Effects of Fatigue on Simulated Space Telerobotics Performance: A Preliminary Study Analysis

by
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B.S. in Aerospace Engineering
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Submitted to the Department of Aeronautics and Astronautics
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Abstract

Astronauts on the International Space Station must perform mission critical space telerobotics tasks consistently despite restricted and slam shifted sleep and circadian schedules and long session durations, which all potentially degrade cognitive function, response time, and attention. A ground laboratory experiment was designed to 1) Determine the effects of fatigue on performance metrics in simulated space telerobotics tasks, 2) Examine the relationships between performance on complex robotics tasks and traditional metrics of cognitive task performance and sleepiness, 3) Assess the efficacy of caffeine and blue light countermeasures, and 4) Evaluate individual subject vulnerability to fatigue.

Subjects were screened for robotics aptitude, and trained on three robotics tasks and a mental workload assessing secondary task at MIT. After a week of 6-hr sleep restriction, they were admitted to the Brigham and Women's Hospital sleep laboratory, a time-cue free environment, and underwent a 13 day double blind protocol including physiologic monitoring and robotic and cognitive testing. Their sleep schedule was repeatedly slam shifted 9 hours earlier then they performed the robotics tasks under different countermeasure conditions. This thesis documents the protocol and details of the robotics training and testing, and includes a preliminary analysis of data from 16 subjects focusing on robotics and secondary task data. Since the study is continuing and investigators are blinded to countermeasure conditions, data from the countermeasure sessions is not included. Thesis goals were to 1) Analyze the predictive capability of spatial ability tests on individual robotics performance, 2) Evaluate the effects on robotics metrics of proxy measures of circadian and time-on-task, and 3) Assess individual differences in performance and vulnerability to fatigue.

The Vandenberg Mental Rotation Test was found to be the best predictor of both robotics screening test and experimental performance, although an average of four spatial ability tests was slightly better for screening purposes. A comparison between a final training and non-countermeasure test session indicated that slam shifting had no significant effect on group average performance in any of the three robotics tasks or the secondary task. However, within the slam shifted session, a time-on-task related effect in secondary task performance was evident, suggesting that mental workload gradually increased even though subjects were able to maintain primary robotics task performance. Inter-subject differences were consistently larger than other effects.

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Title: Senior Lecturer of Aeronautics and Astronautics

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List of Acronyms

AS - Autosequence
AUC - Area Under Curve
BL - Baseline
BWH - Brigham and Women's Hospital
DSST - Digit Symbol Substitution Test
DST - Dynamic Skills Trainer
EEG - Electroencephalography
EVA - Extra-vehicular Activity
FOR - Frame of Reference
FTG - Fly-to and Grapple
GLA - General Luminaire Assemblies
HTV - H-II Transfer Vehicle
ISS - International Space Station
KDT - Karolinska Drowsiness Test
KSS - Karolinska Sleepiness Scale
LED - Light Emitting Diode
MIT - Massachusetts Institute of Technology
MRT - Vandenberg Mental Rotation Test
MVL - Man Vehicle Lab
NASA - National Aeronautics and Space Administration
PSVT - Purdue Spatial Visualization Test
PT - Perspective Taking
PTA - Perspective Taking Ability Test
PVT - Psychomotor Vigilance Test
RHC - Rotational Hand Controller
ROC - Receiver Operator Characteristic
RWSS - Robotics Workstation Simulator
SO - Spatial Orientation
SpA - Spatial Ability
SSLA - Solid State Lighting Assembly
SSLM-R - Solid State Lighting Module – Research
SSRMS - Space Station Remote Manipulator System
ST - Secondary Task
SV - Spatial Visualization
T&C - Track and Capture
THC - Translational Hand Controller
TLX - Task Load Index
VAS - Visual Analog Scale

1. Introduction to the MIT-BWH Robotics Fatigue Study

Telerobotics operations have been an integral part of the construction and maintenance of the International Space Station (ISS). In addition, the robotic arm is used extensively to handle scientific payloads and to help astronauts traverse the station during extravehicular activity (EVA). To date, all ISS telerobotics operations have been successful but not without incident. Fatigue has been identified as a factor in the observed impairment of robotics performance (Paloski et al. 2008).

As detailed later, it is well known that astronauts on Shuttle and Station do not sleep the full 8.5 hours allotted to them in their schedule. In fact, most astronauts sleep about 6 hours or less while on orbit and some sleep less than 4 (Barger, 2008). Restricted sleep can occur when astronauts use a portion of the scheduled sleep time as additional personal time, to fulfill unexpected work requirements, or to work additional hours voluntarily. The lack of normal day/night lighting cues and the noisy environment can lead to circadian desynchrony and reduced sleep. In addition to chronic sleep restriction, astronauts are commonly required to shift their sleep schedules to accommodate the schedule of visiting vehicles or other important mission events. Slam shifts occurred on 13% of the 2,043 days of ISS operations from 2000-2006, typically before and during critical operations including docking, undocking, spacecraft relocations, and EVAs (McPhee, 2006). Acute sleepiness can also occur due to long mission operations, such as telerobotics tasks which may take up to 8 hours. Chronic sleep restriction, slam shifts, long times on task, and the combination of any or all of these could cause performance degradation on tasks critical to mission success.

To better understand the effect of these sleep abnormalities on robotics operations and cognitive performance, a collaborative study was initiated in 2009 by the Man Vehicle Laboratory (MVL) at the Massachusetts Institute of Technology and the Brigham and Women's Hospital (BWH) Sleep Lab for NASA's Human Research Program and the National Space Biomedical Research Institute. The ultimate goal was to improve the safety and reliability of space robotics operations. The specific goals of the study were to:

1) Objectively quantify human performance on primary space robotics tasks and mental workload via a simple visual response secondary task, and assess the effects of prolonged 6-hr sleep restriction, time-on-task, and slam shifting on performance.
2) Determine the relationship between standard cognitive/sleepiness measures and performance on the realistic and complex task of robotics operations.
3) Determine the effects of blue enriched white light and/or caffeine fatigue countermeasures on both robotics performance and cognitive/sleepiness metrics.
4) Evaluate individual subject vulnerability to fatigue

2. Thesis Objective

This thesis documents the hypotheses, experiment design, and data analysis methods used in the experiment, focusing on the space robotics performance and secondary task workload metrics. Also presented is an analysis of a portion of the data obtained to date for the non-countermeasure conditions. The role of individual spatial ability as a predictor of whether a subject would pass our robotics performance screening test is also discussed.

3. Background and Previous Research

For the benefit of readers who are not familiar with space telerobotics performance assessment, and the effects of sleepiness, fatigue and countermeasures on cognitive performance, the following sections provide a brief introduction.

3.1. Space telerobotics: A complex task

Operating the robotic arm on the ISS is an extremely complex task that requires the ability to interpret views from various camera angles, compile those views into a mental map of the environment, and integrate all available information into proper control inputs while in a continuous visual feedback loop. The standard Robotics Workstation (RWS)'s main components consist of three monitors displaying views from various external cameras located outside the station, a translational hand controller (THC), and a rotational hand controller (RHC)(Figure 1).

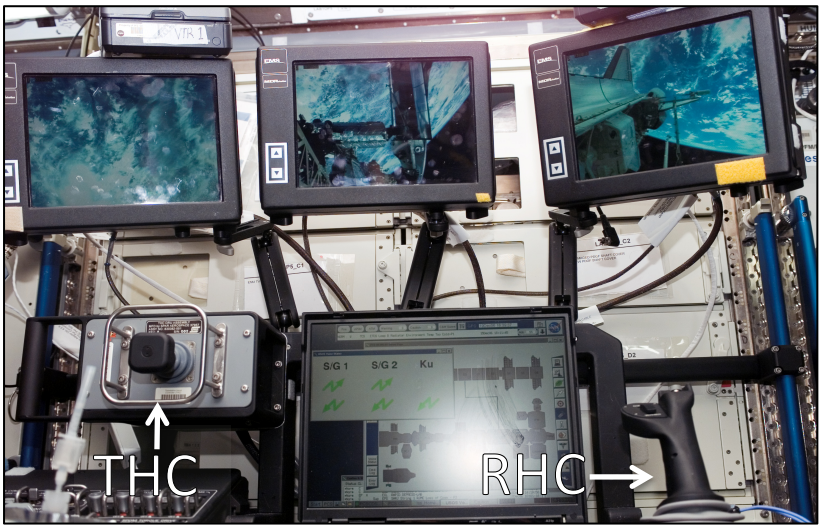


Figure 1: The Robotics WorkStation on the ISS in the Destiny module. Photo Credit: NASA.

