10 Working in Space

Managing Transitions between Tasks

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> Space sure is a busy place.
> I am sensing a common theme: non-stop days.
> There are only two days in a week on ISS: Monday and Friday, with a couple of hours in between.

These three reflections on work in space were captured in the diaries of astronauts living and working aboard the International Space Station (ISS; Stuster, 2010). Working in space has been characterized in many ways. One of the prevalent themes percolating in diaries and interviews with astronauts is the intense timeline where astronauts perform many tasks in a day, each with a small amount of time allocated to it, fueling a constant pressure to monitor the clock and stay on schedule. As one astronaut put it: "It's like a continuous battle against time up here. There is a lot of stress with that. It's just a continuous time battle (Stuster, 2010, p. 24)."

A second prevalent theme is the collaborative and interdependent nature of working in space. Collaboration sometimes describes the interactions within the crew, helping one another, or providing social support: "This is a really good crew to work together and it is more fun that way. I think we all enjoy doing stuff together (Stuster, 2010, p. 22)." At other times, collaboration refers to the crew working with mission control: "Ground has been a huge help, but they cannot win us back time and that is what we need now (Stuster, 2010, p. 24)."

A third prevalent theme is that not all work in space is equally engaging. In fact, many of the tasks that must get done for the station to function can be frustrating:

> This procedure was awful. Steps were missing, the stowage note was wrong in multiple places, nothing made sense. I remarked to X that if this is how things used to be every day on ISS, I can definitely understand why people get fed up with ops here. It was a disaster. And it went about 2 hours over the allocated time, which made it even worse.
>
> *Stuster (2010, p. 61)*

In a similar vein, work in space can be repetitive:

> Sometimes it's a little bit like Groundhog Day. You wake up at the same time every day. You look at the schedule and figure out what you're going to do. Even though the tasks are different, it feels like you're doing the same thing over and over again.
>
> *Stuster (2010, p. 19).*

Taken together, these themes about the nature of working in space provide a useful framework for shaping research and interventions around work design. The picture of work in space is a tight timeline: "your life is marked in 5-minute increments" (ISS astronaut, personal communication). The day is divided into many tasks assigned to tiny increments – 5 minutes to do this, 10 minutes to do that. In addition to the frenzied pace is a tacit collaborative aspect to the work. Indeed, two of this chapter's authors interviewed an ISS astronaut soon after she returned. When we asked her for an example of work tasks that she did alone, she paused. She said that everything in space requires teamwork. Even when a task is assigned to a single astronaut to complete, someone came before and someone will come after. Before, there were the individuals who wrote the procedure, and the astronaut is trying to figure out what they intended. After, there are those who will check on the work. Even when one is working alone in space, there is an imagined web of interdependence. From this we come to understand that not only are astronauts jumping from task to task, they are traversing social dynamics as well. They work with different people, in space and on Earth, from different educational and cultural backgrounds.

A final note about the themes associated with work in space is the constant mention of material artifacts that affect the nature and efficiency of collaboration: schedules, procedures, tools, supplies, computers, sensors. For example, the awareness of a sensor that allows the ground to know what an astronaut is doing: "The freezer cannot be open for more than 1 minute. The ground can see when I open the door and close it, so no cheating (Stuster, 2010, p. 38)." There are also entries that highlight how astronauts come to associate expertise with people in the course of doing their work: “It is a Russian system originally, so X has expertise, especially when it comes to those pesky Russian fluid connectors (Stuster, 2010, p. 38).” A simple email message shapes a crewmember’s perception of what the ground is doing and why they are doing it:

> I received an email from X about the EVA. They were looking at changing the date… The more I am here I can see how much things are analyzed or over analyzed and how much they are trying to protect crew time.
>
> *Stuster (2010, p. 30)*

As such, working in space requires jumping from task to task, traversing social dynamics, and interacting with a variety of material artifacts that can meaningfully shape action and interaction.

Interviews with current and former astronauts as well as reports from astronauts on the International Space Station (ISS) highlight the potential for decrements in crew performance stemming from difficulties in shifting back and forth between independent work and highly interdependent work (Smith-Jentsch, 2015). Given the ebbs and flows of space work, focusing on work transitions allows one to understand the switching costs and flow advantages that come from the particular sequencing of tasks. We define this as a problem of team task transitions. The core idea of this chapter is that the scheduling and sequencing of work affects how easy or difficult it is for astronauts to complete it. In the next section, we elaborate on the factors that shape task transitions.

TEAM TASK TRANSITIONS

The nature of work in space involves completing a variety of tasks and interacting with a variety of technologies and tools. This work also varies in terms of how much interdependence and interaction crewmembers have with their fellow crewmembers, with their disciplinary teams on Earth, and/or with mission control during their work. Therefore, an astronaut’s work involves transitioning among tasks, tools, technologies, and people/teams, which can place cognitive, motivational, and behavioral demands on crewmembers as they adjust to changes in tasks/tools/people. Further, the structure of NASA includes teams of teams working on all aspects of a mission, so the crew’s interdependence with this system of teams often requires individuals to shift goal focus in response to dynamic situational requirements with very little warning. So while an astronaut may be working independently on a task, they could be interrupted to assist with an emergent condition and quickly come up to speed, working interdependently with fellow crewmembers as well as mission control. Their ability to juggle the implications of switching across tasks, tools, and teams ultimately affects performance.

In order to illustrate how the interdependence of work affects how easy or difficult it is to move from one task to another, we present survey data provided by six astronauts as they worked aboard the ISS. Each astronaut provided data on 14 occasions that were approximately evenly spaced across their time on the ISS. We asked these astronauts to rank a series of work transitions in order of how difficult they are, "How difficult is each type of transition for you (1 = least difficulty, 6 = most difficult)". First, we distinguished work tasks that a crewmember completes alone (e.g., stowage, running errands around the station), work tasks completed with the help of one or more crewmembers (e.g., research, airlock tasks), and work tasks requiring direct coordination with mission control (e.g., EVAs). When transitioning work tasks, each transition can involve an increase or decrease in autonomy. For example, when moving from a solo task to a task with Mission Control Center (MCC), the crewmember decreases autonomy and substantially increases the amount of interdependence or mutual reliance on others required by the work. We detailed six transitions. The first three transitions involve an increase in autonomy: moving from a crew task to a solo task (Crew to Solo), moving from a task completed with mission control to a solo task (MCC to Solo), and moving from a task completed with mission control to a task completed with the crew (MCC to crew). The second three transitions involve a decrease in autonomy: moving from a solo task to a crew task (Solo to Crew), moving from a task completed with the crew to one completed with mission control (Crew to MCC), and moving from a task completed alone to one completed with mission control (Solo to MCC).

