Evaluation of Self-Scheduling Exercises Completed by Analog Crewmembers in NASA's Human Exploration Research Analog (HERA)

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NASA human spaceflight missions are inherently dynamic and require frequent scheduling changes in order to adapt to changing mission priorities and objectives. Tactical level changes to the mission plan are traditionally made by a team of expert planners and operations specialists on the ground. However, astronauts are expected to execute missions more autonomously during future long duration missions. Astronauts will need to take on some of the responsibility of managing their own schedule while still abiding by the numerous constraints required by human spaceflight operations. This paper summarizes salient elements of crew performance in NASA's Human Exploration Research Analog Campaign 3. Analog crewmembers completed a series of self-scheduling exercises to evaluate Playbook's usability towards enabling self-scheduling without support from ground control. Playbook is a self-scheduling software tool designed and developed by our team. We also investigated how to best communicate self-scheduling tasks and constraints to the crew in order to facilitate efficient self-scheduling during isolation in a realistic environment. Our analysis identified that 30 minutes was sufficient to complete complex self-scheduling tasks. Our evaluation also identified differences between individual and collaborative performance; analog crewmembers completed self-scheduling exercises more quickly as a team as opposed to individually and reported lower subjective difficulty ratings overall.

I. Introduction

Self-scheduling is a novel concept of operations for in-flight astronauts, allowing crew to schedule or re-schedule a shared timeline. Current NASA programs like the International Space Station do not support manipulation of timelines by crewmembers during nominal operations, and as such, the impacts related to self-scheduling need to be understood. Future long duration exploration missions (LDEMs) will introduce new challenges including communication delay between crewmembers and ground teams which increases the need for crew autonomy. In order to better understand self-scheduling in an operationally-relevant environment, our team conducted an experiment in the NASA Human Exploration Research Analog (HERA), an isolation and confinement analog at NASA's Johnson Space Center [1][2]. HERA Campaign 3 (C3) consisted of four missions in 2016. Each mission was 30 days in duration

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and was supported by four crewmembers. While HERA is primarily focused on studying the effects of isolation, this testbed is also used to evaluate hardware and software tools in similar conditions to those on the International Space Station. This paper summarizes a post-hoc analysis using data from HERA C3 to understand how crewmembers schedule activities both individually and collaboratively as a team using Playbook.

II. Background

A. HERA Research Objectives

In 2016, our principal goal in HERA was to evaluate Playbook in terms of its ability to support self-scheduling, its usability, and crew's overall task completion experience. However, a post-hoc analysis allowed our team to also assess crew self-scheduling performance in additional ways. Our retrospective, exploratory study of self-scheduling tasks during HERA Campaign 3 seeks to draw lessons and insights from participants' subjective ratings of difficulty with performance for various self-scheduling exercises. A number of research questions were posed at the beginning of this exploratory analysis which included:

1. How might we characterize crew performance, given various measures of plan complexity?
2. How does subjective reported performance compare to actual performance?

Since crewmembers do not traditionally plan their missions, this data is key in understanding how crews plan and understand activity constraints. Objectives of this retrospective analysis expand on existing and ongoing research in crew self-scheduling with Playbook. One objective included identifying whether participant performance may be measured as a function of different characteristics of the plan. The exercise plans given to HERA crew to self-schedule were designed with varying levels of difficulty and complexity, including various types of constraints. This analysis investigates whether a higher number of constraints (a function of plan characteristics) may be correlated with participant performance (such as reduced instances of violations).

Another objective included answering and providing evidence for whether participants' subjective ratings of difficulty were related to the plan characteristics. In the instances when user difficulty ratings did not correspond with measures of performance, such as successful completion of an exercise, our analysis investigated whether a different facet of the experiment or the campaign may have contributed to that disparity. This study posed the question of whether participants' perceived performance might correspond with objective measures of plan completion, such as reduced instances of violations remaining in the plan or instances of double banding.