The complexity of telerobotics can be appreciated by the amount of time astronauts spend in training. They complete over 100 hours of scheduled training to become a certified robotics operator and many additional hours in supplemental training sessions with trainers and/or through self-study. Difficult spatial relations among camera views and reference frames make the task cognitively complex. On ISS, cameras can be mounted on the top and bottom of the truss. They are mounted symmetrically about the truss (so that they mirror each other) and although they can pan and zoom, they cannot rotate. Thus the orientation of the views is rotated 180° from one another (Figure 2), which can lead to seemingly contradictory motion (e.g., the arm moves up in one view but down in the other) and can lead to control input mistakes and confusion.

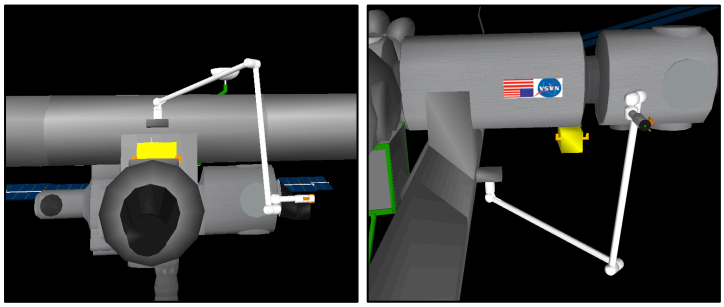


Figure 2: Simulator example of two camera views of the same task that differ by 180° in the up-down direction.

Another aspect of robotics operations that adds to task complexity is the difficulty of understanding, operating in, and switching between different control reference frames which specify the mapping between controller inputs and arm motion. An external control frame is fixed with respect to the station (Figure 3A). In the simulator used for this study, the external reference frame has its origin at the center of the truss, however, in real operations, the origin and orientation of the external frame are often chosen for convenience, e.g. so that one axis corresponds to the major axis of travel and coordinates read all zeros at the final destination. The operator can use key ISS structures seen in the different camera views to determine the proper controller inputs. In contrast, the internal control frame is fixed with respect to the end of the end effector (Figure 3B). In this mode, control inputs move the arm, not with respect to the station, but with respect to the end of the arm itself. Typically, arm control in internal mode is based on the view from the camera located on the end effector (orange box mounted on arm in Figure 3B). This highly intuitive view provides almost first-person perspective as in a video game. Internal mode is used for tasks requiring fine movements and alignment such as grappling a payload. Operating the arm to make large motions around the station is most intuitive using an external control frame along with "big picture" and clearance views available. The "big picture" view shows a large portion of the station, helping the operator visualize the entire space. Clearance views are directed to specific areas of the workspace so operators have a clear perspective (usually orthogonal) on distances between the arm, payload, and station. A robotics

operator must be able to visualize the task in either reference frame and switch between them as necessary without losing spatial and situational awareness.

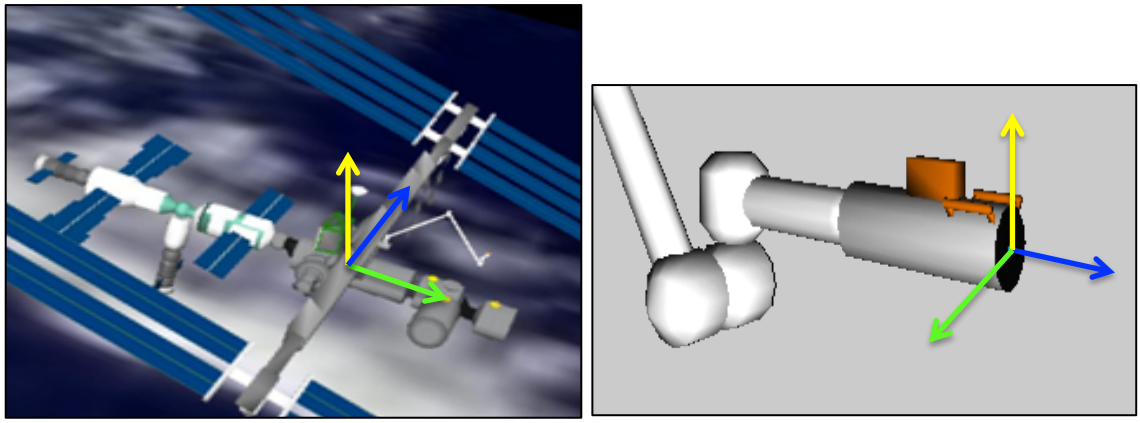


Figure 3: A) In external control mode, the reference frame is fixed with respect to the station. B) In internal control mode the internal reference frame is attached to the end of the end effector and is not anchored to the station.

In addition to cognitive demand, there is a strong physical coordination component to operating the robotic arm. The THC and RHC make up a unique controller interface that requires the operator to parse a 6 degree of freedom motion into its separate translation and rotation components and corresponding motions of the physically different controllers used with each hand. The axis decomposition is analogous to but more complex than that demanded by the classic "Etch-a-Sketch" toy. Making different but coordinated movements with each hand is reminiscent of the difficult "pat your head while rubbing your tummy" challenge. This controller arrangement creates the potential for unwanted bimanual coupling in which the movement of one hand unintentionally affects the motion of the other and therefore affects the control inputs. Although this unwanted coupling can likely be reduced through practice, the unnatural bimodal control design unavoidably adds to the task's overall complexity (Wang, 2012).

3.2. Robotics Performance Measurements

Because mission success is often dependent on robotics operations, efficient and effective training is absolutely vital. From the beginning of space telerobotics training at NASA until today, training and performance evaluations have been based solely on the subjective observations of robotics trainers. There are no quantitative metrics built into the training simulators that can give concrete performance feedback to astronauts as to how they are performing. The implementation of quantitative feedback from the simulator would be particularly useful during self-study, when trainers are not present (Forman, 2011). Since 2007, the MIT MVL has been studying telerobotics performance using objective measures with the ultimate goal of improving space robotics operations

(Menchaca-Brandan, 2008, Tomlinson, 2009, Pontillo, 2010, Forman 2011, Lowenthal, 2012, Wang, 2012).

Many metrics have been used in MVL's studies thus far. Task completion time is useful in measuring performance across identical trials, but becomes an artifact of the trial design when trials are different. The same issue applies to other metrics such as % bimanual movement (% of time translating and rotating simultaneously), % multi-axis movement (% of time translating or rotating in more than one axis), and even discrete measures such as number of clearance violations. For example, in the case of a track and capture task, where the operator must capture a free-flying object from a short distance away, the behavior of the metrics will be quite different whether the vehicle is drifting, rotating, or simultaneously translating and rotating. A well done track and capture task in which the payload is drifting only in translation will result in very little % bimanual movement, even if the task was executed efficiently.

In tasks where the operator must fly the arm large distances around the ISS to a target, grapple it, then move it elsewhere on the station, the position of the target with respect to the starting location of the arm will determine the optimal arm path to reach the target. Greater distances will undoubtedly result in longer fly times, and the position of the target will determine the control inputs used to fly to it. For example, if the target is initially lined up so that the only input in one axis is required, then the % multi-axis movement metric may be relatively low, even though trial performance and efficiency is high.

In trials where the operator must monitor the preprogrammed motion of the arm for clearance violations, the camera views available to a trial can affect where and how often a violation is identified. Again, the trial design can confound the measurement of the primary task.

To mitigate this problem, metrics that are less sensitive to trial design such as the number of input reversals (or unintended arm motions) per movement time, may be a better metric of performance. Large variances in difficulty level of the task or in skill level of the operator will, however, manifest themselves in the results.

Another option is to measure the smoothness of controller inputs. Smooth controller inputs are, due to arm dynamics, extremely important in maintaining control of the arm in space. Jerky control inputs can induce arm oscillations that could hinder performance. A measure of jerk magnitude would be particularly useful during training, when controller skills are being developed, but also potentially useful after training for detecting physiological changes that could change the nature of control movements. For example, fatigue might cause degradation in fine motor control or of the momentary mental capacity necessary to maintain sustained control, which would lead to less measured jerk in control movements.