Figure 10.1 presents the average ranked difficulty of these transitions reported by the six ISS astronauts who participated. The three shifts that involve increases in autonomy are presented on the left, and the three shifts that involve decreasing autonomy are on the right. Interestingly, work transitions that involve a gain in autonomy were reported as easier to make by astronauts. Work transitions that involve a loss in autonomy, or conversely, an increase in interdependence, were ranked as being more challenging to astronauts. The easiest transition to make is to go from working with

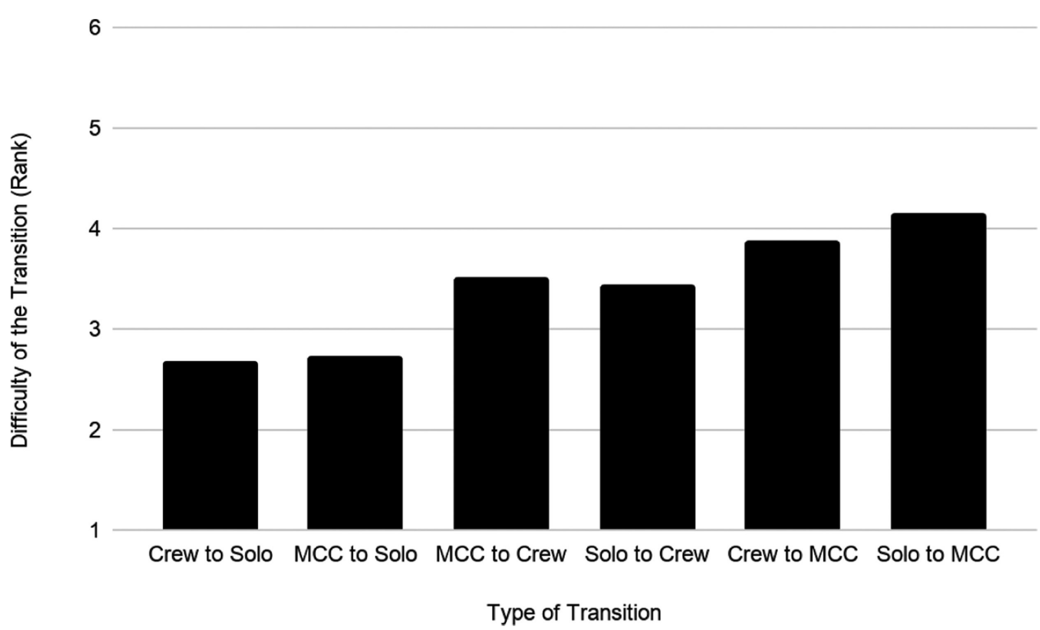

FIGURE 10.1 Astronaut rankings of the relative difficulty of task transitions made while working aboard the International Space Station ($N = 6$).

the crew on something to working on a task alone. In contrast, the most challenging transition is to go from a task an astronaut is completing alone to working on a task with mission control. A key message from this data is that the sequencing of work over the course of day matters.

In order to better understand the complete set of factors that may determine the ease or difficulty of making task transitions, we turned to two research literatures. The first is the literature on task switching within human factors in cognitive psychology (Allport & Wylie, 1999; Payne, Duggan, & Neth, 2007; Monk, Trafton, & Boehm-Davis, 2008; Wickens, Santamaria, & Sebok, 2013). The second is the literature on team effectiveness within social and industrial psychology as well as organizational behavior (DeShon, Kozlowski, Schmidt, Milner, & Wiechmann, 2004; Gersick & Hackman, 1990; McGrath, Arrow, & Berdahl, 2000; McGrath & Kelly, 1986). From a human factors and cognitive psychology perspective, the problem of task transitions has been examined in terms of how individuals allocate their time between an ongoing task and one or more alternative tasks. An operator's decision to remain on the ongoing task or move on to one of many alternative tasks is defined in terms of "choice probabilities" (Wickens et al., 2013). This probabilistic approach to task switching includes weighting factors that contribute to the "stickiness" of the ongoing task (i.e., switch avoidance, task inertia difficulty effect, priority, and interest), and the "attractiveness" of alternative tasks (i.e., alternative task difficulty effect, priority and interest; Wickens et al., 2013). The following quote by a former Skylab astronaut highlights how differences in alternative task attractiveness may have implications for decisions about task transitions:

> We literally pinned the [list of tasks to be done] up on the wall of the spacecraft and when we had a free minute we'd go down and pick a job we felt like doing on [the list], draw a line through it, then go do it.
>
> *Carr (1986, pp. 19–20, as cited in Wittenbaum, & Stasser, 1996, p. 80.)*

A cognitive perspective on task switching does not provide a complete picture of the predictors of adaptive task switching nor of the implications of maladaptive task switching, particularly within environments where individuals must switch among tasks that are independent as well as interdependent, and wherein interdependencies cross team and multi-team boundaries. In these work environments, task switching is also a social phenomenon. From a social/organizational psychology perspective, one reason crewmembers may experience difficulties when switching between work modes may stem from social entrainment to a particular working style (McGrath & Kelly, 1986). When an individual spends a great deal of time working in one task mode (e.g., on independent tasks or with a particular team), he or she may become entrained to a work mode (speed, efficiency, quality) that does not translate efficiently and effectively to a new task or team context, decrementing performance (McGrath et al., 2000). In space, crewmembers can be entrained to the rhythms of their own independent tasks, to the rhythms of other team members (e.g., during interdependent team tasks), to the rhythms of other teams (e.g., ground control), and/or to the rhythms of other external or internal pacers. A crewmember's difficulty in task switching may also stem from other social factors, like varying levels of trust, familiarity, similarity, or experience they have within the various social collectives within which they work (Mortensen, Woolley, & O'Leary, 2007).

Transition costs have a direct bearing on *performance adaptation,* which refers to the "cognitive, affective, motivational, and behavioral modifications made in response to the demands of new or changing situational demands" (Baard, Rench, & Kozlowski, 2014, p. 50). Pulakos, Arad, Donovan, and Plamondon (2000) defined adaptability as a set of behaviors "demonstrating the ability to cope with change and to transfer learning from one task to another as job demands vary" (Allworth & Hesketh, 1999, p. 98). Crewmembers' ability and motivation to switch efforts among different task-based work styles in response to changing environmental demands is an essential element of successful performance adaptation in LDSE.

Building on Baard and her colleagues' (2014) definition of performance adaptation, we define *adaptive team task switching as an individual's cognitive, affective, motivational, and behavioral modifications made in response to team task switches.* Some researchers define performance adaptation as "individuals' willingness to adapt (e.g., Cronshaw & Jethmalani, 2005)", others define it as the "ability to adapt (e.g., Allworth & Hesketh, 1999)," and still others as the "demonstration of effective adaptation (e.g., Pulakos, Schmitt, Dorsey, Arad, Borman, & Hedge, 2002)." We disentangle these in our model to identify the specific factors that lead to adaptive task switching. Doing so is critical to the design of effective countermeasures, as it is plausible that different levers can be used to target each of these important components of adaptive team task switching. For example, certain aspects of crew composition may affect the ability to switch, whereas other aspects of composition may affect the willingness to switch. Similarly, job design countermeasures are likely critical to the motivational aspects of task switching (Hackman & Oldham, 1976).

Astronaut crews must frequently, and sometimes spontaneously, engage in team task transitions, which requires them to shift between one or more core dimensions of their work – tasks, teams, and/or tools – to accomplish new work demands. NASA recognizes that task and team transitions com with switching costs in terms of depleted attentional, cognitive, and motivational resources, and these costs have implications for performance at individual, team, and multiteam levels. Next, we introduce a model that integrates the disparate cognitive and social perspectives on team task switching to highlight five key factors that affect work in space.

