by expert personnel in order to create interpretable products. If astronauts are expected to respond in real-time to discoveries, they need to have access to these usable products nearly instantaneously. It will also be important to ensure that at least one IV crewmember during the EVA would be someone trained to properly read and interpret these scientific products and put them into context for other crewmembers.

If it is determined that have the input of the larger scientific community is of a high enough priority that the architecture of EVAs will be altered, then there are certain EVA architectures that may allow for tactical input from Earth-based personnel. Some Mars analogs—such as NASA's BASALT research program (Lim et al., 2019)—design their simulated-EVAs in such a way that there is a significant gap between the initial investigation of areas of interest and selecting scientific targets in those same areas. This allows Earth-based personnel to review the collected information from the areas of interest and provide feedback before further action is taken.

This mission architecture is heavily reliant on continuous communications between Earth and Mars (even though those communications are still delayed). The current capabilities of Earth-Mars transmissions (a few megabytes once or twice a day) would not enable this kind of mission architecture. If this mission architecture were to be chosen, there would need to be significant improvements to the communication infrastructures to enable continuous communication. In addition to this, the length of the gaps between initial site investigation and further action taken at the same site would change based on the duration of the delay between communications.

Another potential EVA architecture that could be adopted is having astronauts or rovers perform "reconnaissance" EVAs to survey sites of interest, take images and instrument readings, and send that information back to Earth to allow the scientific community at large to select scientific targets and activities for the astronauts to perform on the same site (this is a similar architecture planned for the Mars 2020 rover). This architecture could fit within the current communication infrastructure but would minimize the amount of critical thinking and scientific exploration done by the astronaut during the EVA—something that was considered valuable by many participants. It is also possible that this type of EVA could be completed with fewer IV crewmembers than the more linear model, as the IV crewmembers would not be responsible for the processing/interpretation of collected scientific data. In the interest of safety and expertise redundancy, however, the author would still recommend sending crews on the larger end of the NASA-predicted crew sizes (5 or 6 astronauts).

By using a “reconnaissance” model, instead of focusing more development efforts on automating the processing of instrument data, that increased work would need to be done to further improve the Earth-Mars communication infrastructure to minimize the amount of time it would take to transfer all collected data to Earth and the analyzed products back to Mars (due to the fact that humans will collect more data more quickly than rovers) and minimize the time between the “reconnaissance” EVA and the time that scientific sampling/investigation EVAs. It is recommended that the Mars 2020 mission be monitored closely to gain more insight into this type of EVA model and how it might be improved upon for human missions.

There are advantages and disadvantages to various EVA architectures and the architecture selected will depend on the priorities of the mission. The chosen architecture would also have some impact on the relevant information streams and potential automation gaps that would need to be addressed before a human mission to Mars and could impact the number of astronauts sent on the mission and their areas of expertise. Contrarily, the identified critical information streams and constraints could indicate whether one mission architecture is more feasible to adopt than another. A possible approach would be to design EVA architecture iteratively: determining how changing the architecture changes the information processing requirements and vice versa to determine the most appropriate mission design. In addition to information streams informing mission design, the number of people who can be sent to Mars is also constrained, and therefore more work needs to be done to determine how best to plan a mission within that constraint.

Human-Rover Similarities & Differences

As expressed by one participant, when comparing human and rover missions at a high-level, there are going to be more similarities than when comparing the same missions at a smaller granularity. At a high-level, participants discussed how approaches to exploration, the environments in which exploration is completed, the need for teamwork, constraints, and some general information streams would be directly comparable when comparing human and rover exploration. Participants that focused on more specific mission aspects when answering the question would identify differences in the details of how these missions may be accomplished such as needed technological advancements, specific information streams, and specific mission architectures.

This difference in granularity may explain why some participants discussed a specific mission element as being similar between human and rover operations, while other participants discussed that same element as being different. For example, "reliance on images" was mentioned by participants as being both a human-rover similarity and difference. When considering a higher-level view of the mission, images will still be a mission-critical information stream during a human mission as that is how most individuals on Earth will gain contextual information from the surface. When looking more specifically at the different roles during a human missions to Mars, the reliance on images becomes a difference between the two missions because while images are critical to making tactical decisions for a rover's operations, if astronauts are making decisions for themselves, they will use visual cues from their own eyes, not images to make those decisions. Similarly, when considering broad types of relevant information streams for both missions there may be substantial overlap (e.g. power data, system status, scientific instrument data). When considering those information streams more specifically, differences between the relevant types of information are more apparent (e.g. there may be different instruments used, rover operators do not monitor oxygen levels, etc.).

It is useful to identify these similarities and differences. The identified similarities demonstrate what the space exploration community already has experience with when considering Mars exploration. The identified differences show gaps in expertise and opportunities to develop technological solutions or different approaches to these particular mission elements.

Study I Limitations

Though large amounts of interesting qualitative data were generated through this study, it has some limitations. First, only rover operations personnel were interviewed, and their expertise was rover specific. Some participants admitted that they had never considered how their expertise would apply to human exploration and there are certain aspects of human exploration that were not often considered by study participants but would likely be mission-critical. For example, only a few participants discussed communications between Earth and Mars and what would be the best medium to facilitate communication between astronauts and Mission Control/Support. This is due to the fact that Mars rovers do not have their own opinions or insights into the activities being performed, and this is therefore not a significant consideration for rover operations.

The sample of participants in this study is unbalanced. There were far more participants in certain roles (such as the Payload Uplink Lead) than others (such as the Long-Term Planner). There are also roles that are relevant to the planning process that were not reached for recruitment. Because of this unbalanced sample, there may be an overrepresentation of certain information streams or important planning functions because those are the mission elements that are relevant to the largest proportion of study participants. Some mission elements may be just as mission-critical as those mentioned more frequently, but because only a small number of roles for which that element is relevant were interviewed, fewer participants discussed them. The fact that not all rover planning roles were interviewed also increased the likelihood that the information and conclusions generated from this study are incomplete.

Though the author tried to be as explicit as possible in the descriptions of the codes used to analyze this data (**Appendix E**), it is possible that another coder with the same interview transcripts would assign the same passage to a different code. For example, only scientists discussed the strategic information stream “Orbital Context & Information” (using data taken from orbiters to provide contextual information for strategic planning). This does not mean that the engineering participants did not use orbital data/products for the strategic planning, those participants’ responses were simply coded in more specific codes about the rover’s drive path, the rover location, or the locations on a map of hazards or specific features of interest. It is possible that a different coder would have coded some of the interview excerpts the author coded in more specific categories as belonging to the “Orbital Context & Information” code.

Another limitation for this study is that there was no specific human mission architecture assumed. This resulted in various participants assuming different mission architectures; sometimes participants were explicit about their architecture assumptions, and other times they were not. Depending on the perspective of the participant and the mission architecture on which they were basing their answers, the similarities, differences, and relevant information streams identified could have differed based on these assumptions. Because not all participants were so explicit in describing their assumed mission architecture, it was not always clear whether an identified mission similarity or difference applied to which type of human mission.

Finally, it is important to note that this study specifically investigated the information streams relevant for scientific EVA. There are many different types of EVA that will be performed on Mars, but this study was scoped to include EVAs focused on scientific exploration. While there were information streams identified that will likely be important to many different types of EVA, not all necessary information for all different types of EVA will have been identified in this study. The results of this study should therefore not be taken as a complete picture of information requirements for all potential EVA types.

Study I Future Work

The results from this study were expansive due to the amount of qualitative data that was collected and analyzed. This study builds on previous work to characterize the EVA work domain to identify potential areas of EVA that could be improved with automated algorithms and decision support systems; this work looked to identify more specifically the information streams involved in the performance of scientific EVA and can therefore act as a starting point for various future studies.

In order to send humans to Mars, there is a significant amount of work that still needs to be done. First, an ideal mission architecture needs to be determined. As mentioned by multiple participants, there are multiple potential architectures that can be adopted to facilitate the performance of scientific EVA. Some participants discussed astronauts performing EVA in a very similar way to how geologists traditionally perform field science, while others discussed the use of rovers to survey sites of interest, perform scientific tests, and even take scientific samples. Other mission elements discussed by participants included the amount of information sent back to Earth, how much input Earth-based personnel would have on the performance of an EVA, and how much data processing would occur on Mars. Different assumed architectures affected how participants imagined that information streams would be used during a human mission Mars, and the relevant information streams would occasionally lead participants to assume that one architecture was better than another. Future work needs to be done to determine what the architecture of a future human mission to Mars will be. This will impact the design of automated support systems. Ideally, this work would happen iteratively, to determine which architecture maximizes scientific return, is the most efficient, and best ensures astronaut health and safety.

Once the appropriate architecture is determined, more work will need to be done to more specifically identify the information requirements relevant to that architecture and prioritize which to automate. The participant pool in this study was limited to rover scientists and engineers with no specifically assumed mission design. As mentioned previously, this indicates that the list of information streams generated in this study is incomplete and doesn't consider more human-specific information streams that are critical for the health and safety of astronauts during EVA. While some participants in this study made attempts to consider human-specific data streams, the catalog of information streams generated here could be built upon by performing similar interviews with flight controllers and other Mission Control personnel who have experience supporting human spaceflight on the ISS. While these subject matter experts would have less experience with time-delayed communications, they would likely have more expertise in the information streams relevant to life support systems and human health monitoring. While this dissertation provides a good preliminary assessment of relevant information streams, more individuals with more experience in different fields will need to be consulted to generate a more complete understanding of relevant information.

Using both the information streams identified in this dissertation and more specific information streams that will be identified after a more specific mission design is chosen, work can begin on developing decision support systems and automated monitoring/processing systems to support IV crewmembers during EVA. Though the mission architecture will likely affect how the information streams are used (as discussed above) it is possible that some work on algorithm or system development could begin on certain information streams. It will also be important to ensure that all systems designed to offload situation awareness requirements from IV crewmembers interface well together and are tested to ensure that the systems operate together as intended and keep the human in-the-loop as much as is required to ensure astronaut safety.