Subject variability can also have a large effect on primary and secondary robotics metrics. Although all subjects are given the same training, the interpretation of instructions and resulting operations may still vary from subject to subject. This is most likely in the complex robotics tasks in which decision-making is more important to overall performance. For example, if instructed to move the robotic arm from a starting position to a specified position, subjects may move the arm in a variety of paths, even when attempting to take the most efficient one.

Additionally, learning a complex skill can be a long and challenging process that differs greatly from operator to operator. Learning a complex task does not necessarily follow the traditional asymptotic learning curve because complex tasks may require many different sub-skills that are not executed using the same method. Some are completed using rule-based behavior while others are done using schema-based behavior (Van Merrienboer, 1997). Breakthroughs in understanding and the development of new strategies can occur at various stages in the learning process creating a stair-step learning curve in which performance may drastically improve from one moment to the next.

3.3. Sleep and Fatigue

The importance of sleep has only really begun to be understood in the last few decades. Marjor breakthroughs have been made in understanding the main drivers to the human sleep/wake cycle.

One of these breakthroughs was the discovery that light is a driving circadian factor. In particular the timing of light exposures can have a large effect on the circadian pacemaker, the internal clock that synchronizes sleep and wakefulness with the 24-hour, day-night cycle. Exposure to bright light early in the day can shift the circadian rhythm ahead while intense light exposure at the end of the day can cause a shift back (Zeitzer et al., 2000). This has been a point of interest recently with the increased usage of laptops, smart phones, and e-readers late in the day or right before bed.

The intensity of light is not the only factor in its effect on the circadian rhythm. Recently, a second photoreceptor system in the retina of the eye was discovered. The photosensitive ganglion cells of this system are separate from the rod and cone visual photoreceptors, and have been found to be the primary mechanism for mediating melatonin suppression. This non-visual system is most sensitive to short wavelength light in the blue/green spectrum (Brainard, 2001). It is directly linked to the Suprachiasmatic Nucleus (SCN), the master clock of the body's circadian rhythms, located in the hypothalamus. This new understanding of light's effects on the circadian system has led to interest in using it as a tool to entrain the body's circadian clock, especially in off-nominal sleeping scenarios.

Sleep research in controlled laboratory settings has been pivotal in bringing to light the impairments that suboptimal sleep can have on cognitive function, alertness, health, and overall quality of life. The Borbely Two Process Model proposes two main factors that interact to control the human sleep/wake cycle. The first is the sleep homeostatic process that attempts to maintain the proper total sleep time for an individual. The drive to sleep increases markedly after 18 hours awake. The second is the circadian process that is independent of sleep and waking (Borbely, 1982). Variants of the Borbely model also include a third process accounting for "sleep inertia", the cognitive decrement seen in many people immediately after waking. Using experimental results, biomathematical models have been created to predict the average response of a person (e.g. simple cognitive performance and alertness) to changes in their sleep/wake cycle, light exposure, or work schedule. Not yet included in these and other models are factors such as physical and mental activity levels, which also have an effect on performance (Johns, 2010).

The natural circadian cycle, once thought to vary from 13 to 65 hours, was actually found to be quite consistent between people at 24 hours, 11 minutes ± 16 minutes (95% confidence level). The latter results were found when light levels substantial enough to affect the circadian rhythm were removed from the environment (Czeisler, 1999). Individuals who have a shorter than 24 hour circadian period are "morning people" who tend to wake early and are most alert in the morning, while those with longer than 24 hour periods are "evening people" who exhibit the opposite tendencies. There are also differences in the magnitude of light effects on the shifting of sleep. Trait-like differential vulnerability to impairment from sleep deprivation also exists (Hans et al., 2004). PER3 genetic polymorphisms have been implicated with vulnerability to a single bout of sleep deprivation (Groeger et al., 2008), however the same association was not found for chronic sleep deprivation (Goel et al., 2009).

Independent of circadian and homeostatic effects, time-on-task can also impair performance, at least on simple repetitive tasks. For example, performance decrements in a 20-minute simple visual reaction time response task have been observed, and shown to correlate with dopaminergic polymorphisms, suggesting that there are genetic explanations to individual subject vulnerability for time-on-task effects (Lim et al., 2012). Currently, the biomathematical models used to predict responses cannot account for these types of individual differences.

Key terms used throughout this thesis are defined here for reference. Additional information about how the tests discussed below were incorporated into the experiment can be found in Section 5.3.4 and Appendix 12.6.

Fatigue: weariness resulting from mental or physical exertion. Fatigue has also been defined as the subjectively experienced aversion to invest further effort into the task (Thorndike, 1900). In this thesis, fatigue will be used often as a general term referring to of any one or combination of time-on-task fatigue, sleepiness, and drowsiness.

Time-on-task Fatigue: Mental fatigue that produces a performance decline during a work period even as short as 10-20 minutes (FMCSA, 2005), particularly in repetitive monotonous tasks. Time-on-task fatigue is by definition independent of time awake or the circadian drive.

Sleepiness: Difficulty in maintaining alert wakefulness so that the person falls asleep if not actively kept aroused. The sleepiness is not simply a feeling of physical tiredness or listlessness (ICSD, 2001). To assess subjective sleepiness, the Karolinska Sleepiness Scale (KSS) is often used, which asks subjects to rate their sleepiness during the previous 5 minutes on a scale from 1 (very alert) to 9 (very sleepy, great effort to keep awake, fighting sleep).

Alertness: is the state of paying close and continuous attention or being quick to perceive and act. Alertness decreases as sleepiness increase and can be subjectively measured by the Visual Analog Scale for Alertness (VAS).

Drowsiness: A state of quiet wakefulness that typically occurs before sleep onset (ICSD, 2001). The Karolinska Drowsiness Test is as subjective self-assessment of drowsiness that can be used as a compliment to the KSS. An objective measure of drowsiness can be obtained from Optalert, eyewear outfitted with an infrared sensor that detects decreases in eye reopening rate to determine a Johns Drowsiness Score (Johns,2010).

Microsleep: An episode lasting up to 30 seconds during which external stimuli are not perceived. Microsleeps are associated with excessive sleepiness and automatic behavior (ICSD, 2001). After a microsleep, a person may remain unaware that it occurred experiencing an amnesia-like episode. Microsleep can be detected visually (head nods, closed eyes) as well as with Electroencephalography (EEG) markers. Prolonged response lapses in the Psychomotor Vigilance Test (PVT) can also indicate bouts of microsleep.

Sleep Homeostat: A process included in sleep and circadian models accounting for why cognitive performance depends on the amount of sleep a person has recently experienced. Experiments show that a total of 7-8 hours of sleep is required during each 24-hour period, and that performance declines markedly after 18 hours awake.

Sleep debt: Sleep models and experimental data show that when a person obtains less than 7-8 hours of sleep within a 24-hour period, the sleep homeostat exerts a drive for sleep, often referred to as “sleep debt”. The sleep debt related cognitive impairment increases if sleep is chronically restricted to less than 7-8 hours over a period of days. Some evidence suggests that after chronic sleep restriction, a single night of prolonged (>8-hr) “recovery sleep” is not sufficient to immediately eliminate sleep debt effects.

Slam shift: A change in the sleep/wake schedule in which the normal sleep period is abruptly advanced or retarded by a specific length of time.

3.4. Fatigue Risks and Possible Countermeasures in Space

Robotics operations on the ISS carry high risk. The robotic arm moves slowly, but mistakes could endanger the crew (particularly during EVA), damage the station, the payload, or the arm itself (if collisions were to occur), potentially leading to mission failure or loss of life. A number of incidents have occurred during robotics operations that have been at least partially attributed to crew fatigue including a near collision and input errors that caused undesirable arm motion (Williamson, 2007).

Although the era of using the robotic arm to construct station is over, the robotic arm will remain an integral part of station operations in the future operations such as resupply. Seven free flyer captures (vehicle captured by arm and docked to station) are planned in 2013: 1 Japanese H-II Transfer Vehicle (HTV), 3 SpaceX Dragons, and 3 Orbital Science Cygnus vehicles. This significant increase in the number of vehicles visiting station that require telerobotics operations will also increase the risk of robotics errors. Therefore, it is more important than ever to understand and mitigate all possible risks, including those associated with fatigue.