PART 1: FIVE FACTORS THAT AFFECT WORK IN SPACE

Task management refers to how individuals decide among the tasks they will execute when multiple tasks are available (Wickens, Gutzwiller, & Santamaria, 2015). There is a natural propensity to continue doing what one is already doing, due to the state of flow that develops as an individual continues to engage in a task (i.e., task inertia; e.g., Csikszentmihalyi, 1991). When one is engaged in an ongoing task, there are costs associated with changing tasks. Wickens and colleagues (2015) define "task stickiness" as the sum of the inertial forces acting upon an individual to remain on a given task. Not only do tasks vary in their level of stickiness, they also vary in terms of their level of "attractiveness" (Wickens et al., 2015). A task's "attractiveness" is defined as all attributes of a task that increase the likelihood that someone will switch to that task given the opportunity (Wickens et al., 2015). Some tasks are inherently more interesting, fun, and engaging than others and therefore are more tempting to switch to despite the associated costs of switching. Other tasks are inherently more boring, repetitive, or time consuming, and therefore are less attractive in nature.

A review of the literature as well as interviews with astronauts and support personnel have revealed five core factors that affect task transitions in space: (1) task characteristics, (2) social factors, (3) technology affordances, (4) situational constraints, and (5) individual differences. In this section, we describe the literature on each factor and summarize how it is believed to shape the two critical components of task transitions: stickiness and attractiveness. These factors are visually depicted in Figure 10.2.

Factor 1 – Task Characteristics

The first factor that affects task stickiness and attractiveness relates to the attributes of the task. Research suggests perceptions regarding task (1) difficulty, (2) interest, (3) importance, and (4) salience, have implications for an individual's ability and willingness to switch tasks (Wickens et al., 2015). With regards to *task difficulty*, research has demonstrated that individuals are more likely to switch to an easy task than a difficult task (Wickens et al., 2013), since there is a natural tendency to avoid additional workload, particularly if it may affect their performance (i.e., par hypothesis; Helson, 1949). An exception is that an individual currently working on a difficult task tends to want to complete the difficult task before switching to a new

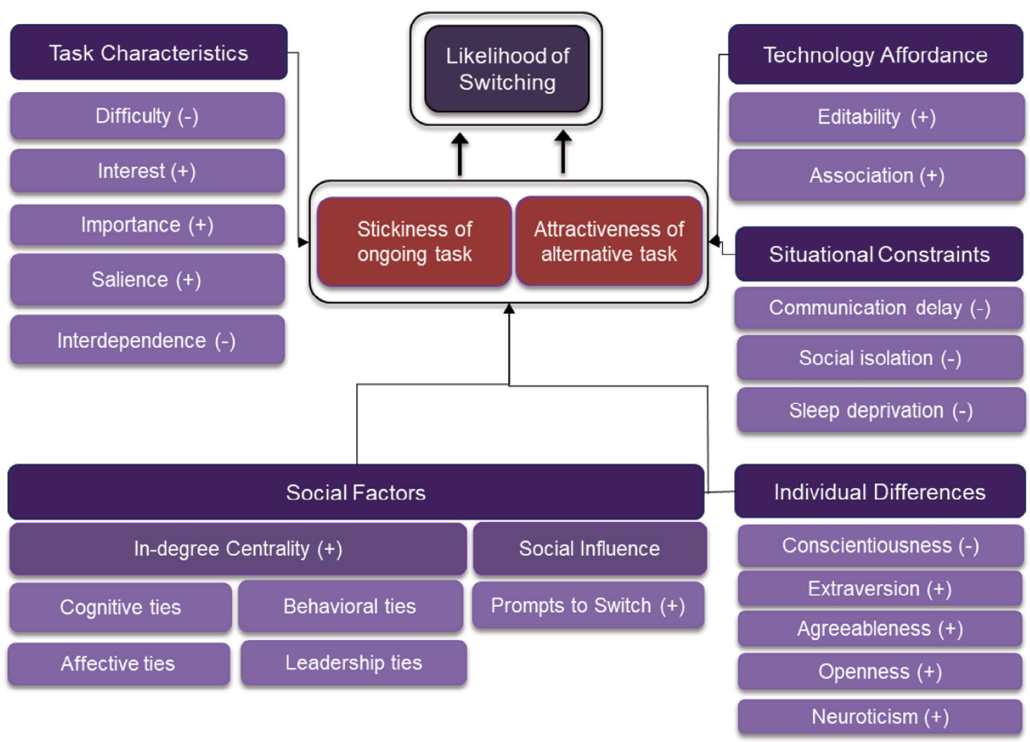

FIGURE 10.2 Conceptual integration of factors affecting task stickiness and attractiveness in space crews.

task (Wickens et al., 2013). Similarly, perceptions of *task interest* may contribute to the likelihood an individual will be inclined to switch tasks. Research supports this idea as individuals have been found to be more likely to switch to an interesting yet difficult task than a boring yet easy task (Wickens et al., 2013). With regards to *task importance*, individuals tend to prioritize tasks based upon their level of importance; alternative tasks perceived to be more important than the ongoing task may prompt a greater willingness to switch. Finally, with regards to *task salience*, some tasks possess characteristics that attract one's attention more than others. For example, a flashing alert on a display may demand an operator's attention away from an ongoing task.

Factor 2 – Social Factors

A second element of team task switching requires individuals to shift attention across teams. Crewmembers on the International Space Station and in long duration space exploration are concurrently members on multiple teams (MTM; O'Leary, Mortensen & Woolley, 2011). Hence they are responsible to all of these teams and likely face differing demands, expectations, and constraints within each team. The multi-teaming aspect of team task switching requires individuals to allocate time and effort across the goals, demands, and constraints of multiple teams. It also requires them to adjust to changes in who they work with on a given task. Even though the tasks performed by these teams are somewhat constant, the particular people they interface with to perform this task can change (e.g., mission control is comprised of functional groups who rotate on three 8-hour work shifts, so individuals within a ground control team may change even though the team itself has not changed). Multi-teaming affects individuals in two ways. First, the amount of time/energy they have to devote to any given team is diminished according to increasing demands of their other team memberships (Mortensen et al., 2007). Second, there is a switching cost associated with moving between teams that may have different behavioral norms, interaction dynamics, etc. Cognitive, affective, motivational, and team composition mechanisms affect both the ability and motivation to switch between teams.

Characteristics of the team may also affect the lateral inertia between the "stickiness of an ongoing team" and the "attractiveness of an alternative team", including (1) cognitive ties, (2) affective ties, (3) behavioral ties, and (4) leadership ties. With regards to *cognitive ties*, shared cognition helps teams cope with changing conditions (Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000). The cost of team switching is diminished if each team is structured such that there are standardized methods for accomplishing work (Zika-Viktorsson, Sundström, & Engwall, 2006), and predictable roles and responsibilities in each team context, thereby facilitating the development of compatible shared mental models within each team. When teams have a similar understanding of their environment, roles, and responsibilities, members are able to effectively function and adapt without explicit coordination (Cannon-Bowers & Salas, 2001). With regards to *affective ties*, team affective states – like familiarity, trust, and cohesion – set the stage for positive working relationships across multiple teams (Mortensen et al., 2007). Further, in MTM contexts where time and effort are limited, resources, familiarity, trust, and cohesion mitigate the risks associated with teamwork (e.g. teammates' failure to contribute to the team task; Hinds, Carley, Krackhardt, & Wholey, 2000), and create a sense of collective efficacy and shared motivation (*behavioral ties*) among the team, likely improving the feasibility of team switching. Finally, *team leadership* factors, like the extent to which leadership is shared/dispersed across members of the team versus being centralized to a subset of team members may affect both the tendency and motivation to switch across tasks.