B. Self-Scheduling with Playbook

Playbook is a mobile, web-based scheduling software tool used on several analog missions and has been adapted to fit a variety of mission profiles [3][4]. Currently, Playbook is used for planning, self-scheduling, and viewing of a mission plan at a strategic and tactical level. During the planning phase, activities are defined, their constraints are modeled, and activities are scheduled. Self-scheduling allows crew to schedule and/or reschedule activities; at this point, activities are already defined and may have constraints. In the spaceflight context, large time-consuming schedule changes occur frequently mid-mission [5]. Planners leverage activity constraint modeling to ensure that schedules abide by the complex set of requirements and constraints involved in a mission. While some planning and scheduling systems leverage automatic planners and/or leverage temporal flexibility in timelines [6], our team has found that mixed-initiative planning and scheduling best supports self-scheduling [13]. Modeling and visualizing constraints enables planners and hence, crew, the flexibility to schedule activities while still abiding to the required complex set of spaceflight operational constraints.

Playbook displays the schedule of all crewmembers horizontally (Figure 1). Crew schedules are composed of multiple activities that are assigned to the various crewmembers. Activities can have constraints, such as "must be done at a particular time of day" or "requires communication bandwidth to complete." At the time of the HERA experiment (2016), most constraints could be modeled and visualized by Playbook, though some cannot (e.g., "a crewmember can only be assigned 2 hours of exercise"). Modeled constraints are constraints that Playbook understands from metadata associated with activities.

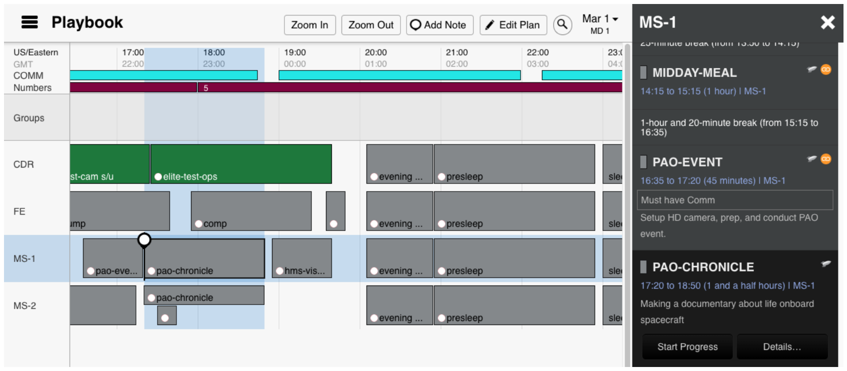

Figure 1. Timeline view within Playbook

III. Experimental Design & Methods

A. Experimental Design

Each crewmember was asked to complete seven self-scheduling exercises over the course of their 30-day mission. To ensure consistency, the seven self-scheduling exercises were done on the same mission day for each of the four missions across Campaign 3. We scheduled one hour of the crew's time for the self-scheduling exercises. Three of those exercises were done individually (without collaboration or assistance from other crewmembers) and four of those exercises were done collaboratively as a team of four. A total of 16 crewmembers each completed seven exercises. Crewmembers submitted a subjective rating of task difficulty (through a survey) after each exercise was complete. Self-scheduling exercises were designed to increase in difficulty over time and presented new challenges, varied scheduling complexity, and constraint types.

The crew was required to use the task list to self-schedule. The task list is a view within Playbook that presents a list of activities and groups that are unscheduled or have yet to be placed in the timeline. Alongside each activity within the task list is information related to that activity like duration, assignment, and constraint information. In order to complete the self-scheduling exercises crewmembers had to use the timeline, the task list, and other views. The exercises also asked the crew to follow a procedure matrix that listed each exercise's respective activities and groups along with the constraints associated with each. The self-scheduling procedure matrix consisted of a spreadsheet (Figure 2) that provided the high-level description of the exercise and asked the crew to schedule activities on either a single day or across two mission days. The matrix provided each activity that needed to be scheduled in a list along with a series of constraints like crew assignment, a description of the activity, equipment constraints, and schedule constraints. If a modeled constraint was not met when scheduled, the violated activity would have a red border, indicating that the activity should be rescheduled. The matrix and procedure were provided in PDF format, separate from the Playbook interface. Crewmembers were asked to create violation-free plans that satisfied activity constraints and to not double band multiple activities in the timeline (i.e., in a violation-free plan, crewmembers can only be assigned one activity at a particular time).