Finally, astronauts will need to be selected based on their expertise and their abilities to monitor, process, and/or interpret the identified relevant information streams and maintain the automated support systems. The makeup of the crew that is ultimately sent to Mars will depend heavily on which information and data are prioritized, and the types of systems that will be designed to support exploration.

Study II Discussion

Physiological Parameter & Task Responsiveness

Heart Rate

When comparing the responses of the three physiological parameters considered in this study (shown in Chapter 5), heart rate appears to respond the most readily and consistently responsive to changes in task. Despite the differences in baseline heart rate readings, there are patterns that can be seen in the responses to different tasks across cases. With the exception of cases 9 and 10, the breaking rocks tasks elicited the highest heart rate responses when compared to other tasks. The traversing task also generated a high heart rate response. The other tasks followed similar patterns with most of the other field tasks eliciting similar heart rate responses.

Based on the common understanding of the breaking rocks and traversing tasks, it is expected that these tasks would elicit higher heart rate responses as they are considered to be the most physically demanding tasks. It is also expected that tasks that require lower levels of physical exertion (e.g. observation tasks compared to instrument use tasks) would elicit similar heart rate responses and demonstrate less consistency with respect to the direction of those differences, which is shown in the results of this study.

The major exceptions to the pattern seen in the majority of heart rate cases (Case 9 and Case 10) show the bagging samples/biological sterilization task as eliciting the highest heart rate responses, despite the fact that this task is not considered to be one of the more physically demanding tasks. It is possible that these participants experienced higher levels of mental stress due to the demands of keeping the collected samples sterile. It is also possible that these tasks occurred directly after the performance of a more strenuous task which may have altered the response of these participants to this task.

Respiration Rate

Respiration rate responses appeared to response less readily to changes in task than heart rate (fewer pairwise comparisons were found to be statistically significant), but it also demonstrated some patterns in participant responses to changes in task. Interestingly, respiration rate appeared to be the most consistent parameter within the same participant, as the distributions of all the data sets corresponding to the same participant were not shown to be statistically significantly different and the data sets could therefore be combined. One of the reasons that respiration rate may respond less readily to changes in task in this study could be because tidal volume (the amount of air inhaled with each breath) was not measured, and it also increases with physical exertion (Watson, 1974).

Similar to heart rate, the breaking rocks and traversing tasks were generally found to elicit the highest respiration rate responses across participations. The exceptions to this pattern are found in Case 7 (where observation tasks elicited a higher respiration rate response than the breaking rocks task) and Case 8 (where the bagging sample/biological sterilization tasks elicited the highest response and the observation task elicited a higher respiration rate than the traversing task). These two respiration rate cases correspond to the same participants as the heart rate cases that demonstrate deviations from the patterns followed by other cases. This may indicate that both these participants experienced tasks differently, or that some more physically strenuous tasks were performed directly before the performance of the tasks eliciting unexpected responses, which affected the readings taken during the performance of those tasks.

Heart Rate Variability

There is little consistency in heart rate variability responses across participants. However, when looking at cases that represent the same participant (Cases 1 and 2, and Cases 5 and 6) there are some consistencies between those data sets. This may indicate that heart rate variability responses are highly individualized (more so than either heart rate or respiration rate), or that the same study participant experienced the same levels of mental stress when performing the same tasks during different deployments. The theory of individualized stress responses is supported by the fact that there are no pairs of tasks that elicit a statistically significant difference in heart rate variability responses across all participants. Overall, heart rate variability demonstrates the lowest responsiveness to changes in task (it has the fewest statistically different pairwise comparisons) indicating task may have less of an effect on stress levels than physical workload.

Overall, the tasks most likely to demonstrate statistically different physiological responses when compared to baseline measurements are the traversing (75% of all comparisons) and observation (71% of all comparisons) tasks. While the traversing task aligns with the author's understanding that it is one of the most physically demanding tasks, the observation task is not considered to be one of the most physically demanding tasks. It is possible that in a significant number of occurrences observation tasks occurred directly after traversing tasks. This means that participant's physiological responses could have been significantly affected by the more physically demanding task.

Task Comparisons

When looking at tasks performed in the field, the pairs of tasks most likely to elicit statistically different physiological responses are the instrument use and the traversing tasks (48%) and the bagging samples/biological sterilization and traversing tasks (32%). This is expected as the instrument use and bagging samples/biological sterilization tasks are among the least physically strenuous tasks and traversing is considered to be one of the most physically strenuous.

Across parameters, comparing tasks performed in the field to baseline measurements were far more likely to elicit statistically significant differences in physiological responses (60%-75%) than comparing pairs of tasks performed in the field (11%-48%). For all heart rate cases, baseline responses were lower than participant responses to all other tasks; this trend was also seen in half of the respiration rate cases, but not all. Most heart rate variability cases demonstrated higher heart rate variability measurements taken during baseline readings (meaning lower mental stress) than all tasks performed in the field (with the exception of Case 9). This indicates that, no matter the task being performed, being in the field has a tangible effect on participant physiology.

The pairs of tasks least likely to demonstrate differences in physiological response are the observation and traversing tasks (11%), and the bagging samples/biological sterilization and instrument use tasks (16%). It is expected that the bagging samples/biological sterilization and instrument use tasks would elicit similar physiological responses as both tasks demand a similar level of physical exertion. However, the similar responses to the observation and traversing tasks are not expected; it is expected that traversing task is much more physically demanding than the observation task. Again, the sequence in which the tasks were performed could have had an impact on the physiological responses in subsequence tasks. At the beginning of each simulated EVA, EV crewmembers would traverse, pause for observations, then traverse again for a period of time. The pauses could be for short durations. If heart rates and respiration rates were elevated during the traversing task, and the observation task was of short duration, there would not be enough time for participants to recover from physical exertion and their physiological responses would remain high. The short duration of each traversing and observation occurrence in this case and the fact that timestamps were taken at a minute-scale could also have resulted in some data points being attributed to an observation task when the participant was traversing, or vice versa.

While some patterns are discernable when looking at responses to different field science tasks, there are significant differences in the baseline readings of different participants and the magnitude of the changes in physiological responses; there are also cases that do not conform to the identified patterns. This lack of consistency supports the claims made in the literature that physiological response is highly affected by individual characteristics and therefore, if action limits or automated algorithms are to be developed, they will need to be personalized to each astronaut. Ultimately, in this study, mean heart rate, respiration rate, and heart rate variability responses were not shown to be ideal parameters for predictably differentiating the workload of different types of tasks.

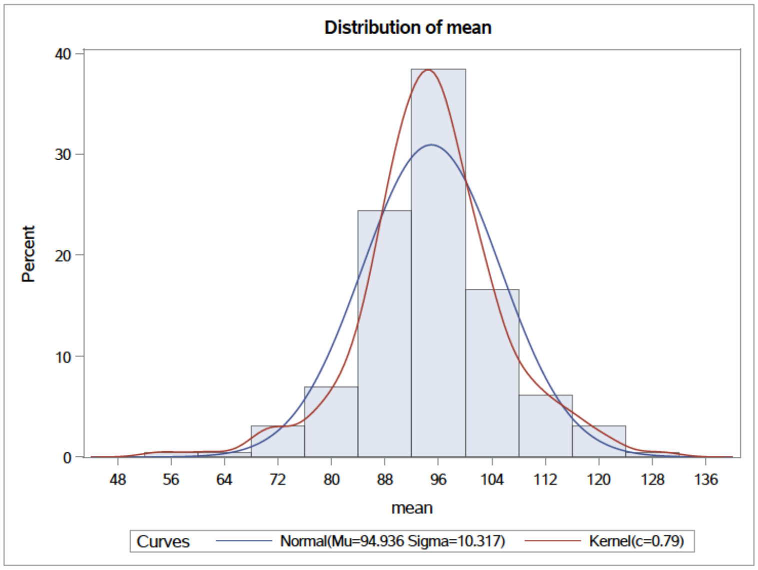
Potential Opportunities for Automation Functionality

There are many possible ways that physiological data can be processed and monitored via an automated monitoring system. While working with the physiological data sets collected in Study

II, the author determined that there may be a simple method of automation to monitor physiological parameters during EVAs on Mars, and alert astronauts to concerning or problematic readings.

It is possible that individual action limits could be set with upper- and lower-bound limits on what are “acceptable” physiological responses for each individual before astronauts go to Mars. An automated support system could monitor the physiological readings and compare them to these action limits and alert IV crewmembers if an EV crewmember’s readings fell below or rose above “acceptable” levels.

As an example, the heart rate distribution of Case 1 is shown in Figure 26. Figure 26 also shows a common “Red-Yellow-Green” (R-Y-G) method of automation; readings within the green rectangle are nominal, readings in the yellow may be outside nominal and should be monitored, and readings in the red are considered concerning or “unacceptable”. A system could alert IV crewmembers when readings enter yellow or red zones.



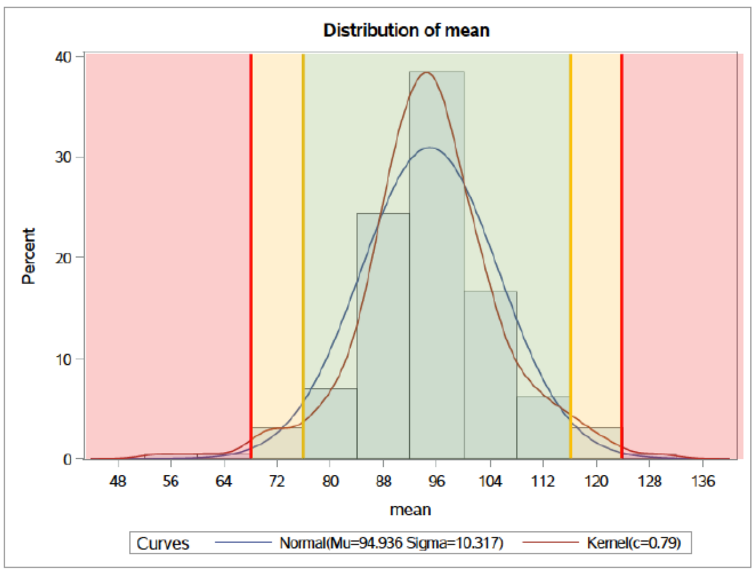


Figure 26: Heart Rate Case 1 Distribution (top) and Potential R-Y-G Action Limits (bottom)

It is important to note that this data set is only a small representation of the possible physiological readings of a participant. None of the measurements taken during any simulated EVA in this study should be considered “unacceptable” readings as the safety and health of participants was prioritized and there were no known cases of participants being pushed past an acceptable exertion level at any point during the study. Figure 26 is only for illustrative purposes. However, the astronauts who will be sent to Mars will be known for years in advance of the mission taking place. It would be possible to collect physiological data from astronauts as they perform a larger variety of tasks and when they may be pushed to their physical limits during training. This would give physicians a much clearer understanding of what are and are not nominal responses for each astronaut. Upper- and lower-bound action limits could then be set by health care professionals who are familiar with each individual and have a better understanding as to what constitutes an acceptable response during an EVA.