Factor 3 – Technology Affordances

Tools and technologies used in the workplace carry with them various attributes and affordances that may affect task transitions. Astronauts' work requires the use of a variety of technological tools. Often these tools have unique interfaces, learning curves, and best practices, placing unique cognitive and attentional demands on the user. Much of the extant literature on multi-tooling discusses the motivations for switching across technologies, e.g., boredom (e.g., Mark, Iqbal, Czerwinski, & Johns, 2014; Gergle & Tan, 2014). This literature explores the motives prompting individuals to freely choose to switch platforms. However, in a space flight context, astronauts have less volition and are often forced to make switches across tools in order to meet the demands of their scheduled work. When forced to switch technology platforms, individuals are likely to experience cognitive interference from differences in the interface characteristics or requirements of the ongoing versus alternative tools.

Characteristics of the tool also come into play in affecting perceptions of stickiness and attractiveness. Software collaboration tools vary by the extent to which they provide "affordances" that enable users to maintain a record of shared information, allow members to edit communications, and/or represent or replicate task/team relationships. Further, when users are accustomed to tool-specific techniques for accomplishing an ongoing task, switching tools may result in "tool interference" wherein techniques used in one tool may take time to drop below threshold and temporarily compete with activation of knowledge relevant to new tools used for an alternative task (Memory for Goals Model; Altmann & Trafton, 2002; Chung & Byrne, 2008; Mayr & Keele, 2000). Further, cognitive engineering models of attention allocation (e.g., the NSEEV Model; Wickens, Hooey, Gore, Sebok, & Koenicke, 2009) describe how individuals develop an expectation that particular pieces of information can be found within elements of a particular technology platform, or that they'll have to store certain information using an external tool (e.g., a post-it note; Zhang & Norman, 1994). When using highly automated systems, automation reliance (Lee & See, 2004) could factor in to one's ability to efficiently and effectively switch to a new technology platform.

Two technology affordances may be especially relevant to working in space: editability and association. Editability refers to the extent to which a tool allows users to modify or revise content they've created, allowing the creator to maintain some control over the information over time (Treem & Leonardi, 2012). Editability enables users additional time to craft content or to complete a task, which ultimately permits more purposeful information sharing across members of a team as well as a greater chance for quality, accuracy, and comprehension. Examples of features that afford editability include asynchronous entries, historical data on edits, and ability to revise/delete content. Association refers to the extent to which a tool establishes connections among individuals or between individuals and content (Treem & Leonardi, 2012). This affordance gives users data regarding the relation between users and content as well as among users. Examples of features that enable the association affordance include lists of editors for entries, indications of who has privileges/rights/contributions, links to related information contributed by others, and lists of others who viewed the same content. Editability and association may be particularly helpful in promoting efficient and effective work in space because they foster the (1) exchange and retention of information within and across teams both in space and on Earth, (2) development and maintenance of shared cognition among team members and within the multiteam system, (3) development and maintenance of transactive memory (e.g., who knows what and who did what) within and across teams, and (4) ease and efficiency by which astronauts can switch to/from various tasks/teams/tools. By seeing a record of who knows what and who contributed what, being able to add to and edit prior content, and being able to identify associations among people and content, more efficient communication and greater retention of information is facilitated. Further, individuals can more seamlessly shift into and out of various tasks/teams/tools as they have access to a "cheat sheet" of prior decisions/information, which will allow them to get up to speed more quickly and decrease instances of performance decrements as well as information loss.

Factor 4 – Situational Constraints

Long duration space exploration carries with it unique situational constraints not as frequently experienced by teams on Earth. The dynamics of space explorations require astronauts to work within the confines of lengthy *communication delays* between the astronauts and supporting teams on Earth. A mission to Mars, for example, may encumber a 42-minute round-trip communication delay between the astronauts on Mars and their ground control on Earth. Such delayed communication requires astronauts to be more self-sufficient than ever before and may have implications for task transitions. Space exploration also forces astronaut teams to live in close quarters and to be *socially isolated* from the outside world. Although they have limited opportunities for virtual interactions with colleagues, family, and friends, these interactions are often more sterile than would be the case if they were executed in person. The experience of social isolation may have consequences for task transitions in that astronauts may either have a tendency toward task entrainment, wherein they are less likely to want to switch tasks or they may be forced to engage in task transitions when there are constrained human resources. Finally, astronauts often work extended shifts, and must work through periods of *sleep deprivation*, which is known to affect mental (Lim & Dinges, 2008) and social processes (Driskell, Salas, & Driskell, 2018; Ellis, 2006; Marques-Quinteiro, Curral, Passos, & Lewis, 2013).

Factor 5 – Individual Differences

The contextual reality within which astronauts work suggests sets of personal characteristics may predict likelihood of switching tasks. These factors are particularly critical to crew composition, and so we focus on the personal characteristics needed to have both the ability and motivation to adaptively switch tasks. One's ability to successfully multitask (i.e., the extent to which an individual is capable of switching among tasks in contexts requiring multi-tasking without compromising performance; König, Buhner, & Murling, 2005; Morgan et al., 2012) is not reliably self-assessed by most individuals. Research suggests multi-tasking ability along with its related construct, polychronicity (i.e., an individual's preference for and comfort with multi-tasking and *motivation* to switch among tasks), have implications for work satisfaction, commitment, withdrawal, and turnover intentions (Fahr, 2011; Kaff, 2004; Mesmer-Magnus, Viswesvaran, Bruk-Lee, Sanderson, & Sinha, 2014), and are best predicted by personality characteristics, like emotional stability (e.g., Conte & Jacobs, 2003; Kantrowitz, Grelle, Beaty, & Wolf, 2012; König et al., 2005; Poposki, Oswald, & Chen., 2009), conscientiousness (Conte & Jacobs, 2003; Girgis, 2010; Kantrowitz et al., 2012; Stachowski, 2011), and extraversion (Sanderson, 2012). As such, our model includes the Big Five dimensions of personality as predictors of task transitions.

PART 2: PERCEPTIONS OF WORKING IN SPACE

In reviewing the task management literature, we identified five factors that affect task transitions. Three of these factors can be shaped in work design interventions such as scheduling: task characteristics, social factors, and technology affordances. One way to think about these three is that each places a set of constraints on the individual. The transitions can be easier or harder depending on the nature of the work (task), the interdependence of the work (social), and the technology affordances (tools).

Astronaut perceptions. In order to better understand the relative impact of each type of factor on work transitions, we asked six astronauts working aboard the International Space Station to rank the difficulty of the three factors: orienting to the task, orienting to the people, and orienting to the technologies or tools used to do the tasks. Since the most difficult transition was from solo work to work involving MCC, we then asked these astronauts to rank "How difficult is each factor when transitioning from a solo task to one involving mission control (1 = least difficult, 3 = most difficult)." Figure 10.3 presents the responses broken out by time in mission. Examining Figure 10.3 shows that overall, astronauts ranked "orienting to the people" as the most difficult, followed by "orienting to the tools," and then by "orienting to the tasks." Interestingly, the rankings change over time. "Orienting to the task" is ranked as "less difficult" relative to the other two as time progresses. "Orienting to the technologies or tools used to do the task" is ranked as "more difficult" relative to the other two as time progresses. "Orienting to the people" has the overall highest ranking, and generally maintains a similar ranking over time relative to tasks and technologies. The data reported by ISS astronauts provides some useful recommendations for designing work in space. The survey results gathered aboard the ISS suggest four observations and associated practical recommendations (Table 10.3, #s 1–4).