Figure 4: Astronaut Mike Fincke holding the SSLA prototype aboard the ISS before installation and a close up view with the fluorescent GLAs (in the background) that will be replaced by the SSLMs in the future. Photo credits: NASA.

The traditional countermeasure to fatigue in space, as on Earth, is caffeine. Continuous low-dose caffeine administration has been shown to improve performance on multiple cognitive tests including the Digit Symbol Substitution Test (DSST) and Psychomotor Vigilance Test (PVT), for subjects under circadian desynchrony and long times awake. For astronauts with similar sleep-wake schedules, continuous low dose caffeine is a potentially effective way to maintain alertness over extended wake duration without significant side effects (Wyatt, 2004).

It has recently been shown that blue-enriched white light is particularly helpful for resetting the body's circadian clock and for maintaining alertness (Lockley, 2006). For ISS, the Solid State Light Assembly (SSLA), a new light unit made of arrays of Light Emitting Diodes (LEDs), has been developed to replace the fluorescent General Luminaire Assemblies (GLAs) (Figure 4). Current plans are to first install the SSLAs in Node 2 outside of crew quarters for maximum impact. The remainder of the station will be outfitted with the solid-state units as the GLAs burn out, estimated to begin in 2014-2015. The SSLAs are efficient replacements because of their lower up-mass, power consumption, heat generation, and use of toxic materials. They are also more resistant to damage and have a longer life than the current GLAs. Additionally, the SSLAs provide the capability to easily control the brightness and wavelengths of the light, making it possible to customize the light for specific operational needs (NASA HRP, 2011). The Solid State Lighting Module – Research (SSLM-R) is an identical unit to the SSLA prototype in its appearance and mechanical connections, however it has broader light output capabilities for research purposes (Brainard, 2012).

To obtain results that can be translated most directly to operations on the ISS, this experiment compares low-dose caffeine administration (in pill form) and blue-enriched white light from four SSLM-Rs as countermeasures for fatigue-induced cognitive performance deficits.

3.5. Workload Measurement

Mental workload is an estimate of the cognitive demands of an operator's duties (Proctor, 2008). In this study, we were interested in understanding the effects of fatigue and fatigue countermeasures on mental workload. Workload measurement techniques are typically organized into three categories: 1) self-assessment or subjective rating scales, 2) psychophysiological measures, and 3) performance measures (including primary and secondary task measures) (Eggemeier et al., 1991).

Common subjective scales used in human factors aerospace research include the Bedford Scale and NASA TLX, in which the subject does a self-assessment after completion of the task. Psychophysiological measures for mental workload include among others: heart rate, respiration, electroencephalography (EEG), and blink rate. If measured with unobtrusive equipment, psychophysiological measurement techniques have the advantage of not affecting performance on the primary task.

Measuring mental workload through primary performance measures (in this case, robotics) assumes that as task difficulty increases, performance of the primary task will degrade as the workload requirements exceed the available mental capacity. However when the primary task shows little or no impairment, a secondary task is needed to measure mental workload. A pilot study performed during the development of this

experiment showed that when subjects performed space robotics tasks after being awake for 18 hours, there was little degradation in their primary robotics metrics even though they had reported feeling sleepier (on the Karolinska Sleepiness Scale). However, the secondary task was sensitive changes in primary task workload and sleepiness, exhibiting an effect of time awake (Lowenthal, 2012).

Another experiment assessed time-on-task effects (roughly 2 hours) in simulated monotonous automobile driving scenarios. From this, time-on-task fatigue was found to be associated with a change in performance strategy that resulted in a restriction of effort costs while protecting primary performance goals (Van der Hulst, 2001).

Multiple-resource theory states that there is not one single pool of attentional resources, but that instead there are many distinct cognitive subsystems each with its own limited pool of resources (Proctor, 2008). When the task sensory modalities do not overlap, for example: a visual and auditory task, performance on both tasks will be maintained. But when two closely related tasks require attentional resources from the same pool, it is more difficult to perform them simultaneously. If priority is given to one of the tasks, the other becomes the secondary task and reflects the spare capacity of the limited attentional resource pool.

We hypothesized that sleepiness affects performance by decreasing overall cognitive capacity, which in turn decreases the available spare capacity in the attentional resource pool for the secondary task, resulting in degraded secondary task performance.

3.6. Effect Size

Many studies have examined the effects of sleep deprivation on various domains of cognitive function. To compare results across studies and domains, an effect size metric can be used. Effect size is a standardized estimate of the magnitude of the treatment effect (Lim & Dinges, 2010). Hedges' g effect size (corrected) is defined as

$$g = \frac{(\overline{x_1} - \overline{x_2})}{s^*}\left(1 - \frac{3}{4(n_1 + n_2) - 9}\right)$$

$$s^* = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$

where s* is the pooled standard deviation and the variables subscripted with 1 and 2 represent the control and experimental groups, respectively (Hedges & Olkin, 1985).

In Lowenthal (2012), the manipulation of time awake (18 hours) on side task response time gave moderate to large Hedges' g values from 0.35 (complex secondary task) to 0.74 (simple secondary task) (Lowenthal, 2012). These values agreed reasonably well

with those found in a meta-analysis examining short-term sleep deprivation on a variety of cognitive variables. In that study the effect sizes ranged from 0.125 to 0.762, with the largest effects corresponding to tests of vigilance or simple attention lapses and reaction times (Lim & Dinges, 2010). In the present experiment, we will continue to examine the Hedges' g effect size of fatigue on simple secondary task responses.

3.7. Spatial Ability

As discussed previously, space station robotics operations require well-developed spatial ability skills in order to integrate camera views, visualize 3-D space, and interpret visual information. Spatial abilities (SpA) can be defined as our ability to generate, visualize, memorize, and transform visual information such as pictures, maps, or 3D images. Over the past 40 years, human spatial abilities have become better understood through psychometric, cognitive, and physiological research. Although there is some debate over the factors that have been shown to contribute to SpA including genetic heritage, gender, childhood education, professional training, and practice, there is general agreement on the importance of two specific classes of spatial abilities, spatial visualization (SV) and spatial orientation (SO).

SV is the ability to manipulate a mental image into other configurations. This capacity is measured by a standard test in which one must imagine what shape a 2D piece of paper will take if folded into 3D space. SO is the ability to imagine how a complex object will look after rotation and is subdivided into perspective taking (PT) and mental rotation (MR). PT requires a person to move their own egocentric reference frame within the fixed world coordinate system to a new viewpoint. During MR, the egocentric reference frame remains fixed and the object is rotated about its intrinsic reference frame. We believe that SO skills are the most relevant to performance in our robotics tasks, particularly in integrating multiple camera views into a single mental representation. Although the tasks do require the subject to mentally transform a 2D image (presented on a screen) into a 3D mental picture--which may suggest SV--manipulation of the objects in the task is not required.

SpA and a variety of robotics tasks have been studied in the past. In the medical field, it was found that SpA correlated with early stages of laparoscopic training performance. (Eyal, 2001). It was also shown that performance on a 2D navigation task with a teleoperated robot correlates with measures of SpA (Lathan, 2002). Viewpoints are particularly relevant components of space robotics operations as described earlier. It is known that when an observer's reference frame is mismatched to the reference frame of the environment in which they are operating, direction errors are more likely to occur (Tversky, 2005). Using the MVL Dynamic Skills Trainer (DST) simulation environment for a generic robotic arm control task, it was found that when operators used camera views with high anglular disparities (larger than 90° but less than 180°), the number of control

input errors increased. Reference frame type (external vs. internal) had an even greater effect on performance errors (Tomlinson, 2009).

More generally, using the same DST environment, Menchaca-Brandan (2009) found that subjects with higher PT ability had more efficient movements and performed the task faster. Additionally, SpA scores correlate particularly well to performance during early stages of robotics training performance (Tomlinson, 2009).

Further, from actual astronaut data, Liu et al. (2012) found that standard spatial ability tests were even predictive of performance on final robotics training evaluations. In that study, logistic regression models were created for four SpA tests to predict perfect vs. non-perfect post training evaluation grades of 50 astronauts. There was a significant model fit for many of the SpA tests and Receiver Operating Characteristic (ROC) curve metrics were used to quantify the predictive capability of each test (Fan, 2006). The area under the ROC curves were all above 0.74, suggesting that while the SpA test scores could potentially be used to help plan or mediate astronaut training, they should not be used to make career defining decisions.