EXERCISE 1 SELF-SCHEDULING MATRIX: MD1								
Activity	Description	Scheduling Constraints						Reference Information
		Duration	# of Instances	Crew	Comm Coverage	Equipment Constraint	Schedule Constraint	Notes
BODY MEASURE	Experiment where two crewmembers assist each other in taking data and measurements of torso.	1:15	1	CDR, MS-1			Requires two crewmembers.	CDR must be assigned to this task; MS-1 is preferred pair assignment.
WEIGHT-CDR	Monthly weigh in of crewmember.	0:30	1	CDR		Weight Machine		All crewmembers must weigh in today but there is only one equipment that can weigh crewmembers.
WEIGHT-FE	Monthly weigh in of crewmember.	0:30	1	FE		Weight Machine		All crewmembers must weigh in today but there is only one equipment that can weigh crewmembers.
WEIGHT-MS-1	Monthly weigh in of crewmember.	0:30	1	MS-1		Weight Machine		All crewmembers must weigh in today but there is only one equipment that can weigh crewmembers.
WEIGHT-MS-2	Monthly weigh in of crewmember.	0:30	1	MS-2		Weight Machine		All crewmembers must weigh in today but there is only one equipment that can weigh crewmembers.
EPO-OUTREACH	Education and outreach activity, answering questions.	1:00	1	CDR	Requires COMM			CDR should be assigned to this activity; reassignment should be justified otherwise in Mission Log.
JOURNAL	Crewmember must complete weekly Journal entry for on-going data collection.	1:00	1	CDR			Must be completed no later than 17:00 on MD1	CDR should be assigned to this activity; reassignment should be justified otherwise in Mission Log.
RESISTIVE EXERCISE - CDR	Crewmembers exercising using resistive exercise machine.	1:30	1	CDR		Resistive Exercise	There should be at least 1:30 between MIDDAY MEAL and RESISTIVE EXERCISE - CDR	Each crewmember must do resistive exercise today but there is only one equipment available.
TREADMILL - CDR	Crewmembers exercising using treadmill machine.	0:45	1	CDR		Treadmill		Each crewmember must run on treadmill today but there is only one equipment available.
PUMP CHECKOUT	Evaluate and record state of pump.	1:00	1	CDR			Before **MAINTENANCE**	CDR should be assigned to this activity; reassignment should be justified otherwise in Mission Log.
MAINTENANCE	Conduct Pump maintenance	3:00	1	CDR			After **PUMP CHECKOUT**	CDR should be assigned to this activity; reassignment should be justified otherwise in Mission Log.

Figure 2. Example of an Exercise matrix listing activities and corresponding constraints

B. Methods

Our post-hoc analysis leveraged the Playbook Data Analysis tool (PDAT) to track the state of a particular plan and experimental trial before and after an exercise is completed. PDAT enables passive data capture through screen recordings, logging interactions between the user and Playbook, and saving varied states of the plan before and after exercises were completed [10]. PDAT was used to capture data on participant trials. PDAT captures interactions based on gesture type, feature, and activity the user is interacting with.

Leveraging the data logs, we were able to identify several objective measures of participant performance from the Campaign 3 exercises including: overall completion of plans, time to complete each exercise (time-on-task), number of violations left in the timeline, and number of instances of double banding over the course of an exercise. Plan completion was measured as either complete or incomplete. If an activity did not conform to the listed constraint in the procedure matrix, it was considered to be "in violation." Each constraint not met was counted as a single violation, regardless of the type of constraint that it may be, such as "Comm," "Equipment," and "Schedule" constraints (see Figure 2). The total number of violations remaining in a plan was determined by comparing the state of the plan from the beginning of the trial with the end of the exercise, and verifying that each constraint listed in the procedure was met. Violations and instances of double banding were counted through analysis of Playbook PDAT recordings or through visual representations of violations which were modeled.

Subjective measures of participant performance were identified via a survey administered at the end of each exercise. The survey asked for the crewmember's role, the level of perceived exercise difficulty based on a Likert scale ranging from "Very Simple" (1) to "Very Difficult" (5), and were asked for any comments related to the exercise. An additional survey was conducted at the end of each mission to gather additional feedback on Playbook as well as the experiment overall.

Despite our best efforts, several factors limited our analysis including: inconsistent and variegated applications of scheduling task complexity factors across exercises, data log inconsistencies, and missing data logs. Trials with incomplete data in either survey responses or missing time-on-task information were omitted from the analysis. Missing violations data have been omitted in all instances where that data was unavailable. Subjective ratings of user difficulty were obtained from all participants for all exercises. While missing and incomplete data may have obscured the identification of trends in the analysis, this study identifies salient elements of participant performance and the self-scheduling experiment itself to be reconsidered for implementation in future experiments.