HERA analog perceptions. Next, in order to understand how these perceptions of work are affected by factors like communication delay that will be encountered on long distance missions, we conducted the survey in NASA's HERA (Human Exploration Research Analog) analog on crews living in the habitat for 45 days performing highly scheduled work under various communication delays. We report

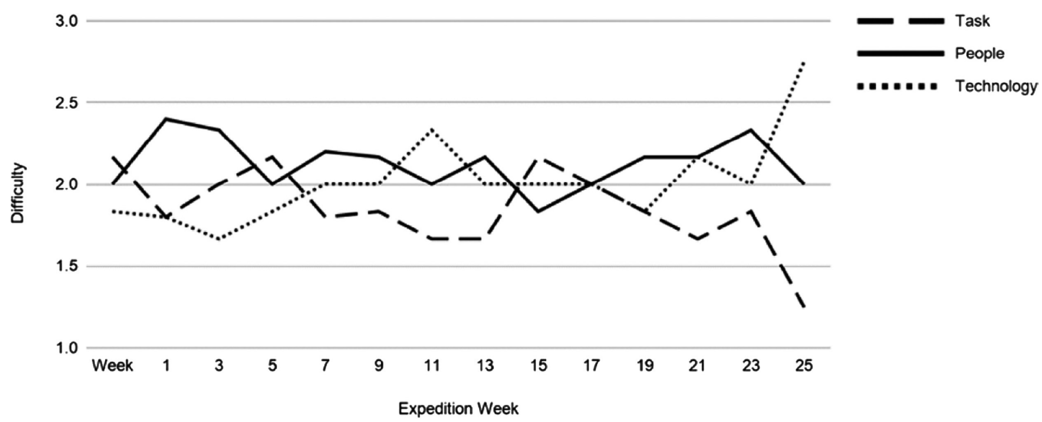

FIGURE 10.3 Astronaut rankings of the relative difficulty of orienting to tasks, people, and technologies when transitioning from solo to multiteam work aboard the International Space Station ($N = 6$).

data from Campaign 4 which included five, four-person crews ($N = 20$ individuals). Due to Hurricane Harvey's landfall in Houston, the second crew (Mission 2) was aborted after they completed four of the surveys. A second crew (Mission 3) experienced a scheduling issue and missed one of the survey administrations. All in all, we present 140 survey responses characterizing crewmembers' work perceptions over time. The task perception survey was administered to each analog participant a total of eight times, evenly spaced throughout the mission.

Each mission within the campaign followed the same mission arc, which entailed a simulated round-trip mission to an asteroid to obtain samples. As HERA moves far enough away from Earth, they begin to experience increasing times for their communications to reach Earth, and from Earth back to HERA. This communication delay begins with a 30 second delay on mission-day 15, reaches its peak of 300 seconds (5 minutes) when HERA reaches their destination on mission-days 20–24, then decreases back to no delay as they approach Earth on mission-days 29–45.

Examples of solo tasks completed in HERA include developing procedures for an onboard system, calculating thruster velocities for reentry, or completing physical fitness regimens. Examples of team **tasks** completed in HERA include the MMSEV task or the rover assembly. Examples of multiteam tasks in HERA include interfacing with mission control to conduct extravehicular activities or to make modifications to systems during a system failure.

HERA crewmembers ranked tasks completed alone (solo), with crewmembers (crew), and working with those outside the crew (MCC) in terms of relative difficulty. For comparison with the ISS data, we have labeled this category MCC though we note that there was not a MCC operating at HERA. In HERA there are two relevant groups outside the crew. The first is the HabCom, or habitat communicator, a person working on console 24 hours a day to ensure the health and safety of the crew. The second is an eight-member Mission Control located at a university that the crew works with on remote problem-solving tasks.

Figure 10.4 presents the average ranked difficulty of these transitions reported by the 20 HERA participants in Campaign 4. The three shifts that involve increases

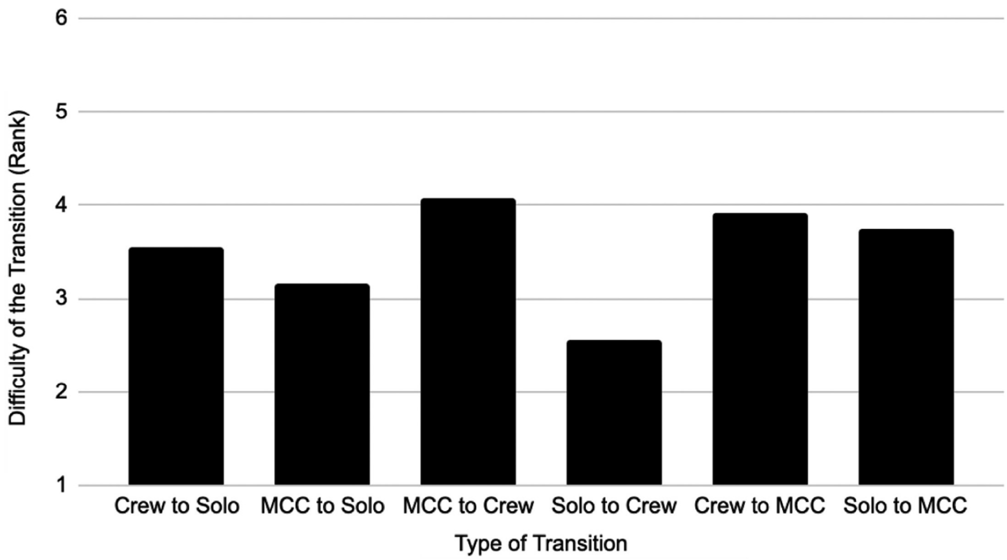

FIGURE 10.4 Analog participant rankings of the relative difficulty of task transitions made while working in HERA ($N = 20$).

in autonomy are presented on the left, and the three shifts that involve decreasing autonomy are on the right. The pattern for HERA participants differs from ISS astronauts. On the ISS, transition difficulty is affected by whether autonomy is being gained or lost. This was true of four of the six types of transitions made in HERA. There were two differences. First, "solo to crew" transitions involve a decrease in autonomy but were the easiest transition reported by HERA participants. Second, transitioning from an MCC task to a crew task, which increases autonomy, was the most difficult transition reported by HERA participants.

In order to understand the relative impact of each type of factor on work transitions, we asked the HERA participants to rank the difficulty of the three factors: orienting to the task, orienting to the people, and orienting to the technologies or tools used to do the tasks. Since the most difficult transition was from solo work to work involving MCC, we then asked these astronauts to rank "How difficult is each factor when transitioning from a solo task to one involving mission control (1 = least difficult, 3 = most difficult)." Figure 10.5 presents the responses broken out by time in mission. Examining Figure 10.5 shows that overall, HERA participants were similar to astronauts in their ranking of "orienting to the people" as the most difficult, followed by "orienting to the tools," and then by "orienting to the tasks." However, the change in rankings during the mission did not mirror that of the ISS astronauts. "Orienting to the people" was ranked as progressively less difficult whereas "orienting to the task" and "orienting to the technology" were both ranked as more difficult as the mission progressed.