4. Study Hypotheses

The top-level study hypotheses focused on the robotics tasks are listed below.

1) Subjects SpA test scores will positively correlate to initial robotics performance during the first training/screening session at MIT.

2) Subjects SpA test scores will positively correlate to final robotics performance measured during the experimental test sessions.

3) Robotics, cognitive, and Sleepiness measures will degrade with:
   A. Slam shifts due to circadian and time awake factors.
   B. Task duration, independent of circadian and time awake.

4) Secondary robotics task (secondary task) measures will degrade more than primary robotics measures because subjects will maintain performance on the primary robotics tasks at the expense of the secondary task.

5) Countermeasures will improve robotics, cognitive, and sleepiness measures compared to the baseline.

6) Even with countermeasures, there will still be time-on-task effects.

7) Inter-subject differences in performance will exist due to individual vulnerability to fatigue.

5. Experiment Description

5.1. Robotics Workstation Simulator

The experiment used the MIT Robotics Workstation Simulator (RWSS), a program created with Vizard, a Python-script-based virtual reality development program that had been used in many previous MVL telerobotics experiments (Forman, 2011, Lowenthal, 2012, Wang, 2012). The RWSS was analogous to the NASA Johnson Space Center Dynamic Skills Trainer used for astronaut training and approximately mimicked the use of the Space Station Remote Manipulator System (SSRMS). Like the Robotics Workstation on the ISS, the simulator interface contained three monitors, a rotational hand controller operated with the right hand, and a translational hand controller operated with the left hand. The simulator also used a keyboard and mouse. The most notable operational differences between the MIT RWSS and SSRMS were the lack of arm dynamics and faster movement rates in the RWSS (50 cm/s vs. 37 cm/s max speeds in translation). In actual operations, a primary and a secondary operator work together to manage the SSRMS, but in the present experiment, only a single primary operator worked alone to operate the arm.

5.2. Robotics Tasks

Study subjects were taught and tested on three distinct task types: 1) Track and Capture, 2) Fly-to and Grapple, and 3) Autosequence. Both internal and external control reference frames (see Section 3.1) were used, depending on the task. In addition, a vernier mode was available, in which the motion of the arm was significantly slowed (max speed 5 cm/s) allowing for finer adjustments and safe grapple operations. At the start of each testing session (discussed in detail later), subjects were given a binder that included a task sheet for each trial that gave all necessary information to complete the trial (Appendix 12.4). The key commands necessary for the trials are listed below (Table 1).

Table 1: Key commands and actions used in robotics tasks

Keystroke	Action
b	Brake on or off
i	Internal mode
e	External mode
v	Vernier mode on or off
D	Indication that subject is done with FTG trial
A	Initiation of autosequence trial
F1	Change camera view on Monitor 1
F2	Change camera view on Monitor 2
F3	Change camera view on Monitor 3

5.2.1. Track and Capture

The track and capture (T&C) task required the subject to move the arm toward and grapple a free-flying payload moving at a set drift rate in a motion that is not known to the subject before the start of the trial. These trials simulated the capture of an H-II Transfer Vehicle (HTV), a Japanese unmanned resupply module. The T&C trials had a time limit of 90 seconds to complete capture, the standard window of time for a safe abort on ISS. Additionally, the drifting motion of the payload was unpredictable for the subject; the vehicle did not begin drifting until the subject had released the brake to begin arm motion towards it. T&C trials began with the end effector lined up 2 meters away from the target. The same three camera views were maintained throughout the trial, with the end effector camera view on the center monitor (Figure 5). All T&C trials were performed using an internal command frame and vernier modes. Twelve unique T&C trials were repeated in random order throughout the experiment. Trial order was the same between subjects so that time-on-task would be the same for each trial for every subject.

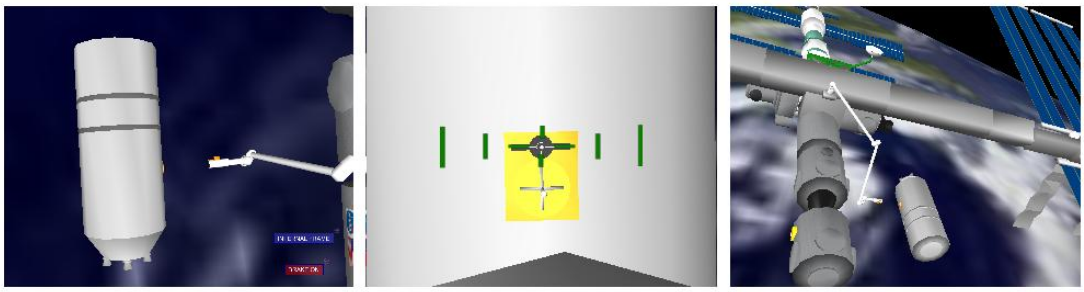


Figure 5: T&C views at start of trial.

5.2.2. Fly to and Grapple

The fly-to, grapple, and berth trials (FTG), the most complex trial type, simulated the move to, grapple, and repositioning of a payload to a berthing position on ISS. Each FTG trial consisted of three stages. In Stage 1, Fly-to, the arm was moved in the external frame towards the target payload into pre-grapple position, defined as 1.5-2 meters away (judged visually) and perpendicular to the target (Figure 6). Stage 1 began when the subjects released the brake and ended when they switched from external to internal mode.

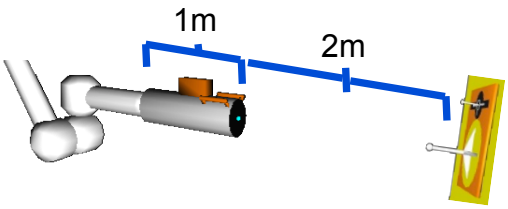


Figure 6: Pre-grapple position

In Stage 2, Grapple, the subject changed the control frame to internal frame and changed at least one camera (as specified on the task sheet) to make the end-effector camera view available. The arm was then moved towards the target and aligned for grappling. When the arm was perceived to be about 0.5 meters from the target, the subject changed into vernier mode (slow) and continued motion towards to the target. When the grapple requirements were met, the trigger was pulled which latched the payload to the arm. Stage 2 began when internal mode was entered, and ended when the payload was grappled.

In Stage 3, To Berth, the end-effector camera view was replaced with a different pre-specified view, and the control mode was switched back to external. The payload was then moved to a specified berthing position elsewhere on station, described to the subject by a brief written description and by three pictures corresponding to the three final camera views that show the payload in the desired position. When the subject believed they had positioned the payload within 2 meters and 10 degrees of the desired position shown in the pictures, they pressed 'D', indicating that they were done with the trial. Stage 3, therefore began after the object was grappled and ended when the subject pressed 'D'. Stage 3 was similar to Stage 1 in that external control mode was used in both to move large distances around the ISS, however stage 3 was more difficult since a payload was attached to the arm, requiring more attention allocated to clearance monitoring.

For most FTG trials, camera changes were required throughout the trial, not only pre- and post-grapple. The time allotted to complete an entire FTG trial was 10 minutes. If the subject completed the task in less than 10 minutes, they remained seated and waited for the next trial to automatically start. If the subject never completed the trial (ran out of time before pressing 'D'), Stage 3 ended when the trial time ran out.

5.2.3. Autosequence

Autosequence (AS) trials were the least physically demanding trial type since the hand controllers were not used, but they required the subject to be extremely vigilant. AS trials simulated the programming of arm motion, followed by visual monitoring of the arm for possible clearance violations as it moved automatically. To begin an AS trial the subject entered arm motion information in one of 2 modes, Frame of Reference (FOR) or Joint Angle. FOR mode was the most automated mode in which the subject selected

Option 1, 2, 3, or 4 from a drop down menu, pressed the Load button, got confirmation from ground control, removed the brake, and then pressed the Confirm button. In Joint Angle mode, the subject manually entered the final joint angles for all 6 degrees of freedom then pressed the Load button and performed the remaining steps as in FOR mode (Figure 7). The subjects then monitored arm motion for clearance violations defined by the arm within 1.5 meters of structure. When they detected a violation, subjects would press 'b' (for brake) on the keyboard to stop the motion of the arm. A dialog box would acknowledge the brake application and allow subjects to restart the arm motion. An AS trial had 0, 1, 2, or 3 clearance violations. The arm motion stopped automatically at the end of the trial (10 minutes total).