Study II Limitations

Through the analysis of the physiological data collected in this study, only statistically significant differences were detected; none of the work done in this study assesses whether the differences detected are of practical significance. The range of physiological responses for each individual are dependent on a variety of factors and therefore practically significant differences in physiological responses to different tasks would need to be established by a healthcare professional familiar with the physiology of each individual (much like the upper- and lower-bound action limits discussed in the previous section). No literature was found on a universal practical difference in physiological responses therefore the author cannot determine what constitutes a practical difference in response.

As mentioned in the previous section, no one in this study was pushed past an acceptable level of exertion. Combined with the fact that taking the mean responses to each task made the data sets smaller, the distributions of the physiological responses for each participant are limited in scope. Individual action limits would need to be set on data sets that encompass a wider range of activities and levels of physical exertion.

It is important to note that baseline measurements were taken whenever participants had the time to do so. This included during extended periods when they were sitting in meetings, or for a shorter duration when they were driving to the field site before the start of an EVA. Thus, these baseline measurements are not "true" baselines where participants would need to sit still, relax, and not speak. It was not feasible with the other responsibilities of the study participants to collect "true" baselines.

Another limitation of this study is the fact that the author had no control over which tasks were performed, for how long, or in which order. This study was a part of the much larger BASALT research project and manipulating the performance of tasks in such a way would compromise other aspects of the research project. Because of this, tasks usually happened in similar orders throughout the EVA, which may have affected the physiological responses to different tasks. For example, the breaking rocks task generally happened at the end of the simulated EVA when it was time to sample, meaning study participants were likely already tired from the performance of the rest of the EVA earlier in the day. While this lack of control over the performance of tasks in the field adds a level of “messiness” to the data, it also adds a level of realism; messy data like this collected in an uncontrolled environment will more closely resemble the data that will be collected from astronauts on Mars than data generated in a laboratory setting.

Finally, the fact that the durations of some tasks were short, but the quickest timestamps could be taken was on a minute-scale is another source of data “messiness”. It is possible that some data points were timestamped as being part of a different task due to the timescale of the timestamps. With any discrepancies between the internal BioHarness™ timestamp and the timestamp on the computer, and the limitations to how quickly the author is able to assign timestamps to different tasks performed by two different participants, it was not possible to increase the speed with which timestamps were assigned.

Study II Future Work

As stated previously, mean heart rate, respiration rate, and heart rate variability responses did not demonstrate consistent discernable differences between the workload of different field science tasks. However, it is possible that analyzing this data in different way could reveal useful trends in the data that were not seen here. For example, there may be patterns in the raw, time series data set that demonstrate different responses to different tasks that would not be seen by taking the mean response to each task. Depending on what information researchers want to glean from this data, many different types of statistical analyses could be performed on these (or similar) data sets. In addition, the author was not able to find a widely accepted, well-known, easily implemented method for analyzing this type of data set. It would be beneficial not only for human spaceflight applications, but for many other fields (e.g. healthcare, military) if different methods were developed and tested to create “rules of thumb” when analyzing physiological data sets.

Though the physiological parameters analyzed here did not show consistent differences in mean response to different tasks, that does not mean that other physiological parameters would not more effectively assess participant workload. It would be useful in the future to investigate using other physiological parameters (e.g. VO2 Max, tidal volume, etc.) to attempt to differentiate responses to different tasks. It is also possible that combinations of responses of different parameters (including the ones used in this study) demonstrate more predictable differences with respect to different tasks than any one parameter in isolation.

As mentioned previously, no participants were pushed to an “unacceptable” limit in this study. Therefore, if action limits are going to be set on physiological parameters, it will be important to collect data from astronauts during training as they perform activities that elicit “unacceptable” physiological responses so that medical professionals familiar with an astronaut’s physiology is aware of what such unacceptable responses are. When astronauts are selected to be a part of a human mission to Mars, physiological data should be collected from them as they perform a wide variety of tasks. This will not only provide more data on the performance of a larger range of tasks (many that could be good analogs for the tasks that will be performed during EVA) but will also allow for the collection of more data points during the performance of each task. This may reveal more consistent patterns in the physiological responses of individuals.

Though the setting of action limits will need to be set by a healthcare professional for each individual astronauts, automated monitoring systems can be developed and tested in the near future to determine if the “red-yellow-green” system proposed in this study is an effective form of automation, or if a more complex algorithm is required.

7. CONCLUSION & SIGNIFICANCE OF WORK

When considering human exploration on Mars, the paradigm of how EVA is performed needs to evolve and change from the design of current operations; it is infeasible to simply apply an ISS model of EVA to planetary exploration on Mars. The long duration of deep space missions, the time delays on communications, communication blackouts, and the distance between Earth and Mars will necessitate that astronauts be able to work more independently from Earth-based Mission Control/Support. In addition to this, the complexity of the systems required to keep astronauts alive and healthy on the surface will necessitate the development of automation and function allocation in order to ensure in-space crews are not overwhelmed.

This dissertation aims to help with the evolution of the EVA paradigm by identifying mission-critical information streams for scientific EVA, as well as outlining potential areas for function allocation and automated support systems. This work also investigates the analysis and potential methods to automate the monitoring of a specific mission-critical information stream: astronaut physiological status.

Study I used current Mars rover operations as a homology to human exploration on Mars in order to identify information requirements needed to effectively perform science on another planet. Interviews with Mars rover operations personnel identified relevant information streams, the timescales on which that information acted, information sources, team collaborations, and potential differences/similarities between rover and human operations on Mars. The mentioned information streams were then related to the same or similar information streams for human exploration and those best suited to automation or function allocation were identified (as well as those information streams that are poorly suited to automation).

The results of Study I can be used to inform the development of automated support systems for human Mars missions—with the relevant information streams identified, methods of automation can be identified and systems to support that automation can be designed and developed. The results of this study also demonstrate how many of these systems need to be well coordinated to ensure that they work well together. In addition, the information requirements identified in this study as they related to scientific EVA can be a starting point for work in exploring information requirements for other kinds of EVA, or to more completely develop a list of information streams by looking at other homologous systems (e.g. ISS operations).

Study II built on the author's previous work by investigating in more detail the analysis and potential automated monitoring of physiological parameters from astronauts during EVA. Astronaut physiological status has always been (and will continue to be) considered as a mission-critical information stream during EVA. It is therefore important that methods to analyze this data to draw meaningful information from it are well-known. It would also be beneficial to automate this information stream to minimize the attentional resources astronauts will need to spend monitoring this data stream. The results of Study II not only determined a feasible way to analyze physiological data sets, but also identified a potential automated monitoring method that would be easy to implement.

There were few consistent trends seen in the physiological responses analyzed in Study II. It may be that this is due to insufficient data. The results of this study can be used to inform future studies of physiological monitoring of individuals in uncontrolled environments that may wish to better understand human physiology in response to certain types of field science tasks. In addition, the work done with this data has given insights into how astronaut physiology can be studied before going to Mars in order to inform automated monitoring systems; healthcare professionals should be familiar with nominal and off-nominal physiological responses of each individual astronaut, and upper- and lower-bound action limits could theoretically be assigned to each individual. Should this method of physiological monitoring be adopted, it will also need to be tested prior to the start of the mission. If this method is unsuitable for the application, then the physiological responses shown in this work could be used to inform the design of future monitoring algorithms.

Conducting human exploration on another planet, under time-delayed communication constraints will be a significant challenge. Many technological advancements and changes to human exploration operations will need to be developed to successfully respond to this challenge. This dissertation work seeks to aid the process of developing support systems for astronauts to allow for humans to one day walk on Mars.

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APPENDIX A. STUDY I RECRUITMENT EMAIL

Hello [Name],

My name is Jordan Hill and I am a PhD Candidate at Purdue University in the School of Industrial Engineering. You are receiving this email because as a [potential participant role], you have significant expertise in the **performance of operational surface activities of a Mars rover**.

You are invited to participate in a **research interview.** Your participation can help researchers better understand the information requirements for both human and rover scientific exploration of Mars.

- Interviews will be conducted **in person on Purdue University's West Lafayette campus**, **Online via Video-conferencing software** (e.g., Skype) or **by telephone**.
- Interviews are expected to take **45 minutes** and will be **audio-recorded**
- Your participation in this study is completely voluntary.
- You must be over 18 years of age.
- Only the Principal Investigator (Dr. Barrett Caldwell, PhD, bscaldwell@purdue.edu) and myself will have access to the data, and we will maintain confidentiality to the extent of the law.

If you are interested in participating and helping add to the research in this area, please send an email to hill265@purdue.edu to schedule a time slot.

Please feel free to forward this message and share with other rover engineers who may be interested.

Best,
Jordan R. Hill

APPENDIX B. STUDY I PARTICIPANT INFORMATION SHEET

RESEARCH PARTICIPANT CONSENT FORM

Information Requirements for Function Allocation during Mars Mission Exploration Activities

Jordan Hill, M.S., & Barrett Caldwell, Ph.D.
School of Industrial Engineering
Purdue University, West Lafayette, IN

This form describes a research study, what you may expect if you decide to take part, and important information to help you make your decision. Please read this form carefully.

Being in this study is voluntary – it is your choice. If you join this study, you can change your mind and stop at any time. There are minimal risks from participating in this study.

What is the purpose of this study?