IV. Analysis & Results

A. Approach

Participant data was grouped into three categories: plan complexity data, performance data, and survey results. Our quantitative data was used to evaluate the role of plan complexity on performance and to understand how individual performance compares to collaborative performance. Exercise difficulty was determined by evaluating multiple elements of plan complexity (i.e., number of activities, number of constraints, and constraint types). Subject matter experts were also asked to provide subjective ratings of exercise difficulty as a baseline for comparing crew ratings.

B. Time-on-Task

Time-on-task (in minutes) is the length of time it took a participant to complete one self-scheduling exercise. The mean time-on-task across C3 was 29.5 minutes for individual exercises and 22.9 minutes for collaborative exercises (see Table 1).

	Ex 1 (Indiv)	Ex 2 (Collab)	Ex 3 (Indiv)	Ex 4 (Indiv)	Ex 5 (Collab)	Ex 6 (Collab)	Ex 7 (Collab)	Individual Exercises	Collab Exercises
Mean	32.8	19.26	23.23.	31.17	27.29	20.93	23.1	29.52	22.95
Median	34.94	19.3	20.43	28.02	22.11	15.87	17.7	26.77	20.46
Min	14.97	12.5	12.2	20.2	18.5	13.63	13.72	12.2	12.53
Max	43.7	25.9	52.6	47.1	46.43	30.4	45.7	47.1	46.43
Standard Deviation	8.7	5.49	11.96	10.11	12.96	8.05	15.1	10.69	10.35

Table 1. Descriptive Statistics of Time-on-Task (minutes) for HERA C3

In Figure 3, time-on-task is plotted sequentially in order of completion. The median is represented as the black line within the box range, and the mean is represented as the white dot within the box range. The individual exercises (1, 3, and 4) were designed to be progressively more challenging. A learning effect was not observed. Overall, the trend indicates exercises completed individually took slightly longer than those completed as a team (i.e., collaborative), though the average difference is only about 6 minutes.

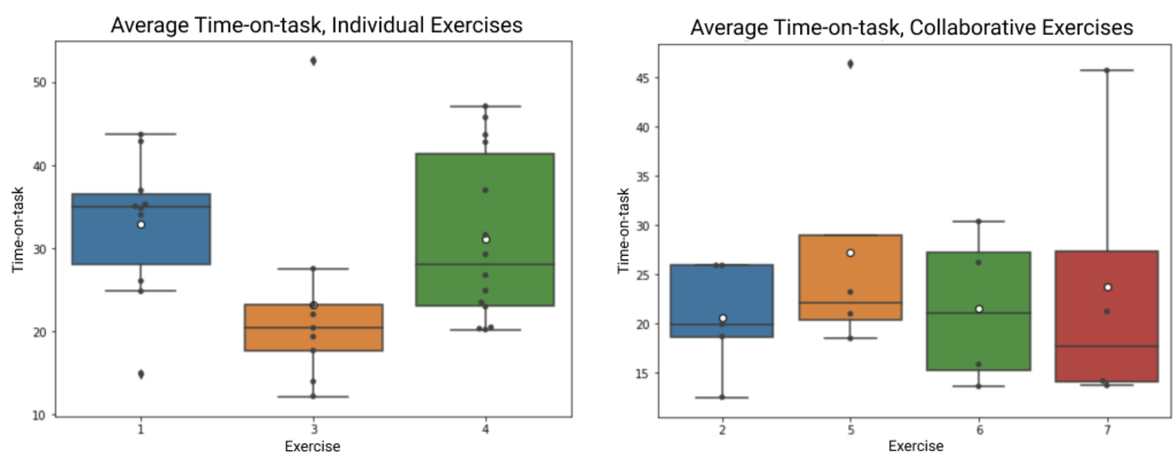

Figure 3. Average Time-on-task, Individual & Collaborative Exercises

C. Subjective Difficulty & Time-on-Task

Figure 4 shows the distribution of subjective difficulty (as ranked by participants) for all the exercises. Notably, only one participant (out of 16) rated one exercise (Exercise 5) as "Very Difficult". In general, most rated the exercises 2 or 3. The collaborative exercises (2, 5, 6, & 7) tended to be rated 2. While subjective ratings are useful, they do not necessarily correlate with objective scheduling performance measures, as will be described below.