Figure 7: Two autosequence initiation modes, FOR and Joint Angle.

5.2.4. Secondary task

During each of the three trial types described above, the subjects also performed a concurrent simple secondary task. Subjects had to respond to the appearance of an on-screen message box that appeared on the bottom of the left monitor whose color alternately flashed green and yellow (Figure 8) within 10 seconds by pressing a side button on the RHC. After 10 seconds, if there was no response the message disappeared and the subject was charged with a missed response. The interval between secondary task messages was random and between 2 to 10 seconds. Subjects were instructed to give priority to the primary robotics task when unable to attend to the secondary task. Because the simple visual secondary task required attentional resources from the same pool necessary to do the primary robotics tasks, it can be considered a measure of spare attention and workload.

Figure 8: Enlarged secondary task message.

5.2.5. Robotics Metrics

Each of the three robotics tasks provided many metrics (Table 2). Those were calculated once per trial, but the FTG trials were also divided further into their (3) distinct stages based on when particular keystrokes were pressed.

Table 2: Robotics Metrics Defined

Metric	Data Type	Description	T&C	FTG	AS	Data collection during robotics
Grapple Time	Continuous	Time from release of brake to grapple of payload	X	X		1 measure per trial
Grapple Position Error	Continuous	Distance error of end effector at time of grapple	X	X		1 measure per trial
Grapple Angular Error	Continuous	Angular error of end effector at time of grapple	X	X		1 measure per trial
Fly Time	Continuous	Time from grapple of payload to placement at final position indicated by 'D'		X		1 measure per trial
Final Position Error	Continuous	Distance Error of end effector at final payload placement when 'D' pressed		X		1 measure per trial
Final Angular Error	Continuous	Angular Error of end effector at final payload placement when 'D' pressed		X		1 measure per trial
Failed Grapple	Discrete	Number of times trigger pulled without successful grapple	X	X		1 measure per trial
Collision	Discrete	Number of collisions (arm - arm, arm - station, arm - payload, payload - station)	X	X		1 measure per trial

Metric	Data Type	Description	T&C	FTG	AS	Data collection during robotics
Clearance Violation	Discrete	Number of occurrences when arm or payload comes within 1.5 meters of station		X		1 measure per trial
Joint Hardstop	Discrete	Number of arm hardstops that occurred		X		1 measure per trial
Singularity	Discrete	Number of arm singularities that occurred		X		1 measure per trial
Resets	Discrete	Number of times arm is reset by subject		X		1 measure per trial
% Bimanual	Continuous	% bimanual control inputs	X	X		1 measure per trial 3 for split FTG
% MultiAxis	Continuous	% multi-axis control inputs	X	X		1 measure per trial, 3 for split FTG
Modified FlyTime	Continuous	Time from grapple of payload to when payload is within 2 m and 10 degrees of desired final position		X		1 measure per trial
Excess Correction Time	Continuous	Time after position of payload is in the envelope but before subject indicates 'D'		X		1 measure per trial
Jerk Metric Translation	Continuous	Measure of smoothness of controller inputs	X	X		1 measure per trial 3 for split FTG
Jerk Metric Rotation	Continuous	Measure of smoothness of controller inputs	X	X		1 measure per trial 3 for split FTG
Input Reversals Rate Translation	Continuous	Number of reversal of controller input directions per minute	X	X		1 measure per trial 3 for split FTG
Input Reversals Rate Rotation	Continuous	Number of reversal of controller input directions per minute	X	X		1 measure per trial 3 for split FTG
AS Brake Error	Discrete	Number of brake applications when no clearance violation existed			X	1 measure per trial
AS miss %	Discrete	Number of missed clearance violations out of number possible			X	1 measure per trial
AS Late Catch %	Discrete	Number of late catches out of number possible			X	1 measure per trial
Missed ST Percentage	Continuous	% of secondary task missed responses	X	X	X	1 measure per trial 3 for split FTG
Inv ST response time	Continuous	Inverse of average secondary task response time	X	X	X	1 measure per trial 3 for split FTG

A few metrics warrant further explanation:

- Joint Hardstops occurred when one of the robot arm's joints reached its rotation limit. This occurred when the direction of rotation did not accommodate the shortest path available to the desired position.
- Singularities are kinematic limitations of the arm. They occurred when 1) the elbow pitch joint was extended all the way (0 or 180 degrees), 2) when the wrist yaw joint was at 90 degrees, and 3) when the wrist was located directly over the shoulder vertically.
- % Bimanual Movement was the percentage of all controller inputs that were done with more than one hand at a time. This fraction was the number of instances in which a THC input occurred at the same time as an RHC input divided by the total number of samples in which control input occurred.
- % Multi-Axis Movement was the percentage of all controller inputs that consisted of more than one axis of motion with the same hand. This was calculated by dividing the number of instances in which a THC or RHC control had inputs in more than one axis by the total number of samples in which there was a control input.
- Jerk Metric for translation and rotation were defined by the equations:

$$JM_T = \frac{\overline{|jerk_T|}}{\overline{|velocity_T|}} \quad , \qquad JM_R = \frac{\overline{|jerk_R|}}{\overline{|velocity_R|}}$$

  where velocity and jerk were calculated as the first and third (approximate) derivatives, respectively, of the translation or rotation resultant vector. As in other control movement studies, the jerk magnitude was divided by the velocity magnitude (or speed) so that the metric was a measure of jerkiness only, not confounded with changes in overall movement speed (Frascarelli, 2009, Rohrer, 2002).
- Input Reversal Rate was defined as the sum of the number of times an input in X,Y,Z (translation) or Pitch, Yaw, Roll (rotation), crossed over the zero (neutral, no movement) position divided by total time spent on the task. The input reversal rate was a measure of how often a subject made incorrect motion control inputs, or how often they were incorrectly guessed the appropriate control input.

In addition to the robotics data, there is a rich set of data from the cognitive, sleepiness, and circadian tests given in the additional test block and throughout the subjects' stay in the sleep lab not discussed in this thesis (Appendix 12.6).

5.3. Experiment Protocol

5.3.1. Recruitment

Subjects were recruited by the BWH Sleep lab. All subjects had a Bachelor's Degree, were between 26 and 55 years of age (comparable to astronaut age range). Equal numbers of men and women were recruited. The primary source of inquiries (over 75%) for the labs studies came from advertising in the jobs and volunteer sections of Craigslist.org for Boston, Hartford, Rhode Island, New Hampshire, Maine, and Vermont. Additionally, ads were placed in a variety of clinical trial consolidation sites and other social news websites like reddit.com. The advertised maximum compensation was $2510. The actual paid amount varied based on the number of days subjects were required to maintain the experiment mandated sleep schedule before the experiment began, which could be more than planned due to the logistics of trainer, subject, and lab availability.

5.3.2. Screening

The general screening flow was as follows. Subject first had to pass an initial screening questionnaire given by BWH (See Appendix 12.1) before signing the experiment consent form (See Appendix 12.2). After they were consented, subjects were scheduled for an initial robotics training/ screening session at MIT. After passing the robotics screening subjects had to pass standard BWH Sleep Laboratory's medical and psychological screening exams.

We were aware that our subject population probably differed in overall aptitude for robotics from the astronaut population, and that it was desirable that our subjects performance on the various robotics tasks had largely reached asymptote prior to entering the sleep lab portion of the study. Therefore we screened our subjects for basic robotic aptitude during their first training session. To remain in the study, the subject had to satisfactorily perform 8 out of the 12 Fly to Grapple trials in under 10 minutes each, with minimal help from the trainer. As in NASA Generic Robotics Training, the trainee also had to demonstrate an understanding of the both the external and internal reference frames by describing the desired hand controller and resulting arm motion correctly, and by correctly recognizing when the arm motion produced by controller inputs was as intended, or was in an unintended direction.

The initial screening questionnaire and medical and psychological exams administered through BWH screened for any evidence of sleep or circadian disorders, other health issues, and psychological factors that would suggest that the subject might not successfully complete the entire study. Because the BWH screening exams were expensive to administer, they were ordered only after the subject had passed the

robotics screening and before any subsequent robotics training sessions (to avoid expensive tests and time consuming training for subjects who would not be eligible to participate in the study for medical reasons).