The purpose of this study is to further our knowledge and understanding of the information requirements for performing robotic scientific exploration on Mars, and how these information streams compare to those required for human exploration of Mars.

What will I do if I choose to be in this study?

If you do decide to participate in this study, you will be asked to participate in a 30-45 minute audio-recorded interview either in person, or over video-conferencing software (e.g., Skype, FaceTime, WebEx) or the telephone.

How long will I be in the study?

The estimated time to complete the interview is 45 minutes.

What are the possible risks or discomforts?

There are minimal risks associated with participation in this study. If you are uncomfortable for any reason and wish to discontinue the interview, you may do so. You are free to stop at any time for whatever reason, and will not be penalized for choosing to end your participation.

Are there any potential benefits?

There are no direct benefits to you beyond the possibility of feeling helpful for contributing to furthering the research in this field.

Will information about me and my participation be kept confidential?

We make every effort to maintain confidentiality to the extent of the law.

Participant demographic information will be hand recorded prior to the start of the audio recording of the interview. This information will be kept in a locked filing cabinet at Purdue University. The audio-recorded interviews will be transcribed after the session and destroyed.

The results of this research study may be presented at meetings or in publications, however, your identity will be kept private. The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight. The details of individual data will not be disclosed to any other people except the researchers (Jordan Hill and Barrett Caldwell). In the future, the data will be only used for future subsequent studies on supporting planetary exploration only by the authors (Jordan Hill and Barrett Caldwell).

What are my rights if I take part in this study?

Your participation in this study is voluntary. You may choose not to participate or, if you agree to participate, you can withdraw your participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Who can I contact if I have questions about the study?

If you have questions, comments or concerns about this research project, you can talk to one of the researchers. Please contact the primary investigator, Barrett Caldwell (bscaldwell@purdue.edu or 765-494-5412) or the graduate research assistant, Jordan Hill (hill265@purdue.edu or 765-543-8559).

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu) or write to:

Human Research Protection Program - Purdue University
Ernest C. Young Hall, Room 1032

155 S. Grant St.,

West Lafayette, IN 47907-2114

Documentation of Informed Consent

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research study, and my questions have been answered. I am prepared to participate in the research study described above. I will be offered a copy of this consent form after I sign it.

____________________________________ ______________________

Participant's Signature Date

____

Participant's Name

____________________________________ ______________________

Researcher's Signature Date

APPENDIX C. ENGINEERING MODERATOR GUIDE

Introduction:

Thank you for agreeing to participate in this research study. Is now still a good time to talk?

First, do you have any questions about the research study? I have a copy of the information sheet I sent to you via email if you would like to review anything. Please remember that you can stop the study at any time for any reason.

Before I begin, I would like you to confirm some information about yourself, and your work experience. This information is for demographic purposes only and will not be recorded.

1. With which rover(s) have you been or are you involved?

2. What was/is your role?

    a. What is/was your major motivation day to day (for example, research activities, instrument usage, rover health and safety)?

    b. Please tell me about the major responsibilities of that role.

3. How many years of experience do you have working with rover operations?

Thank you. I am going to be reading from a script today to maintain consistency across participants. I am going to start the recording device now.

[TURN ON AUDIO-RECORDING HERE. STATE 'PARTICIPANT CODE [#]']

Information Streams and Goals Questions:

Now I am going to ask you some questions about your experiences working with Mars rovers and the information streams you monitor to perform your role and meet your goals.

1. When you first begin your day on "Mars-time", how do you know what your personal goals are? How do you know what your team's goals are?

    a. How do you set up your personal tasks to achieve those goals? How does the team prepare to achieve those goals?

    b. How do you know what the tactical (short-term) goals are/if they have changed?

    c. How do you know what the strategic (long-term) goals are/if they have changed?

        i. [Probes—on what timescales do these goals operate? Which timescales are the most important for you?]

    d. Who else, and what other functions do you need information from to do these jobs/plan to achieve these goals?

[Ask participants, if relevant, where they would like to talk about supratactical planning]

2. What specific data/information do you look at to determine strategic [and supratactical] (long-term) goals?

        i. [Example—images, readouts, maps, documents, scans, etc.]

    b. What was the timeline for setting those goals (i.e. the day before, that morning, 2 days before, a month before, etc.)?

c. How much goal planning/re-planning do you do based on the data you receive (and how much of it is predetermined)?

d. How much of this data is presented directly, and how much requires further analysis to be understood?

i. [Probe—please elaborate on some of the analysis/sense-making]

e. How often do you get information from this information stream (i.e. every day, every week, twice a day, etc.)?

3. What specific data/information streams do you look at to determine tactical [and supratactical] (short-term) goals?

a. What was the timeline for setting those goals (i.e. the day before, that morning, 2 days before, a month before, etc.)?

b. How much goal planning/re-planning do you do based on the data you receive (and how much of it is predetermined)?

c. How much of this data is presented directly, and how much requires further analysis to be understood?

i. [Probe—please elaborate on some of the analysis/sense-making]

d. How often do you get information from this information stream (i.e. every day, every week, twice a day, etc.)?

Rover-Human Comparison Questions:

To wrap up, I am going to ask you some questions about whether or not you think some of the information streams you monitor will or will not be applicable to human operations on Mars.

4. From what we've discussed, what do you think will be similar when humans are on Mars? What do you think will differ?

    i. [Example—when humans are exploring new terrain on Mars or when astronauts on a spacewalk are determining the best location in a given area to take scientific samples]
    ii. [Clarification—many current spacewalks are very rehearsed, and spacewalks on Mars are going to require more autonomous decision making by astronauts; it is possible that some of that increased autonomy is related to rover operations]

  b. Will there be many more different data streams?

  c. Can we use some/most of what you have learned in your rover-related role to support spacewalks on Mars?

    i. [Probe—what aspects of your expertise?]

  d. What do you think will be the biggest difference?

Thank you so much for your participation in this interview today. I appreciate the time you have taken.

If you have any questions for me, please feel free to ask.

If questions about this research arise, please do not hesitate to contact me.

APPENDIX D. SCIENCE MODERATOR GUIDE

Introduction:

Thank you for agreeing to participate in this research study. Is now still a good time to talk?

First, do you have any questions about the research study? I have a copy of the information sheet I sent to you via email if you would like to review anything. Please remember that you can stop the study at any time for any reason.

Before I begin, I would like you to confirm some information about yourself, and your work experience. This information is for demographic purposes only and will not be recorded.

4. In what scientific area(s) do you have expertise?

    a. In what kinds of scientific activities do you take part (i.e. field science, laboratory science, modelling, remote sensing etc.)?

5. Have you been directly involved with the scientific operations of a rover or rovers?

    a. Which rover(s)?

    b. What was your role?

        i. What is/was your major motivation day to day (for example, research activities, instrument usage, rover health and safety)?

        ii. Please tell me about the major responsibilities of that role.

6. How many years of experience do you have in your field?

    a. How many years of experience do you have working with rovers [if applicable]?

Thank you. I am going to be reading from a script today to maintain consistency across participants. I am going to start the recording device now.

[TURN ON AUDIO-RECORDING HERE. STATE 'PARTICIPANT CODE [#]']

<u>Information Streams and Goals Questions:</u>

Now I am going to ask you some questions about your experiences working with Mars rovers and the information streams you monitor to perform your role and meet your goals.

5. When you first begin your day on "Mars-time", how do you know what your personal goals are? How do you know what your team's goals are?

    a. How do you set up your personal tasks to achieve those goals? How does the team prepare to achieve those goals?

    b. How do you know what the tactical (short-term) goals are/if they have changed?

    c. How do you know what the strategic (long-term) goals are/if they have changed?

        i. [Probes—on what timescales do these goals operate? Which timescales are the most important for you?]

    d. Who else, and what other functions do you need information from to do these jobs/plan to achieve these goals?

[Ask participants, if relevant, where they would like to talk about supratactical planning]

6. What specific data/information do you look at to determine strategic [and supratactical] (long-term) goals?

    i. [Example—images, scans, readouts, maps, documents, etc.]

    a. What was the timeline for setting those goals (i.e. the day before, that morning, 2 days before, a month before, etc.)?

    b. How much goal planning/re-planning do you do based on the data you receive (and how much of it is predetermined)?

    c. How much of this data is presented directly, and how much requires further analysis to be understood?

    ii. [Probe—please elaborate on some of the analysis/sense-making]

    d. How often do you get information from this information stream (i.e. every day, every week, twice a day, etc.)?

7. What specific data/information streams do you look at to determine tactical [and supratactical] (short-term) goals?

    a. What was the timeline for setting those goals (i.e. the day before, that morning, 2 days before, a month before, etc.)?

    b. How much goal planning/re-planning do you do based on the data you receive (and how much of it is predetermined)?

    c. How much of this data is presented directly, and how much requires further analysis to be understood?

i. [Probe—please elaborate on some of the analysis/sense-making]

d. How often do you get information from this information stream (i.e. every day, every week, twice a day, etc.)?

Rover-Human Comparison Questions:

To wrap up, I am going to ask you some questions about whether or not you think some of the information streams you monitor will or will not be applicable to human operations on Mars.

8. From what we've discussed, what do you think will be similar when humans are on Mars? What do you think will differ?

i. [Example—when humans are exploring new terrain on Mars or when astronauts on a spacewalk are determining the best location in a given area to take scientific samples]

ii. [Clarification—many current spacewalks are very rehearsed, and spacewalks on Mars are going to require more autonomous decision making by astronauts; it is possible that some of that increased autonomy is related to rover operations]

b. Will there be many more different data streams?

c. Can we use some/most of what you have learned as a rover scientist to support spacewalks on Mars?

i. [Probe—what aspects of your expertise/role?]

d. What do you think will be the biggest difference?

Thank you so much for your participation in this interview today. I appreciate the time you have taken.

If you have any questions for me, please feel free to ask.

If questions about this research arise, please do not hesitate to contact me.