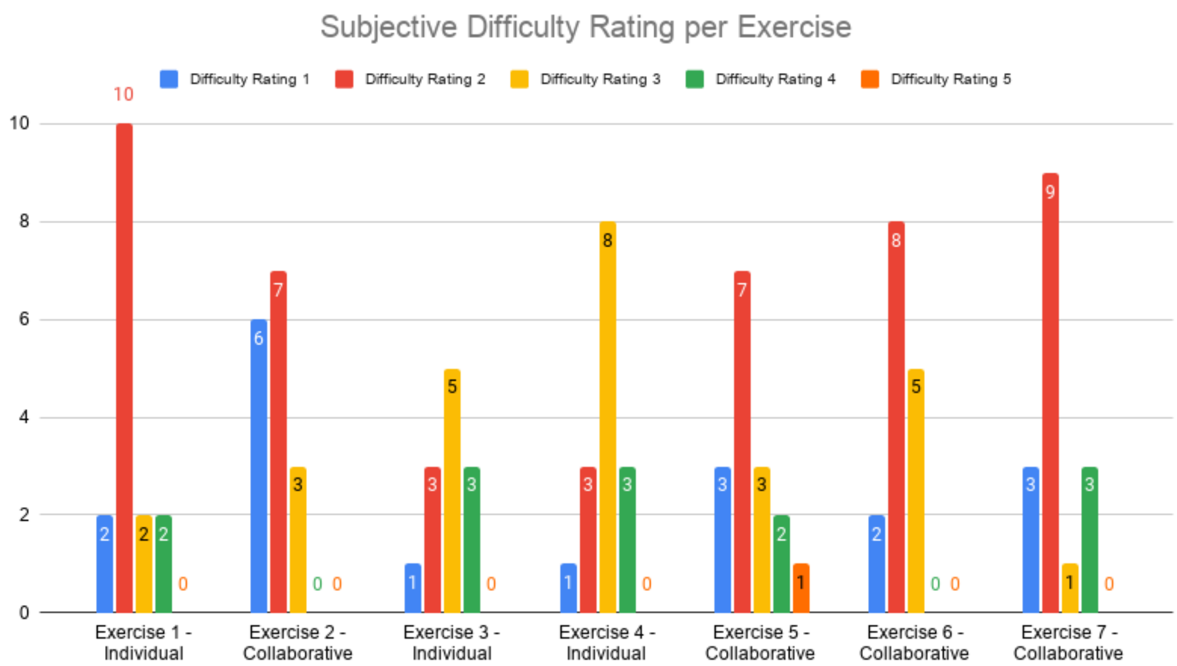

Figure 4. Subjective Difficulty Rating per Exercise

Our analysis explored whether subjective rating was correlated to time-on-task (see Figure 5). The exercises completed individually and those completed collaboratively were evaluated separately. Collaborative exercises only have one time-on-task value (the result of multiple participants working together), each analog crewmember to complete an individual exercise had a distinct time-on-task measured. A salient trend for individual exercises is that time-on-task seems to increase with subjective difficulty rating. In collaborative exercises, most participant groups rated plan difficulty lower than individual participants, with few difficulty ratings given as 4 or 5. Collaborative exercises tended to be completed in a range between 15-30 minutes with few instances completed over 45 minutes.