Additionally, after passing all screening, subjects had to adhere to the requested sleep schedule (8-hr and 6-hr, See Figure 13) and diet (no caffeine, drugs, etc.). Adherence to sleep schedules (in and out of lab) was monitored through the use of an Actiwatch, a wrist worn sleep wake monitor, sleep logs, and phone call-ins.

5.3.3. Robotics Training

Robotics training was accomplished through a combination of self-paced tutorials, hands-on practice, and trainer guidance. PowerPoint slides were used to give a general introduction to robotics (basic concepts and terminology) and to introduce each specific task type in detail (Appendix 12.3). Subjects were allowed to read through these presentations at a self-set pace and to ask questions at any time. Practice trials were done after each new task was taught. The amount of help and feedback given by the trainer gradually decreased as training progressed. Quantitative feedback available after trials included time to compete the task, % multi-axis control, # of clearance violations, and # of collisions.

A typical robotics training flow is shown below (Table 3) although it varied slightly by subject according to the rate of individual progress. The amount of progress a subject could make in a session depended on their skill and on how much time they spent reading through the training PowerPoints. A key part of the training was the repetition of practice trials. Although the number of different practice trials was fixed, subjects repeated them as needed during their training depended on the trainer's judgment of their progress.

Table 3: Example training session training flow

Training 1 (3.5 hrs)	Training 2 (3 hrs)	Training 3 (3 hrs)	Training 4 (3 hrs)
SpA Test: PTA	Review ppt	Review ppt	Review All ppt
General Training ppt	FTG Training ppt	Repeat FTG trials	Repeat T&C with ST trials
Fly-to Training ppt	3 FTG trials	Repeat T&C trials	Repeat FTG with ST trials
12 Fly-to trials	T&C Training ppt	AS Training ppt	Review AS procedures
SpA tests: Card, MRT, PSVT	18 T&C trials	6 AS trials	8-hr Baseline Test
Robotics Screening Decision		Secondary task Training ppt T&C with ST trials FTG with ST trials	

SpA tests were given to every subject on the first day of training, but they were not used to screen out subjects. The same four standard tests from Liu et al. (2012) were used to assess spatial ability (Table 4, Figures 9-12).

Table 4: Spatial abilities tests used

	Perspective Taking (PT)	Mental Rotation (MR)
2D	PTA: Perspective Taking Ability Test	Card: Card Rotations Test
3D	PSVT: Purdue Spatial Visualization Test	MRT: Vandenburg Mental Rotations Test

Card (Ekstrom, 1976)
The subject must tell if each shape to the right of the divider can (or cannot) be made to conform geometrically to the original shape (to its left) by a rotation in 2D space. The score is determined by the difference between the number of shapes marked correctly and incorrectly (or left unanswered).

Figure 9: Card test example

MRT (Vandenburg, 1978)
Same process as the Card Test, but the object is to be rotated in 3D space. The score is determined by the difference between the number of shapes marked correctly and incorrectly (or left unanswered).

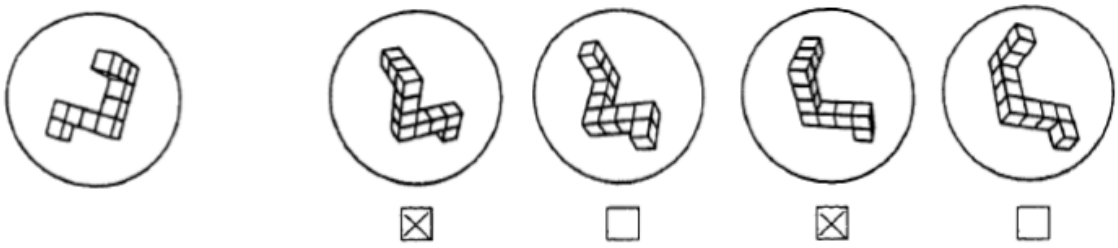


Figure 10: MRT test example

PTA (Kozhevnikov, 2006)
The subject imagined being the central figure in the diagram surrounded by labeled objects. An object in the set was highlighted by a flashing red light and the subject chose one of the arrows below to indicate the egocentric direction to the object specified. The total score was based on the response time for each of the 58 scenarios and the angle difference between the right response key and the subject's response (Δα, in 45° increments from 0 to 180).

$$Total\ Score = mean\left(\frac{100}{(Itemized\ RT + 2)\left(1 + \left(\frac{\Delta\alpha}{22.5}\right)^2\right)}\right)$$

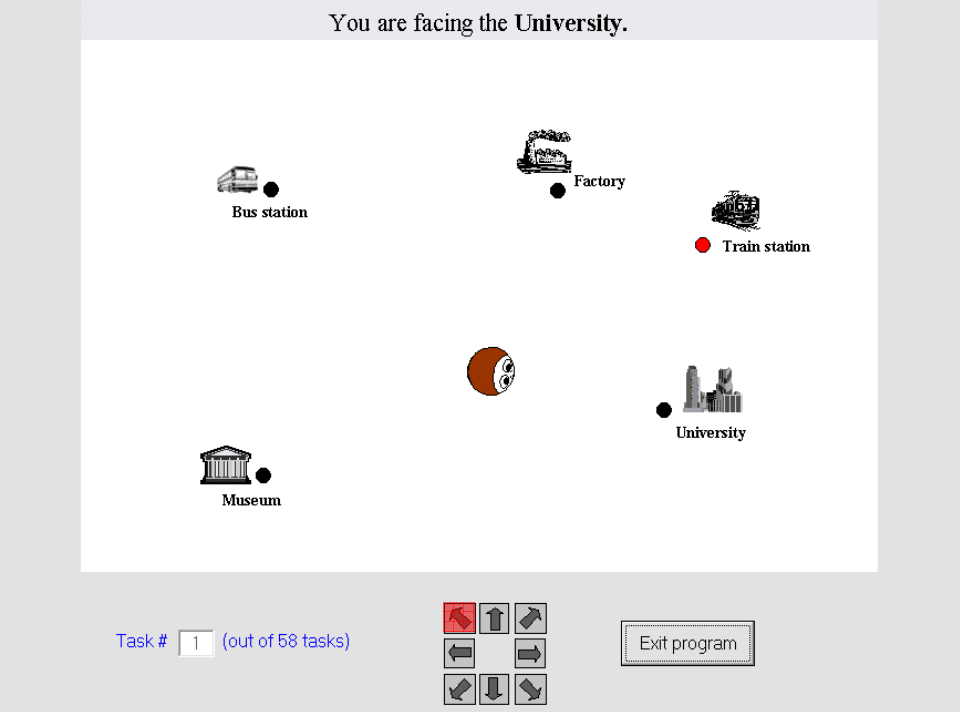


Figure 11: PTA test screenshot

PSVT (Guay, 1977)
The subject identified the appearance of the shape inside the cube from the corner of the box indicated by the black dot. The score was determined by the difference between the number of shapes marked correctly and a quarter of those marked incorrectly (or left unanswered).