APPENDIX E. CODEBOOK

Table 34: Codebook

Code Category	Category Description	Code Name	Code Description
Direct Strategic Data	Data that is used directly by the team for strategic operations with little to no computer/data processing.	Images	Includes images from the rover and orbital images.
		Rover Telemetry Downlink	Values directly from the rover (power, data volume, temperature, etc.)
Direct Tactical or Supratactical Data	Data that is used directly by the team for tactical/supratactical operations with little to no computer/data processing.	Images	Images from the rover.
		Rover Telemetry Downlink	Values directly from the rover (power, data volume, temperature, etc.)
Existing Rover Automation	Automation (e.g. computer algorithms, scripts, automatic processing, etc.) that already exists within rover operations to process raw information/data.	-	-
Goal Source	Source where rover operations personnel learn of the current strategic, supratactical, or tactical goals and if those goals have changed. Source where rover operations personnel learn of the current strategic, supratactical, or tactical goals and if those goals have changed.	Another Role (or their reports)	When another person communicates the goal to you. Includes reports or plans created by another role.
		Liens	Goals/tasks to be accomplished/fit into a plan.
		Mission Goals	Overall mission goals. Includes primary and extended mission.
		Previous Person in Role	Goals given to a person in a specific role by the last person who filled that role.
		Previous Plans	The current plan or plans created in a previous planning cycle. Does not include handover plans/reports generated by another role or the previous person in a role. Includes plans that may have been discussed at meetings or telecoms, or where no specific role was mentioned who was responsible for communicating the role.
		Role Definition	Goals that stem from the responsibilities of a certain role.
		Universal and Constant Goals	Goals that never change.

Table 34 continued

Goal Timescale	Relevant timescales for the setting and achievement of goals.	Strategic	Relevant timescales for the setting and achievement of strategic goals.
		Supratactical	Relevant timescales for the setting and achievement of supratactical goals.
		Tactical	Relevant timescales for the setting and achievement of tactical goals.
Human-Rover Difference	Differences between current rover operations and imagined human operations on Mars.	Automation Advances	Need for more automated support systems (than those present in rover operations) to process data/present derived data products to astronauts.
		Autonomy	The need for and ability of humans to be able to think: act autonomously (without input from Mission Control), notice things on their own, react to changing situations, have their own ideas/insights.
		Communication Frequency	The need to have communication transmissions more often between Earth and Mars than are currently available/required with a rover.
		Complexity	Increased complexity of sending humans to Mars (and keeping them alive and healthy) versus sending a rover to Mars.
		Data Pruning, Preprocessing, Analysis	The ability of the astronauts to prune data for saliency, process and analyze the data and send derived products back to Earth, and provide their own data interpretations/context versus a rover sending back only raw data.
		Different Instruments	The expectation that astronauts will have access to more instruments take different measurement on Mars, and that those instruments may be more sophisticated than those currently on the rover. Includes instruments that will be used in a potential lab.
		Environment Manipulation	Increased human ability to manipulate the environment (pick up a rock, describe tactile sensation, break a rock with a hammer, etc) versus a rover.

Table 34 continued

		Health & Safety	The increased prioritization and difficulty of keeping humans alive/safe on Mars (monitoring, risk-profiles, etc.) over rover health & safety.
		Human Fatigue & Mental Health	Mental health & physical/mental fatigue considerations for humans that do not exist for rover operations.
		Immediate Instrument Analyses	The need for instruments used by astronauts to give results instantaneously/near-instantaneously, in a human-readable format.
		Increased Transmission Bandwidth	The need to be able to transmit more information (in bits) to Earth during human mission than is currently possible with the Mars communication infrastructure.
		Less Structured Operations	The ability for humans to be given higher-level commands/goals to execute or to explore and make discovery-based decisions, instead of the lower-level commanding that needs to happen with a rover.
		Life Support Data	Monitoring of life support data for human missions that is not present in rover missions.
		Mobility and Maneuverability	The increased mobility and maneuverability of a human over a rover.
		More Data Processing & Storage	The need to have in-space storage for more data and increased processing power for a human mission than for a rover mission.
		More Structured Operations	The potential to adopt current EVA protocols and have more highly rehearsed activities than during rover operations.
		Multiple Time-Delay Regimes	The need to coordinate and deconflict different human and robotic activities in different time-delay regimes operating simultaneously.
		New Information Streams & Analyses	Unspecified new data/information and the analyses/synthesis associated with those new data stream that will be involved with human operations on Mars.

Table 34 continued

		Possible Research Questions & Activities	Related to the human ability to do activities/tasks that a rover cannot and how that allows for the performance of different scientific activities to answer different research questions.
		Reliance on Images	Ability of humans to notice more than a robot taking pictures and therefore more reliance will be placed on the astronaut's observations with their eyes than on images taken.
		Rover Operation	How the operation of rovers (whether by astronauts or ground crews) with the goals of supporting human missions will differ from the current way a Mars rover is operated.
		Speed	Human exploration happening more quickly than rover exploration.
		Video Usage	Human missions involving regular use of video transmissions, something rover operations rarely use.
		Visual Cues	The efficacy of human vision when it comes to path planning and scientific information gathering/synthesis, which is not present on a rover.
Human-Rover Similarity	Similarities between current rover operations and imagined human operations on Mars.	Communication Frequency	The fact that the frequency with which communication transmissions can occur between Earth and Mars are limited. Includes limitations based on OWLT delay.
		Data Management & Transmission Considerations	Considerations regarding available transmission bandwidth limitations, onboard data storage needs, and the effective management of data collected during the mission.
		Faults and Issues	Similarities in how rovers have fault modes and how humans will have issues during operations.

Table 34 continued

		Goal Planning & Re-planning	Similarities between rover and human operations regarding planning and re-planning goals. Includes science planning, route planning, information synthesis as it affects goals, consideration of resource constraints, etc.
		Hazard Avoidance	Similarity between stereo image way-finding and how humans avoid obstacles/hazards.
		Health & Safety	Similarities between rovers and humans with respect to health & safety considerations.
		Information Streams	Similarities in the relevant information streams associated with both human and rover operations.
		Instrument Usage	The fact that instruments will still be integral to human operations as it is with rover operations, and that similar instruments will be used.
		Martian Environment	The fact that humans will be operating on the Martian surface, of which rover operators are familiar.
		Reliance on Images	How personnel on Earth or IV crew members will still be reliant on imaging to remain in-the-loop.
		Remote Participation	The fact that, during a human mission, most (if not all) data will still be sent back down to experts on Earth, and those experts will be actively participating in the process.
		Rover Operation	Similarities between how rovers that will assist human operations are operated, and how current Mars rovers are operated.
		Self-contained & sufficient	Due to the time delay on communications, astronauts on Mars will need to be more self-sufficient, like rovers somewhat are.
		Small Exploration Area	The fact that both human operations and rover operations will gain only a small part of the scientific knowledge to be gained on Mars.

Table 34 continued

		Teamwork	The fact that astronauts will need to work in a team, just as rover operations personnel do.
		Unrehearsed exploration	The fact that both rover operations and future human exploration activities will be largely reactionary to discoveries, and unrehearsed.
Information Source	Source where rover operations personnel receive relevant strategic, supratactical, or tactical information.	Chat & Sync Comms	Face-to-face, one-on-one communications or one-on-one communications through a chat tool.
		Email	Communications/information transfer through emails.
		Instrument Analyses	Information gained through the analysis of rover instrument results.
		Meetings & Teleconferences	More formal/planned meetings and teleconferences involving multiple roles/individuals. Includes specific presentations in meetings.
		Orbital Data	Information gained from Mars orbiters (e.g. HIRISE imagery, maps, etc.).
		Reports or Plans	Information gained by looking at reports from various roles or formalized, existing plans.
		Rover Images	Information gained by looking at images sent back to Earth from the rover.
		Rover Telemetry	Information sent back to Earth from the rover. Does not include imaging or instrument result analyses. Includes rover status data, power, etc.
		Technological Tools or Databases	Information gained from looking at specific technological tools (e.g. a simulation tool) or repository of information.
Interesting Contributions	Participant contributions that do not address specific research questions but are of interest and may indicate areas for future study.	Adapting operations to new missions	Operations adapt and evolve mission to mission and some things remain the same and others change.
		Argument Against Human Missions	Reasons against sending humans to Mars.

Table 34 continued

		Field Geology	How geologists already do field geology and how that relates to the activities that astronauts will need to perform.
		General vs Specific Applicability of Rovers	The more specifically a rover operation is examined, the more different it will look from human operations on Mars.
		Maintaining Institutional Knowledge	The challenge of rover missions maintaining institutional knowledge as people leave the missions and new people are brought in.
		Mission Architecture & Design	Different kinds of mission architectures that human missions to Mars could adopt. The fact that the architecture under which human missions will operate has not yet been determined and it will affect operations.
Role Collaboration	Collaborations between operations personnel (e.g. sharing information, consultations, etc.) in order to meet goals.	Campaign Lead & Engineering	-
		Campaign Lead & Upper Mission Management	-
		LTP & Engineering	-
		LTP & Mission Lead	-
		LTP & Science Team	-
		LTP & sTL	-
		LTP & SuTL	-
		LTP & TUL	-
		LTP & Upper Mission Management	-
		PDL & Engineering	-
		PDL & Instrument Systems Lead	-
		PDL & LTP	-
		PDL & Payload Downlink Coordinator (PDC)	-
		PDL & PUL	-

Table 34 continued

		PDL & Upper Mission Management	-
		PUL & Engineering	-
		PUL & EUL (Engineering Uplink Lead)	-
		PUL & Instrument Rep	-
		PUL & LTP	-
		PUL & MDM (Memory Data Manager)	-
		PUL & Mission Lead	-
		PUL & PUL	-
		PUL & sTL	-
		PUL & TUL	-
		PUL & Upper Mission Management	-
		RP & LTP	-
		RP & Mission Lead	-
		RP & PUL	-
		RP & Sci Team	-
		RP & Science Planner	-
		RP & SOC	-
		RP & SOWG	-
		RP & SPS	-
		RP & sTL	-
		RP & TDL	-
		SOC & Eng	-
		SOC & Sci Team	-
		SOWG & Engineering	-
		SOWG & LTP	-
		SOWG & PDL	-
		SOWG & PUL	-
		SOWG & Science Team	-
		SOWG & sTL	-
		SOWG & TUL	-

Table 34 continued

		SOWG & Upper Mission Management	-
		sTL & Engineering	-
		sTL & Upper Mission Management	-
		SuTL & Engineering	-
		SuTL & RP	-
		SuTL & SOC	-
		TAP & LTP	-
		TAP & TDL	-
		TDL & Instrument Sys Lead	-
		TDL & Mission Lead	-
		TUL & Mission Lead	-
		TUL & PDC	-
		TUL & RP	-
		TUL & Sci Planner	-
		TUL & Sci Team	-
		TUL & TAP	-
		TUL & TDL	-
Strategic Info	Information relevant to the strategic process (e.g. setting goals, achieving goals, re-planning goals).	Drive Path	The planned/outlined traverse path of the rover. Includes distances/time estimates to reach specific areas.
		Duration of Activities	The time requirements for the completion of each activity/set of activities.
		Flight Rules & Constraints	Semi-constant constraints (usually in the form of flight rules) that impact activity planning.