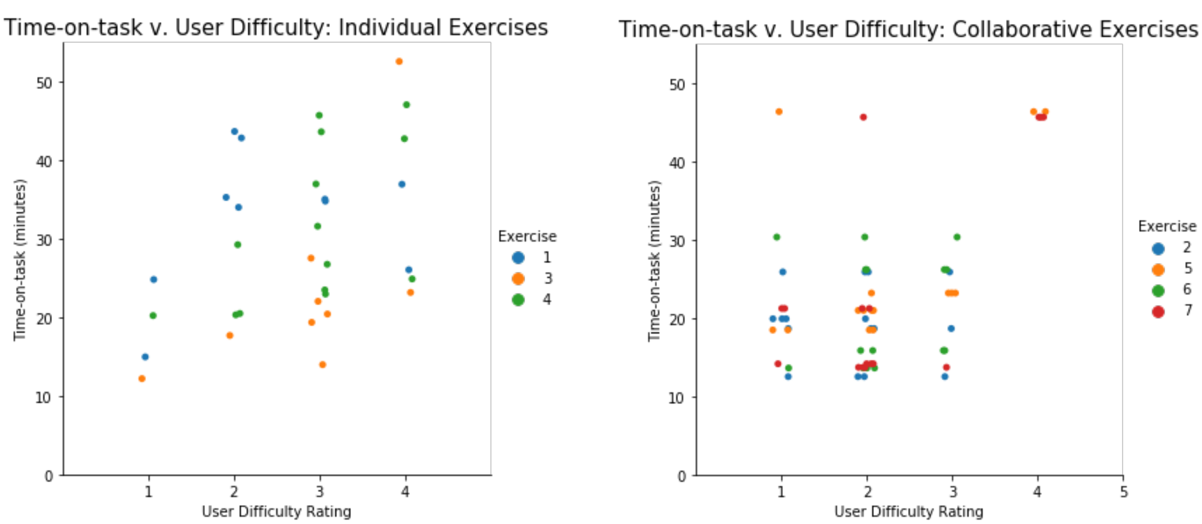

Figure 5. Time-on-task v. User Difficulty; Individual & Collaborative Exercises

While we identified that time spent for individual exercises increases with subjective difficulty rating, we found no relationship between time spent on collaborative exercises and subjective difficulty. Self-reported subjective ratings of difficulty suggest that, over time, crewmembers found the exercises easier, however, the variability suggests that other factors (such as plan complexity) played a role.

D. Violations & Constraints

We expected that increased plan complexity would lead to increased violations, time-on-task, and overall difficulty. However, this was not always the case; the number of violations across each exercise was not correlated with plan complexity. With respect to the total number of violations remaining in the timeline at the conclusion of an exercise, the data is quite sparse. For individual exercises across 4 missions, violation data was missing for roughly 20% of trials due to data loss. Nonetheless, in all individual exercises (1, 3 and 4) 50% or more trials resulted in fewer than 10 violations remaining in the plan at the conclusion of the experiment. The average number of violations for individual exercises was 2.5, whereas the average number of violations remaining in the plan for collaborative exercises was 5 There appears to be a slight trend due to order; so, the more exercises completed by participants, the fewer violations remained (see Table 2). However, the number of potential or possible violations across exercises is not consistent, and this may be due to the exercise setup. Exercise 1 appears to have the most variability with respect to the number of violations—this might indicate that participants did not receive sufficient training to easily complete the first task. Data on violations remaining in collaborative exercises is too sparse to conclude any definitive trends, and violations data was not able to be retrieved for missions 3 and 4 due to data loss (missing files).

Comparing remaining violations to modeled constraints within exercises, a slight trend seems to be that the performance of individual exercises improves over time. However, this pattern is not indicative of performance for collaborative exercises given that the data and sample size is severely limited. In comparing both violations and double banding remaining in the plan with user difficulty, subject ratings of difficulty do not seem to be indicative of performance. In instances where more violations occurred and yet users rated low subjective difficulty ratings, instructions for the plan activity may have been misinterpreted, or may not have been clearly described.

	Ex 1 (Indiv)	**Ex 2 (Collab)**	**Ex 3 (Indiv)**	**Ex 4 (Indiv)**	**Ex 5 (Collab)**	**Ex 6 (Collab)**	**Individual Exercises**	**Collab Exercises**
Mean	6.58	6.5	4	5.09	4.5	3.86	2.5	5
Median	6.5	6.5	3	3	4.5	3	2.5	4
Min	0	1	0	1	4	3	2	1
Max	15	12	11	11	5	5	3	12
Standard Deviation	4.7	5.88	4.24	4.23	0.53	1.07	0.71	3.56

Table 2. Descriptive Statistics of Violations Remaining in Plan for HERA C3

E. Correlation Analysis

In order to understand the impacts of plan complexity on performance we ran a correlation analysis on four variables: time-on-task, subjective difficulty, number of constraints, and number of violations post exercise. Our correlation analysis was broken down further into individual and collaborative exercise groups to understand the differences between the two exercise types. We used the Pearson's Correlation Coefficient (r) [11] to understand the relationship between participants' subjective ratings of difficulty with performance. In Table 3, we present correlations between the four variables along with the number of data points (n), the mean (M) and standard deviation (SD). We found a significant correlation between time-on-task and subjective difficulty for individual exercises $r(34) = .40$, $p = .019$. The correlation decreases when looking at the collaborative exercise data set $r(15) = .17$, $p = .52$. Constraints and resulting violations were not correlated with time-on-task or subjective difficulty. There was a moderate negative correlation between violations and time-on-task for collaborative exercises. It may be that constraints were not fully understood by participants, likely due to the large number of constraints, ranging from 81-138 constraints per exercise.