The data reported by HERA participants also provides useful insight for designing work in space, particularly related to a high autonomy mission. The ISS astronauts work closely with mission control each relying on the other in crucial ways in order to accomplish work. In contrast, the HERA crew is largely autonomous as a crew. They experience extended periods of communication delay and must rely on

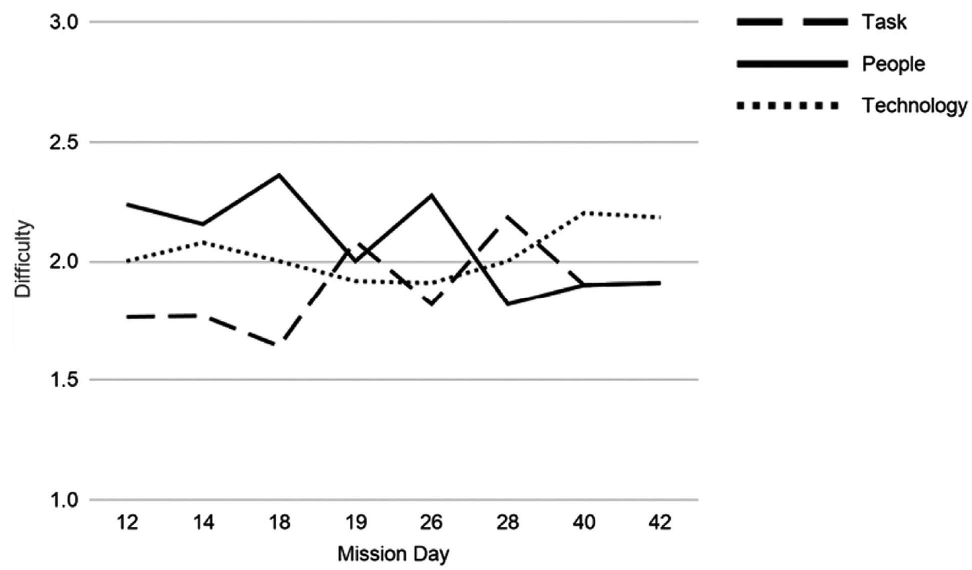

FIGURE 10.5 Analog participant rankings of the relative difficulty of orienting to tasks, people, and technologies when transitioning from solo to multiteam work in HERA ($N = 20$).

one another to answer questions and resolve issues that arise. This difference was born out in some of our survey data about the relative difficulty of task transitions. Overall, an additional preliminary recommendation for designing work for more autonomous missions follows (Table 10.3, # 5).

PART 3: COMPUTATIONAL MODELING OF WORKING IN SPACE

Whereas some work design recommendations can be usefully grounded in astronaut accounts of work, there are some additional considerations that require a different approach. Astronaut accounts are especially useful for designing work in space aboard the ISS or in work situations that will be similar to the work completed on the ISS. There are particular features of this situation that generalize well to planned missions to the moon (e.g., Artemis), but there are also particular aspects of this situation that may not generalize very well to missions beyond low Earth orbit (LEO) such as a mission to Mars. In this case, the aid of a computational model that can harness data gathered from analog recruits becomes a highly useful decision aid. Computational models afford insights into emergent behavior resulting from actions and interactions that occur within complex systems and are useful for understanding social context in the area of teams and multiteam systems (Harrison, Lin, Carroll, & Carley, 2007; Macy & Willer, 2002; Monge & Contractor, 2003; Sullivan, Lungeanu, DeChurch, & Contractor, 2015). Such a model allows us to do two things. First, we can use the model to conduct virtual "what if" experiments of conditions that would be prohibitively costly to conduct in a space environment. Second, we can extrapolate to conditions that may not be observable in current space missions. In this final section, we describe our efforts at building such a model that can be used to inform work design recommendations.

In this section of our chapter, we present the development of an agent-based model that estimates the stickiness of an ongoing task and the attractiveness of an alternative task to predict the probability that an individual will switch from an ongoing task to an alternative task. This model incorporates the task, social, technological, contextual, and individual factors that affect the perceived stickiness and attractiveness of ongoing versus alternative tasks. Then we parameterize the agent-based model using empirical data collected in HERA to better simulate and understand the context of work in space.

CONTEXT: PROJECT RED

The ABM was parameterized using data collected on analog participants as they participated in a complex problem-solving task. This period of observation had the analog crew working with a remote mission control on a series of tasks, some of which were completed alone, with the crew, with functional teams, and with the full group. The data reported here were collected as part of NASA's HERA space analog Campaign 3. The four-member crew in our study underwent a 30-day mission in which the goal was to journey to the asteroid "Geographos" and collect rock samples before returning home. In order to reach the surface of the asteroid, crewmembers participated in a variety of tasks, one of which is Project RED. Crewmembers spend the first half of the mission (days 1–15) in the outbound phase in which they simulate the trip to the asteroid. Crewmembers rendezvous with the asteroid on mission-day 16 and spend the next few days conducting operations on the asteroid. Crewmembers then leave the asteroid on mission-day 19 and are in the return phase of the mission from mission-days 19–30, returning to earth on day 30.

Multiteam task: Project RED. We conducted our experiment on mission-days 9, 16, and 28. On each of these days, the crew worked with a different eight-member mission control on Project RED, which is a 12-member online software platform that requires 12 specialized members to design a well on Mars. In order to represent the essential features of a multiteam system, or "team of teams", we designed the task so that individuals use specialized expertise to pursue team goals, but must collaborate across teams to attain the superordinate goal. The four teams were: Space Geology, Space Robotics, Extraterrestrial Engineering, and Space Human Factors. One HERA crewmember was trained in each of the four functions. The remaining two team members of each of the four functional teams were "back on Earth" in MCC.

Each team pursued a different goal. **Geology's** team goal was to find a location for the well that has the most water available for a future colony. **Robotics**' team goal was to develop a well construction plan that minimizes the total direct cost (i.e., the amount of money required to build the well using robots and rovers). **Engineering's** team goal was to design a well that maximizes total clean water output, determined by the total water output and the number of contaminants in the water. **Human Factors'** team goal was to minimize the terrain cost (i.e., the amount of money that will need to be spent constructing and utilizing the well). The superordinate goal of the multiteam system was to determine a plan for the location and design of the well that would support as large a colony on Mars as possible. All four teams' expertise was required to accomplish the MTS goal.

Each member of the MTS had a unique information database with role-relevant information and had an individualized view of the Martian landscape where he or she could look up information and run calculations related to their specific goals. Members discussed options and jointly negotiated the plan for the well for up to

30 minutes. After 30 minutes, the interface prompted members to input their final values and sign off. Sign off completed the task.

Experiment conditions. In order to understand the effects of mission phases on task transitions, we conducted Project RED sessions on mission days 9, 16, and 28. The early-misison data collection was conducted on mission-day 9. The HERA crew worked with an eight-member MCC on the Project RED task. The HERA crew was not experiencing communication delay on this day, and so all communication in and out of the habitat occurred in real time (i.e., normal conditions). The mid-mission data collection occurred on mission-day 16. The crew worked with a different eight-member MCC on the Project RED task. At this point in the mission, the crew was experiencing a 1-minute communication delay as they were farther from Earth (hypothetically). Thus, all communication in and out of the habitat was lagged by 1 minute each way. Finally, the late-mission data collection was conducted on mission-day 28. Although the crew was no longer experiencing communication delay at this point, as this was nearing the end of their mission, the crew was now in their 28th day of social isolation (i.e., extended isolation).