Table 34 continued

		In Situ Context & Information	Results of tests/activities done by the rover that provide contextual information for planning. How the tactical results/data fit together to make a clearer picture. Does not include discoveries that quickly/dramatically change the plan due to being unexpected. Includes images that put features viewed from orbit into context. Includes science trends that can influence future activities.
		Location of Interesting Science Targets or Areas	The location of areas on the Martian surface with interesting scientific targets or points of interest.
		Orbital Context & Information	Data gathered from orbit that provide contextual information or information for planning. How the data are used to create plans/drive routes/scientific points of interest. Includes putting the rover location and imagery/results into context. Generally scientific information.
		Orbiter Passes & DSN Availability	When orbiters are passing overhead for relays, whether the rover is in a good position to communicate with those orbiters, and availability of DSN.
		Overall Rover Status	Overall physical status of the rover. Includes body and instrument status (i.e. drill failure, wheel motor failure). Includes vehicle degradation over time. Includes unresolved anomalies.
		Overarching Mission Goals	The larger purpose/goals of the entire mission. Includes both primary and extended missions and the goals of each.
		Past Activities & Performance	Activities performed with the rover in previous planning cycles and the rover's performance while completing those tasks. Includes context as well as activities that need to be performed in a specific sequence. Includes performance degradation over time.

Table 34 continued

		Planned Activities	Specific activities the team want to perform in a certain area/during a certain time period.
		Power	Power availability on the rover, state of charge of the batteries, and the amount of power required by certain activities. Includes factors that affect power availability.
		Readiness of New Capabilities	Strategic development efforts to enhance vehicle capabilities or recover vehicle capabilities.
		Recent Results & Findings	Results of recent rover tests/features in images. Includes findings that may be surprising or interesting and affect or alter the established strategic plan. Discoveries.
		Rover Location	The location of the rover on the surface with respect to points of interest or the planned drive path. Includes general features around the rover.
		Science Objectives or Hypotheses	The research questions that scientists are trying to answer, the hypotheses they are testing, and the priority given to each research question/objective. Includes how certain rover activities relate to answering those questions.
		Scientific Interest of Location or Landing Site	Whether or not an area is scientifically interesting and what is interesting about that location.
		Strategic Plans	Current or past strategic plans. Includes sol-paths/decision trees.
		Terrain Traverse-ability	Whether or not the rover can traverse a certain terrain/area of a map.
		Unexpected Occurrences	Things that happen unexpectedly with the Martian environment or the rover hardware/software that will affect the strategic plan. Does not include unexpected or surprising science results.
Strategic Data Updates	How often strategic data streams are updated.	APXS	How often APXS data updates (as it relates to strategic planning).
		ChemCam	How often ChemCam data updates (as it relates to strategic planning).

Table 34 continued

		CheMin	How often CheMin data updates (as it relates to strategic planning).
		Images	How often new images are received from the rover (as it relates to strategic planning).
		Orbital Data	How often orbital data updates (as it relates to strategic planning).
		Rover Telemetry	How often rover telemetry data updates (as it relates to strategic planning).
		SAM	How often SAM data updates (as it relates to strategic planning).
Strategic Data Processing or Analysis	Analysis or processing done on a strategic data stream before it is used in the strategic process.	APXS	Processing/analysis done on APXS data.
		ChemCam	Processing/analysis done on ChemCam data.
		CheMin	Processing/analysis done on CheMin data.
		DAN	Processing/analysis done on DAN data.
		Images	Processing/analysis done on images.
		Orbital Data	Processing/analysis done on orbital data.
		SAM	Processing/analysis done on SAM data.
Strategic Re-planning Occurrence	The frequency with which strategic goals need to be re-planned.	-	-
Supratactical Info	Information relevant to the supratactical process (e.g. setting goals, achieving goals, re-planning goals).	Activity Priority	Which desired activities have higher priority than others.
		Arm Orientation	The orientation/position of the rover arm.
		Data Storage & Transmission Management	Considerations surrounding the amount of onboard storage on the rover, when transmissions will occur, and the amount of data transfer that will occur during orbiter passes. Includes considerations on the amount of data activities generate.
		Drive Path	The planned/outlined traverse path of the rover. Includes distances/time estimates to reach specific areas.
		Duration of Activities	The time requirements for the completion of each activity/set of activities.

Table 34 continued

		Liens	A "to do" list of activities for the rover that need to be fit into a tactical plan.
		Past Activities & Performance	Activities performed with the rover in previous planning cycles and the rover's performance while completing those tasks.
		Power	Power availability on the rover, state of charge of the batteries, and the amount of power required by certain activities. Includes factors that affect power availability.
		Recent Results & Findings	Results of recent rover tests/features in images. Includes findings that may be surprising or interesting and affect or alter the established supratactical plan. Discoveries.
		Required Activities	Activities that need to be performed in order to allow other activities to move forward or ensure the health & safety of the rover.
		Rover Position	The position of the rover with respect to targets of interest, the planned drive path, cardinal direction (north/south, etc.) and tilt.
		Rover Status	Whether all rover systems, including instruments, are nominal or whether there are anomalies that need to be resolved/investigated.
		Scientific Targets and Planned Activities	Specific activities the team want to perform, and on which targets.
		Strategic Goals & Plans	Established strategic plans and goals to meet.
		Sun Position and Light Conditions	What the light conditions and sun position will be at a certain time of day, in a certain location, at a certain heading.
		Supratactical Plans	Existing supratactical plans or the current supratactical plan.
		Surface Roughness or Texture or Hardness	The hardness of a surface (to determine whether or not it can be drilled by the rover).

Table 34 continued

		Task Ordering Constraints	Constraints that exist that mandate certain tasks be performed in a certain sequence.
		Unexpected Occurrences	Things that happen unexpectedly with the Martian environment or the rover hardware/software that will affect the supratactical plan. Does not include unexpected or surprising science results.
Supratactical Data Updates	How often supratactical data streams are updated.	Rover Telemetry	How often rover telemetry data updates (as it relates to supratactical planning).
Supratactical Data Processing	Analysis or processing that has to be done on a supratactical data stream before it is used in the supratactical process.	Images	Processing/analysis done on images.
		Rover Telemetry	Processing/analysis done on rover telemetry data.
Supratactical Re-planning Occurrence	The frequency with which supratactical goals need to be re-planned.	-	-
Tactical Info	Information relevant to the tactical process (e.g. setting goals, achieving goals, re-planning goals).	Activity Priority	Which desired activities have higher priority than others.
		Arm Orientation	The orientation/position of the rover arm. Includes whether or not a movement of the arm can be done safely.
		Data Storage and Transmission Management	Considerations surrounding the amount of onboard storage on the rover, when transmissions will occur, and the amount of data transfer that will occur during orbiter passes. Includes considerations on the amount of data activities generate.
		Decision or Information Priority	Which decision or piece of information has higher priority than others and should therefore be addressed first.
		Drive Path	The planned/outlined traverse path of the rover. Includes distances/time estimates to reach specific areas.
		Duration of Activities	The time requirements for the completion of each activity/set of activities. Includes the amount of time available to do various activities.

Table 34 continued

		Experimental Conditions	The specific experimental conditions reached during the performance of an experiment on the rover.
		Instrument Capability	Understanding the capabilities of an instrument and whether or not it can accomplish a task.
		Interactions between Rover Elements	Making sure that no commands cause different elements of the rover to interfere with each other.
		Liens	A “to do” list of activities for the rover that need to be fit into a tactical plan.
		Location Context	Details of a particular location once you first arrive there with the rover after a drive. Includes determining the scientific interest of the location. Does not include potential targets in the workspace.
		Overarching Mission Goals	The larger purpose/goals of the entire mission. Includes both primary and extended missions and the goals of each.
		Past Activities & Performance	Activities performed with the rover in previous planning cycles and the rover’s performance while completing those tasks.
		Power	Power availability on the rover, state of charge of the batteries, and the amount of power required by certain activities. Includes factors that affect power availability.
		Recent Results & Findings	Results of recent rover tests/features in images. Includes findings that may be surprising or interesting and affect or alter the established supratactical/tactical plan. Discoveries.
		Required Activities	Activities that need to be performed in order to allow other activities to move forward or ensure the health & safety of the rover.
		Rover Position	The position of the rover with respect to targets of interest, the planned drive path, cardinal direction (north/south, etc.) and tilt.

Table 34 continued

		Rover Status	Whether all rover systems, including instruments, are nominal or whether there are anomalies that need to be resolved/investigated.
		Science Objectives or Hypotheses	The research questions that scientists are trying to answer, the hypotheses they are testing, and the priority given to each research question/objective. Includes how certain rover activities relate to answering those questions.
		Scientific Targets & Desired Observations or Activities	Specific activities the team want to perform, and on which targets. Includes targets of opportunity.
		Strategic Goals & Plans	Current strategic plan and strategic goals.
		Sun Position & Light Conditions	Where the sun will be at a particular time and how that will affect the light conditions around the rover or on a chosen target.
		Surface Roughness or Texture or Hardness	Information about surfaces of rocks/ground on Mars. Includes prevalence of dust.
		Tactical & Supratactical Plans	Existing tactical/supratactical plans or the current tactical/supratactical plan. Includes contingency plans.
		Task Ordering Constraints	Constraints that exist that mandate certain tasks be performed in a certain sequence.
		Terrain Details & Travers-ability	Details about the terrain surrounding the rover and whether or not it can traverse a certain terrain. Includes the risks and hazards associated with driving a certain direction or taking a certain path.
		Unexpected Occurrences	Things that happen unexpectedly with the Martian environment or the rover hardware/software that will affect the tactical plan. Does not include unexpected or surprising science results.