Individual Exercises	n	M	SD	1	2	3	4
1. Time-on-task	33	29.52	10.69	-			
2. Subjective Difficulty	33	2.73	0.94	0.40*	-		
3. Violations	20	8.85	7.14	-0.01	-0.05	-	
4. Constraints	33	95.30	12.33	0.22	0.12	-0.23	-

Collaborative Exercises	n	M	SD	1	2	3	4
1. Time-on-task	17	23.12	10.04	-			
2. Subjective Difficulty	17	2.18	0.88	0.17	-		
3. Violations	6	5.67	4.08	-0.28	-0.37	-	
4. Constraints	13	106.46	23.36	0.34	-0.27	-0.15	-

Table 3. Correlation Analysis, *p < .05

F. Additional Qualitative Feedback

The crew was asked to complete an additional questionnaire at the conclusion of each mission which asked crewmembers to provide feedback on improvements, suggestions, and feature requests for Playbook. The survey also prompted users to comment on the tool's general operability and ease-of-use within a communication delayed environment. The data from the surveys and questionnaires were placed into an affinity map (a thematic analysis method) [12] used to generate emergent insights, recommendations, and feature improvements for Playbook. Our insights were grouped into two categories: 1) self-scheduling exercises improvements and 2) Playbook's ability to communicate and represent the implications of constraints within the tool.

The survey responses indicated that crewmembers experienced frustration due to the separation between the self-scheduling exercise timeline and the actual operational mission timeline. Self-scheduling exercises used a separate plan with unique activities and goals which required reorientation. This insight enables the recommendation that, in order to better understand crew self-scheduling, future self-scheduling exercises should either self-schedule within the actual operational mission timeline or use the same activities and groups as the mission timeline to reduce confusion. Participants were also required to have two web browser tabs open at once: the exercise plan and the procedure matrix. The survey results indicated that going back and forth between the matrix and the plan was inconvenient and often frustrating for crewmembers. Crewmembers had to commit a number of tasks and constraints to memory which led to increased frustration. Crewmembers suggested physical paper copies of the matrix may help to reduce cognitive load.

Participants also found the wording and complexity of the matrix and instructions confusing, likely adding time to the self-scheduling exercise. One recurring request from participants included the possibility of being able to highlight matrix steps so that crew could easily identify the current step they are on. Certain activities within the timeline contained modeled constraints; and if these constraints were not met during trials, the activity would produce violation (represented as a red border within Playbook). Other activities were not modeled and were only represented in the matrix and therefore did not or could not produce a visual violation affordance. In future experiments such as HERA C6, Playbook is anticipated to model more constraints so that visual affordance will apply for all violated activities. Conversely, crewmembers suggested adding a positive affordance within the interface to indicate when an activity was scheduled properly.

V. Conclusions

Of the various measures identified within our analysis, we found that for individual self-scheduling exercises subjective difficulty had a strong, positive correlation with time-on-task. We were not able to identify the same result for collaborative exercises. During collaborative exercises, participants reported only average levels of difficulty even as exercises became more difficult over the course of the mission. This suggests that self-scheduling performance varies substantially based on whether the task is completed individually or as a team. Future self-scheduling exercises as well as experiments for future long duration missions may consider additional research to characterize the ways in which collaborative performance differs from individual crewmember performance in self-scheduling. Additional avenues of research may strive to improve constraints intelligibility to eliminate any potential confusion or performance decrements by participants. HERA C6 (which is planned for 2021 and 2022) will use Playbook as a planning and scheduling tool. Self-scheduling will occur within the operational mission timeline. In anticipation of C6, we have identified new countermeasures and design aids including expanded constraint modeling and communication, priority indicators, and expanded visualizations. This future experiment is larger in scope and will produce new insight into plan quality as well as self-scheduling strategies used to solve difficult scheduling problems.

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