Collaborative behavior. As participants were interacting with the Project RED software, a server log was documenting their actions. As part of the design of the multiteam task, we developed a comprehensive list of required solo, team, and multiteam tasks. Every log entry for every individual was mapped onto a solo, team, or multiteam task. For example, a solo task would be using the decision calculator to examine role specific costs; a team task would be using the chat interface to communicate with one's teammates; and a multiteam task would be proposing a well location to a member of another functional team. Using these server logs, we classified the amount of time each person spent on solo, team, and multiteam tasks. We also created metrics reflecting the number of transitions each participant made during the task. By examining sequences of tasks, we computed the number of (1) vertical transitions (e.g., when an individual transitioned between a solo task to a team/MTS task or vice versa), and (2) lateral transitions (e.g., when an individual switched between tasks requiring the same degree of interdependence, such as moving from one team task to another team task).

THE MODEL: CREST (CREW RECOMMENDER FOR EFFECTIVELY SWITCHING TASKS)

We built an agent-based model of the Project RED task, and used a combination of survey, server, and ratings data to obtain empirical estimates of all variables thought to explain what work individuals choose to complete: solo, team, and/or multiteam tasks. We based our model on the conceptual model presented in Part 1 of this chapter, Figure 10.2.

Model development. The agent-based model (ABM) was used to explain and predict task transitions based on theories from human factors (e.g., Wickens et al., 2013), organizational psychology (e.g., McGrath & Kelly, 1986), and social networks (e.g., Hinds et al., 2000). The model estimates the stickiness of an ongoing task and the attractiveness of an alternative task to derive the probability that an individual will switch from one task to another task. The ABM consists of three steps.

In the first step, at each timestep (t) each individual (i) assesses his/her own likelihood of switching from an ongoing task (m) to an alternative task (n) at time $t + 1$. This likelihood is the difference between the attractiveness of the alternative task (*n*) at time (*t*) and the stickiness of the ongoing task (*m*) at time (*t*). Individual (*i*) assesses a total of (*T*) likelihood scores for all possible alternative tasks. $n \in T$ The perceived stickiness of the current task for an individual (*i*) is modeled as a function of task attributes, his/her social relations, tool affordances, situational constraints, and his/her individual attributes. Similarly, the perceived attractiveness of an alternative task is modeled as a function of the aforementioned factors that pertain to the alternative task being considered. We additionally estimate the effect of social influence that other individuals exert upon the focal individual in switching to a particular task. These likelihood scores are submitted to a logistic function to derive the binomial probability $Pr(i, m, n)_{t+1}$ of individual (*i*) switching from an ongoing task (*m*) to an alternative task (*n*) at time *t + 1*. That is:

$$Pr(i, m, n)_{t+1} = \frac{e^{\text{likelihood}(i,\, m,\, n)_{t+1}}}{1 + e^{\text{likelihood}(i,\, m,\, n)_{t+1}}}$$

In the second step, each individual decides whether to continue to work on the current ongoing task (*m*) or switch to another task (*n*) based on the maximum of the likelihoods that was assessed in the first step. This binary "stick vs. switch" decision is based on the probability of switching to the most attractive alternative task at that point in time (i.e., $\max(Pr(i, m, n)_{t+1})$). Hence, with $\max(Pr(i, m, n)_{t+1})$, an individual decides to switch to an alternative task (*n*) and with $1 - \max(Pr(i, m, n)_{t+1})$, the individual decides to continue to work on the current task (*m*). If the individual decides to continue to work, no further steps are taken and the model proceeds to the next iteration. On the other hand, if the individual decides to switch to another task, s/he goes through an additional procedure (third step) to decide which alternative task s/he will work on in the next time period. Again, the individual makes a probabilistic decision among the alternative tasks where the probabilities are proportional to the binomial probabilities of each alternative task. Once all individuals update their decisions, the simulation proceeds to the next iteration. The simulation ends when ProjectRED ends.

Model validation. The model was implemented in the NetLogo ABM platform (Wilensky, 1999) using the process described above. After the agent-based model was built, the parameters were fitted to the empirical data collected from the ProjectRED task. Specifically, model parameters were fitted using the BehaviorSearch tool (Stonedahl & Wilensky, 2010). BehaviorSearch is a calibration tool for models implemented in NetLogo (Thiele, Kurth, & Grimm, 2014). The aim of calibration is to find the parameter combination that best fits the observational data (Railsback & Grimm, 2012). Calibration describes the process of manipulating a model to get closer to a desired behavior. In this case, the desired behavior is matching the tasks performed by each individual at each time point in the ABM with the tasks performed in ProjectRED.

To investigate the space of parameters, we used the standard genetic algorithm search method with "GrayBinaryChromosome" representation. Genetic algorithms offer a flexible meta-heuristic search mechanism which has been successful in combinatorial optimization and search problems. Gray codes have generally been found to give better performance for search representations. The optimization function was measured as the minimum objective function over ten simulations. Each simulation contained 20,000 model runs with five replications of each previous best model obtained. The variables in the model were all weighted to fall between 0 and 1. Additionally, all parameters were specified to range between –1 and 1. We performed the validation separately for each condition: (1) early mission, normal conditions, no communication delay, (2) mid-mission, 1-minute communication delay, and (3) late mission, extended isolation, no communication delay.

Model results. Tables 10.1 and 10.2 present the values of the parameters estimated for ongoing task stickiness and alternative task attractiveness. Table 10.1 displays the parameters indicating the degree to which each factor affected task stickiness at each of the three mission phases. Table 10.2 displays the parameters reflecting the influence of each factor on task attractiveness. The results of the computational model generally show two things. First, the magnitude of these estimates is generally above/below zero indicating all five sets of factors are explaining stickiness and attractiveness. Second, there is substantial variation in the weights associated with each factor early-, mid-, and late-mission. A few effects are consistent across observed conditions. For example, individuals confined to the

TABLE 10.1
ABM Results: Parameters Estimated for Ongoing Tasks Stickiness

	Early Mission: Normal Conditions	Mid Mission: Communication Delay	Late Mission: Extended Isolation
		Task Characteristics	
Difficulty	–0.39	–0.98	–0.96
Importance	0.11	–0.34	–0.99
Interdependence	0.53	0.79	–0.18
		Social factors	
Leadership	0.51	0.20	–0.14
Behavioral ties	–0.51	0.50	–0.20
Affective ties	–0.86	0.06	0.57
Cognitive ties	0.61	–0.08	–0.27
Affect toward synchronous collaborators	0.77	–0.01	–0.19
		Technology Affordances	
Editability	0.67	0.35	–0.76
Association	0.06	–0.06	0.09
		Situational Constraints	
Confinement	0.65	0.06	0.91
		Individual differences	
Extraversion	–0.52	0.17	–0.37
Agreeableness	–0.20	–0.74	–0.93
Conscientiousness	0.21	–0.91	–0.93
Openness	0.90	–0.78	–0.52
Neuroticism	0.63	0.64	0.02