Table 34 continued

		Workspace	Potential targets (or lack of potential targets) within reach of the rover's instruments.
Tactical Data Updates	How often tactical data streams are updated.	APXS	How often APXS data updates (as it relates to tactical planning).
		ChemCam	How often ChemCam data updates (as it relates to tactical planning).
		CheMin	How often CheMin data updates (as it relates to tactical planning).
		Images	How often new images are received from the rover (as it relates to tactical planning).
		Rover Telemetry	How often rover telemetry data updates (as it relates to tactical planning).
		SAM	How often SAM data updates (as it relates to tactical planning).
Tactical Data Processing or Analysis	Analysis or processing that has to be done on a tactical data stream before it is used in the tactical process.	APXS	Processing/analysis done on APXS data.
		ChemCam	Processing/analysis done on ChemCam data.
		CheMin	Processing/analysis done on CheMin data.
		Images	Processing/analysis done on images.
		Orbital Data	Processing/analysis done on orbital data.
		Rover Telemetry	Processing/analysis done on rover telemetry data.
		SAM	Processing/analysis done on SAM data.
Tactical Re-planning Occurrence	The frequency with which tactical goals need to be re-planned.	-	-
Tasks to Achieve Goals	Scripts/procedures/priorities/ tasks for different roles.	Campaign Lead Script	Scripts/procedures/priorities/tasks for a Campaign Lead.
		Instrument Sys Lead Script	Scripts/procedures/priorities/tasks for an Instrument Systems Lead.
		LTP Script	Scripts/procedures/priorities/tasks for a Long-Term Planner.
		Mission Lead Script	Scripts/procedures/priorities/tasks for a Mission Lead.
		PDC Script	Scripts/procedures/priorities/tasks for a Payload Downlink Coordinator.
		PDL Script	Scripts/procedures/priorities/tasks for a Payload Downlink Lead.

Table 34 continued

		PUL Script	Scripts/procedures/priorities/tasks for a Payload Uplink Lead.
		RP Script	Scripts/procedures/priorities/tasks for a Rover Planner.
		Science Planner Script	Scripts/procedures/priorities/ tasks for a Science Planner.
		SOWG Script	Scripts/procedures/priorities/ tasks for a SOWG Chair.
		sTL Script	Scripts/procedures/priorities/ tasks for a Science Theme Lead.
		SuTL Script	Scripts/procedures/priorities/ tasks for a Supratactical Lead.
		TDL Script	Scripts/procedures/priorities/ tasks for a Tactical Downlink Lead.
		TUL Script	Scripts/procedures/priorities/ tasks for a Tactical Uplink Lead.

APPENDIX F. DATA SET DISTRIBUTIONS

The distributions of the data sets for each case are provided below. The figures provide visual demonstrations of the data distribution (red line) as compared to a normal distribution with the same mean and standard deviation (blue line). The goodness of fit tests are provided below each figure for each case. Those tests that indicate the distribution is approximately normally distributed (fails to reject the null hypothesis that the distribution is normally distributed at the α=0.05 level) are shaded.

Heart Rate

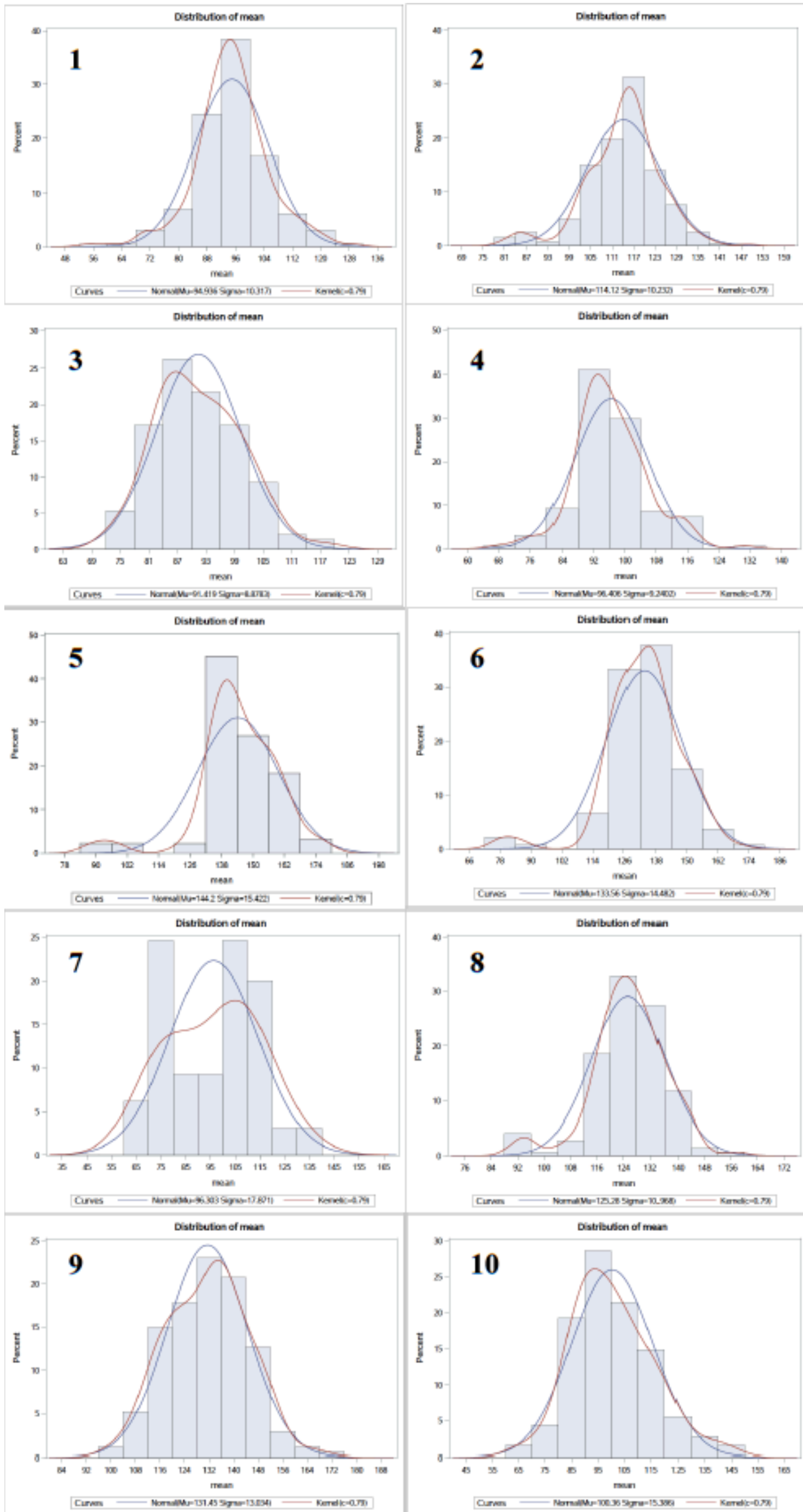

Figure 27: Heart Rate Distributions per Case

Table 35: Heart Rate Goodness of Fit Tests

Case	Test	Kolmogorov-Smirnov	Cramer-von Mises	Anderson-Darling
1	**Statistic**	0.0703	0.3253	1.9171
	p-value	<0.010	<0.005	<0.005
2	**Statistic**	0.0682	0.4804	3.0053
	p-value	<0.010	<0.005	<0.005
3	**Statistic**	0.0746	0.1354	0.7437
	p-value	0.038	0.039	0.052
4	**Statistic**	0.0652	0.2441	1.5150
	p-value	0.087	<0.005	<0.005
5	**Statistic**	0.1547	0.3115	2.3576
	p-value	<0.010	<0.005	<0.005
6	**Statistic**	0.0881	0.1887	1.6863
	p-value	0.011	0.008	<0.005
7	**Statistic**	0.1303	0.2097	1.1682
	p-value	<0.010	<0.005	<0.005
8	**Statistic**	0.0751	0.1597	1.3336
	p-value	0.043	0.019	<0.005
9	**Statistic**	0.0603	0.0754	0.4420
	p-value	0.123	0.240	>0.250
10	**Statistic**	0.0639	0.1691	1.0053
	p-value	0.070	0.014	0.012