TABLE 10.2
ABM Results: Parameters Estimated for Alternative Task Attractiveness

	Early Mission: Normal Conditions	Mid Mission: Communication Delay	Late Mission: Extended Isolation
		Task Characteristics	
Difficulty	–0.62	0.94	–0.82
Importance	–0.10	–0.78	0.70
Interdependence	–0.04	0.05	–0.45
Salience	–0.30	–0.37	–0.87
		Social Factors	
Leadership	0.17	0.26	–0.47
Behavioral ties	0.93	–0.12	0.55
Affective ties	–0.48	0.56	–0.34
Cognitive ties	0.58	0.55	0.50
Social influence from close neighbors	–0.51	0.82	0.63
Social influence from far neighbors	0.88	–0.09	–0.16
		Technology Affordances	
Editability	0.03	–0.08	0.67
Association	0.68	0.29	0.90
		Situational Constraints	
Confinement	0.62	0.22	0.55
		Individual Differences	
Extraversion	–0.15	–0.89	0.28
Agreeableness	–0.74	0.53	–0.25
Conscientiousness	–0.08	0.39	0.03
Openness	–0.35	–0.02	0.18
Neuroticism	0.94	–0.86	0.71

analog found all tasks to be stickier and more attractive than did the participants who were in the remote mission control. The confinement parameter was always positive. Difficult tasks were always less sticky, and salient ones more attractive. Personality variables also showed interesting patterns. Consider trait agreeableness. Agreeable individuals are described as being warm, cooperative, considerate, kind, and sympathetic to others. Agreeable individuals found all tasks to be less sticky across all conditions. They found all tasks to be less attractive as well, except under communication delay when agreeableness was positively associated with task attractiveness. The interpretation of each parameter is less important than the global observation that the most important factors, and the weights of these factors, differ across mission stages. This leads us to a final recommendation based on our computational model (Table 10.3, #6).

TABLE 10.3
Observations and Recommendations

#	Observation	Recommendation
1	***Gaining autonomy is easier than losing it.*** Task transitions involving decreasing autonomy (increased interdependence) are reported to be more difficult than those that increase autonomy (Figure 10.1).	***Schedule interdependent work first.*** Task transitions involving decreasing autonomy (increased interdependence) are reported to be more difficult than those that increase autonomy (Figure 10.1). Thus, it is preferable to schedule interdependent work first, followed by more independent work.
2	***Orienting to people is a challenging aspect of transitioning tasks.*** Orienting to the people is rated as the most difficult aspect of work transitions (Figure 10.3) overall.	***Provide interventions that lessen the resources required to orient toward different groups of people.*** Interventions that lessen the resources required to orient toward different groups of people will benefit collaboration between the crew and mission control. In addition, when designing work schedules there may be a benefit to grouping tasks that are completed with the same crewmembers or with the same mission control members/groups. By grouping tasks completed with the same individuals together, the cognitive resources needed to transition can be reduced fostering a smoother transition.
3	***Orienting to the task is a challenging aspect of task transitions at early mission stages.*** Orienting to the tasks is rated as the most difficult aspect of work transitions early in the mission and decreases over the course of the mission (Figure 10.3). Conversations with astronauts confirm that interpreting procedures and initially adjusting to work in space can be challenging during the first few weeks of the mission.	***Provide interventions that make task instructions, procedures, and resources clear during early mission stages.*** Interventions that make task instructions, procedures, and resources clear are most valuable at early mission stages as crewmembers are in their initial adjustment phase. Interventions to improve the clarity of procedures during this early period can make task transitions easier.
4	***Orienting to the technology is a challenging aspect of task transitions at late mission stages.*** Orienting to technologies and tools needed to complete work is reported to be relatively more difficult as the mission progresses (Figure 10.3).	***Provide interventions that make technology easier to use during later mission stages.*** Interventions that make technology easier to use may be especially valuable in later mission phases. It is also desirable to ensure that whenever possible, technology interfaces use similar user interfaces and social affordances in order to ease transitions lessening the cognitive demands placed on crewmembers as they interact with different onboard tools and interfaces.

(*Continued*)

TABLE 10.3 (*Continued*)
Observations and Recommendations

#	Observation	Recommendation
5	***Work transitions toward and away from mission control are the most challenging for autonomous crews.*** The most challenging task transitions reported by HERA crews involved moving into work tasks requiring interaction with mission control or moving from work with mission control to working with the crew (Figure 10.4).	***Schedule work with mission control early in the crew's work day.*** As with recommendation one, during periods of high autonomy, it would be desirable to schedule interactions with mission control at times most convenient to the crew in terms of their sleep-wake cycle. Given that crew and MCC days will not always overlap, scheduling work with mission control early in the crew's day will ensure the most difficult to handle work transitions occur first, followed by easier transitions as cognitive resources are depleted over the course of the day.
6	***The factors affecting work transitions change across mission stages.*** Whereas our model estimates sizeable effects of all five sets of factors on task stickiness and attractiveness, the relative importance of these characteristics changes over the mission (Tables 10.1 and 10.2).	***Work designs should be customized to the mission phase.*** Our genetic algorithm shows the most important factors that explain how long individuals persist on tasks, and how likely they are to start them, changes over time based on conditions like communication delay. This means that work design interventions should be developed based on computational models that account for these changing dynamics.

Computational models like this one can be used to design interventions by conducting synthetic or virtual experiments. Models with empirically validated parameters provide a powerful platform to conduct computational experiments (Monge & Contractor, 2003). In computational experiments, we create large numbers of virtual agents (in the computer) to mimic human participants. Conducting computational experiments with these virtual agents enables us to ask "what-if" questions to assess the impact of changing the value of certain variables on outcomes before conducting an actual experiment to collect data. Hence, they offer a low-cost strategy to assess if, and how, differences in the values of certain variables impact outcomes.

CONCLUSION

The nature of work in space is likely to undergo a transformation in the near future as space exploration traverses longer distances from Earth. Distance equals communication delays between the crew and mission control on Earth, and thus introduces the potential for greater crew autonomy and disengagement from counterparts on Earth. Space exploration crews will need to complete tasks that vary in terms of interdependence (solo, team, and multiteam tasks), though there will be greater potential for crewmember "choice" in when and how to execute tasks during longer duration and distance missions than has historically been the case.

Human factors research suggests perceptions of task difficulty, importance, and interest affect the likelihood an individual will want to stay with a current task or switch to an alternative task. We extend this work drawing on adjacent literatures and detailing four sets of factors that affect task stickiness and attractiveness. These include social factors like the quality of interpersonal relationships, technology affordances like the degree of editability, situational constraints like extended confinement, and individual differences like trait agreeableness.

Surveys administered on the ISS and in HERA suggest shifts in autonomy affect the ease of transitioning tasks, and that orienting to people is the most difficult aspect of transitioning into highly interdependent work like coordinating with mission control. We also illuminate how agent-based modeling can shed light on how a human crew may respond under a variety of circumstances so that mission control might know when support mechanisms and interventions are particularly important for crew and mission welfare. We highlight six observations suggesting recommendations for designing work in space.

In sum, interviews, diaries, and other accounts of work and life in space are remarkably consistent in their depiction of the importance of scheduling, collaboration, and engagement as central to the experience of work. By exploring how perceptions of independent and interdependent tasks change as a function of time in the mission and extent of communication delay using analog experimentation and agent-based modeling, we shed light on new and important implications for the timing and development of countermeasures that support and promote effective crew process and performance.

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