Respiration Rate

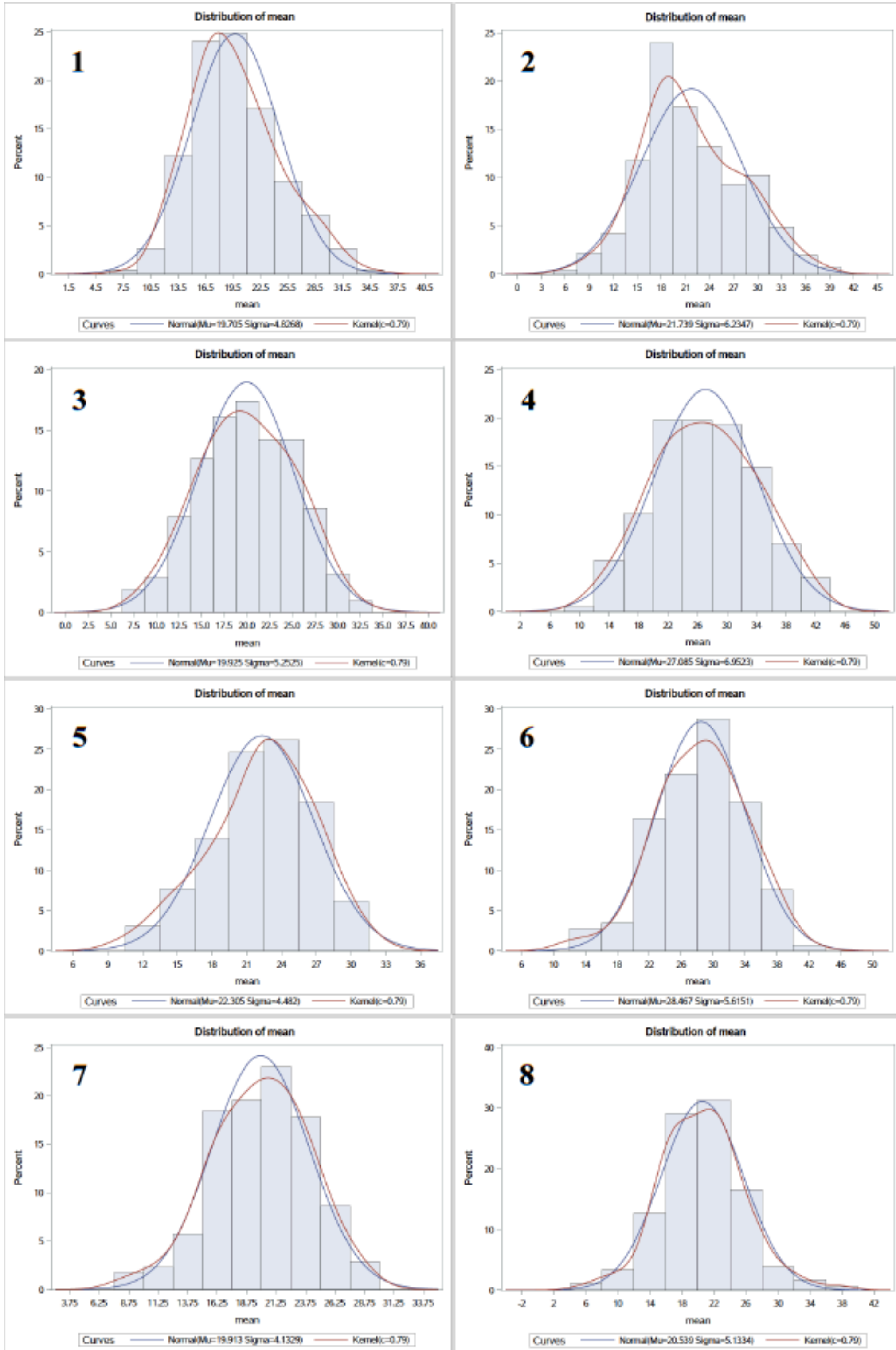

Figure 28: Respiration Rate Distributions per Case

Table 36: Respiration Rate Goodness of Fit Tests

Case	Test	Kolmogorov-Smirnov	Cramer-von Mises	Anderson-Darling
1	**Statistic**	0.0685	0.2417	1.4649
	p-value	<0.010	<0.005	<0.005
2	**Statistic**	0.0774	0.4969	2.5694
	p-value	<0.010	<0.005	<0.005
3	**Statistic**	0.0411	0.0666	0.4286
	p-value	>0.150	>0.250	>0.250
4	**Statistic**	0.0369	0.0572	0.3925
	p-value	>0.150	>0.250	>0.250
5	**Statistic**	0.0878	0.0744	0.4473
	p-value	>0.150	0.244	>0.250
6	**Statistic**	0.0433	0.0297	0.2463
	p-value	>0.150	>0.250	>0.250
7	**Statistic**	0.0421	0.0357	0.2445
	p-value	>0.150	>0.250	>0.250
8	**Statistic**	0.0466	0.0601	0.4787
	p-value	>0.150	>0.250	0.238

Heart Rate Variability

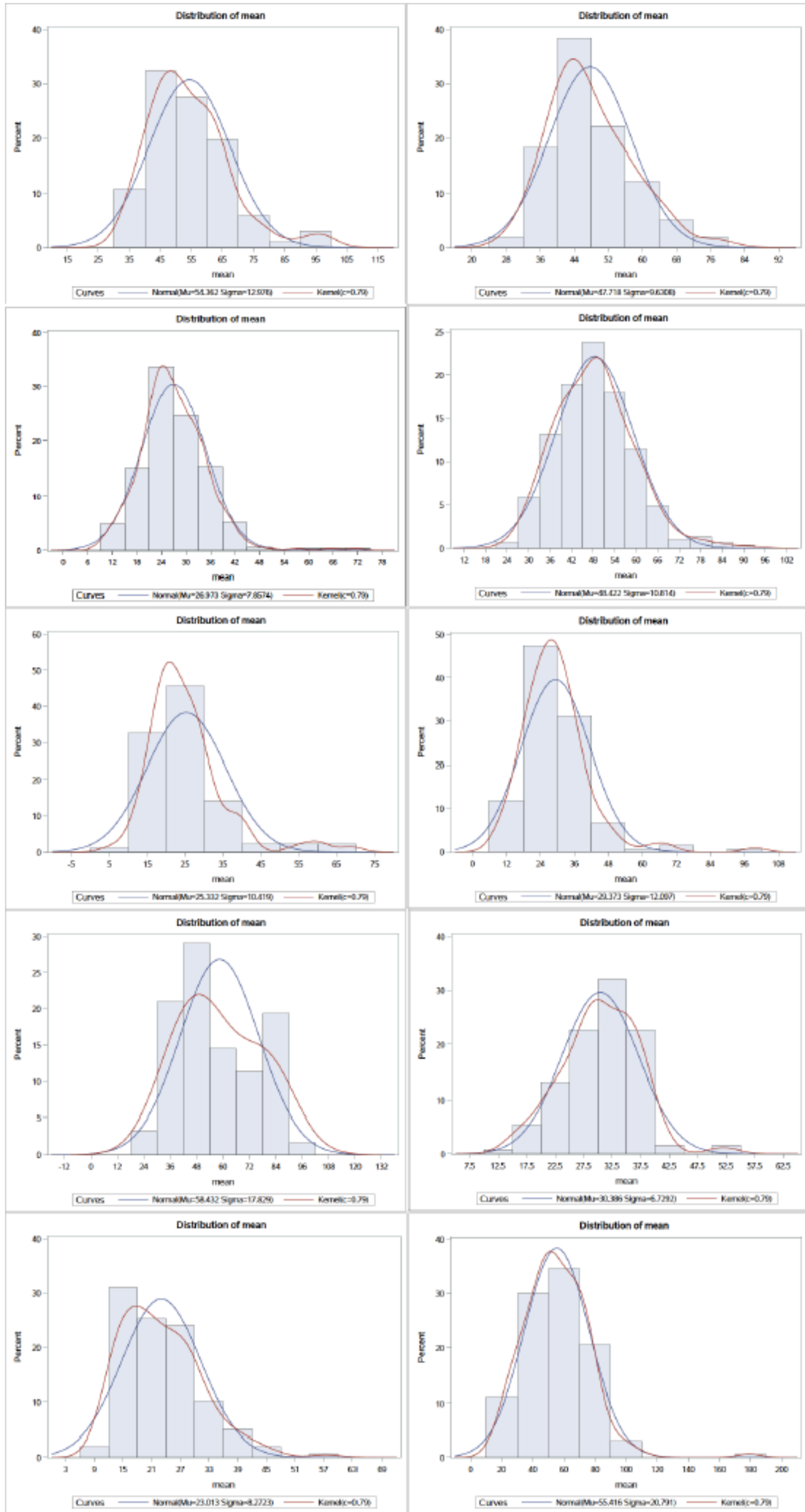

Figure 29: Heart Rate Variability Distributions per Case

Table 37: Heart Rate Variability Goodness of Fit Tests

Case	Test	Kolmogorov-Smirnov	Cramer-von Mises	Anderson-Darling
1	**Statistic**	0.0934	0.2168	1.5940
	p-value	0.027	<0.005	<0.005
2	**Statistic**	0.1031	0.2086	1.1336
	p-value	0.010	<0.005	0.006
3	**Statistic**	0.0595	0.2972	1.8321
	p-value	<0.010	<0.005	<0.005
4	**Statistic**	0.0450	0.1115	0.8493
	p-value	0.134	0.083	0.029
5	**Statistic**	0.1532	0.5369	3.3323
	p-value	<0.010	<0.005	<0.005
6	**Statistic**	0.1119	0.4260	2.7729
	p-value	<0.010	<0.005	<0.005
7	**Statistic**	0.1382	0.2242	1.3321
	p-value	<0.010	<0.005	<0.005
8	**Statistic**	0.0604	0.0907	0.6455
	p-value	>0.150	0.150	0.092
9	**Statistic**	0.0843	0.2788	1.9964
	p-value	<0.010	<0.005	<0.005
10	**Statistic**	0.0587	0.0881	0.8019
	p-value	>0.150	0.166	0.039

PUBLICATIONS

Journal Publications

Hill, J. R., Caldwell, B. S., Downs, M. T., Miller, M. J., & Lim, D. S. S. (2019). Remote physiological monitoring in a Mars analog field setting. *IIE Transactions on Healthcare Systems Engineering*, 8(3), 227-236.

Conference Papers

Hill, J. R., & Caldwell, B. S. (2019). A bootstrap method for the analysis of physiological data in uncontrolled settings. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting,* Oct. 28-Nov. 1, 2019.

Caldwell, B. S., Nyre-Yu, M., & **Hill, J. R.** (2019). Advances in Human-Automation Collaboration, Coordination and Dynamic Function Allocation. *26th ISTE International Conference on Transdisciplinary Engineering.* Tokyo, Japan. Jul. 30-Aug. 2, 2019.

Hill, J. R., & Caldwell, B. S. (2018). Toward better understanding of function allocation requirements for planetary EVA and habitat tasks. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting,* Oct. 1-5, 2018.

Hill, J. R., Caldwell, B. S., Miller, M. J., & Lees, D. S. (2016). Data Integration and Knowledge Coordination for Planetary Exploration Traverses. *18th International Conference on Human-Computer Interaction.* Toronto, Canada. Jul. 17-22, 2016.

Conference Posters

Caldwell, B. S., & **Hill, J. R.** (2019). Human-Systems Integration and Function Allocation for Human Exploration of Mars. Presented at: *2019 NASA Human Research Program Investigators' Workshop.* Galveston, TX. Jan. 22-25, 2019. Presented by: Barrett S. Caldwell.