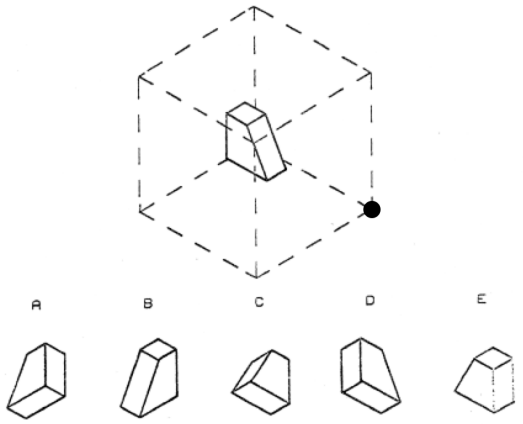


Figure 12: PSVT test example

5.3.4. Test Sessions

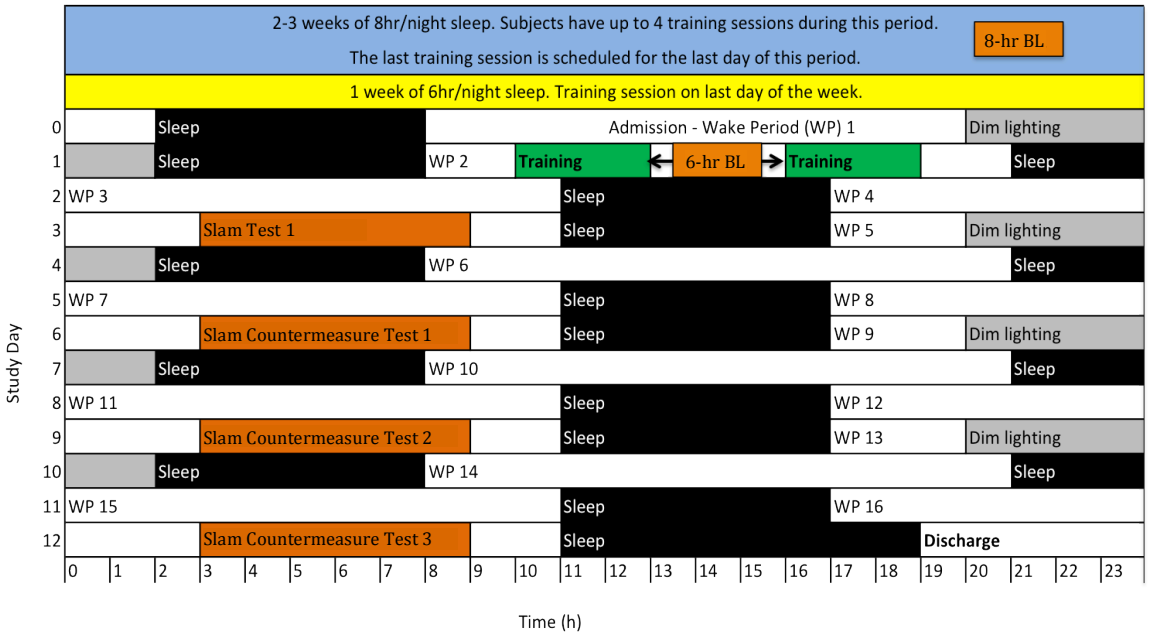


Figure 13: Experiment protocol with study day and time of day.

The experimental protocol (Figure 13) consisted of 6 testing periods (in orange) under various sleep schedules. First, subjects maintained 8 hours of sleep per night for 2-3 weeks, which ended with the first test session, the 8-hr (of sleep per night) Baseline. This was a 2-hour test at the end of either the third or fourth training session at MIT

(depending on the subject's natural aptitude). We did not compare the 8-hr baseline test data to the other robotics test data because the experimental environment was different (at MIT instead of BWH) and the equipment although of the same design was different. Instead, this session can be viewed as a practice session in which subjects learned the basic protocol of testing, which differed most notably from training in that trainers could not provide help or talk to the subject. During testing, the subjects also had to wait between trials for the allotted trial time to expire instead of automatically advancing, as they did in training.

Following the 8-hr Baseline subjects slept 6 hours per night for one week. After this, they were admitted to BWH sleep lab suite for the 13 day experimental protocol. The lab suite had a bed, a desk, and a TV (for use with DVDs only). Anything (including the behaviors of the trainers and administrators) that could give a cue as to the time was rigorously excluded. The RWSS and SSLM-R units were brought into the suite only for the robotics sessions and were removed and stored elsewhere at all other times. The workstation, SSLM-R lights, and chair were placed by measurement and marked so that placement was consistent within and between subjects. On study day 2, a test session identical to the 8-hr Baseline, called the 6-hr Baseline (due to the 6-hr sleep schedule), took place. The two training time blocks (in green, Figure 13) in study day 2, were allocated for refresher training and the 6-hr baseline test, respectively. The second training block, however, was never needed. Every subject was able to complete refresher training satisfactorily (as judged by the trainer) and the 6-hr Baseline within the first block of time.

The four main experimental test sessions occurred on study days 3, 6, 9, and 12. Before these sessions, the subjects' were repeatedly allowed a 3-hour nap, and then their sleep schedule was slam-shifted by 9 hours while still maintaining a 6-hr per night sleep schedule. Robotics performance was tested during the period 3-9 hours after their nap. The subjects then were permitted a 6-hour period of recovery sleep, and returned to their original sleep schedule the next day before beginning the next slam shift cycle. The first main experiment session, Slam Test 1, was the baseline test for the slam shift without countermeasures. The following three main experiment sessions, Slam Countermeasure Test 1-3 included countermeasures (See section 5.3.5). At the end of the experiment the subjects were permitted an 8-hour recovery sleep period before discharge.

In order to avoid confounding fatigue effects with robotics trial differences, the experiment protocol was identical for each subject (except countermeasure order) such that robotics trials were not randomized between subjects in any way.

One aim of this study was to determine the effects of slam shift on complex task performance while under prolonged 6-hr sleep restriction. Sleep debt caused by prolonged 6-hr sleep restriction leads to impairment on tests of alertness, memory, and performance, particularly after the first night of sleep restriction after which the effect

seems to stay relatively constant (Drake et al., 2001). For this reason, subjects were 6-hr sleep restricted for a week prior to testing. For simple task performance it has been shown that circadian slam shifting has detrimental effects on performance particularly in the several hours before wake time (Dijk et al., 1992). Accordingly, the slam shifted test sessions in the study begin 5 hours before normal wake time in order to measure the maximum slam shift effect.

Another aim was to quantify time-on-task effects. In this study it is not possible to definitively separate out a true time-on-task effect from sleep homeostatic and circadian desynchrony effects which are all potentially further confounded with prolonged sleep restriction. Modeling of the study protocol suggested that a wake time of 16-18 hours is necessary before the sleep homeostat would begin to have an effect. To avoid large sleep homeostatic effects, subjects reach 16 hours of wake time exactly at the end of the test session. However it is possible that the addition of 6-hr sleep restriction may cause an earlier homeostatic effect not seen in the model, which assumed unrestricted sleep. Overall, we believe that in this study pure time-on-task fatigue will have the largest effect during the test sessions.

A.

8 hr baseline, 6-hr baseline	60 min	Block 1	12 T&C	90 sec each, 20 min total
			FTG 1	10 min
			AS 1	10 min
			FTG 2	10 min
			AS 2	10 min
	3 min	Break		
	60 min	Block 3	12 T&C	90 sec each, 20 min total
			FTG 5	10 min
			AS 5	10 min
			FTG 6	10 min
			AS 6	10 min

B.

Main Experiment Sessions 1-4	60 min	Block 1	12 T&C	90 sec each, 20 min total
			FTG 1	10 min
			AS 1	10 min
			FTG 2	10 min
			AS 2	10 min
	30 min	Additional Tests + 7 minute break.		
	60 min	Block 2	12 T&C	90 sec each, 20 min total
			FTG 3	10 min
			AS 3	10 min
			FTG 4	10 min
			AS 4	10 min
	30 min	Additional Tests + 7 minute break		
	15 min	Break		
	60 min	Block 3	12 T&C	90 sec each, 20 min total
			FTG 5	10 min
			AS 5	10 min
			FTG 6	10 min
			AS 6	10 min
	30 min	Additional Tests + 7 minute break		
	60 min	Block 4	12 T&C	90 sec each, 20 min total
			FTG 7	10 min
			AS 7	10 min
			FTG 8	10 min
			AS 8	10 min
	30 min	Additional Tests + 7 minute break		

Figure 14: A) 8- and 6-hr baseline test design. B) Four main experiment sessions design

Table 5: Additional Tests

Abbrev.	Test	Time	Source
NLT	Number Letter Test	6 min	Rogers and Monsell, 1995
VAS	Visual Analog Scale for Alertness	1 min	Monk and Embrey, 1989
KSS	Karolinska Sleepiness Score	1 min	Akerstedt and Gillberg, 1990
DSST	Digit Symbol Substitution Test	2 min	Adapted from Wechsler, 1981
PVT	10 min Psychomotor Vigilance Test	10 min	Dinges, 1985
KDT	Karolinska Drowsiness Test	3 min	Gillberg, et al., 1996

Each testing session consisted of 2 or 4 robotics blocks with each block including all three trial types, T&C, FTG, and AS (Figure 14). The 8- and 6-hr baseline tests were identical subsets of the main experiment robotics blocks (Blocks 1 and 3), making them half as long as the full experiment sessions. This aspect of the design was driven by schedule limitations. There were 8 unique AS and FTG trials, not repeated within a session and 12 unique T&C trials that were randomized per block. The additional 30 min test blocks in the four main experiment sessions consisted of 23 minutes of neurocognitive and (subjective and objective) sleepiness/drowsiness tests (Table 5) and 7 minutes of break time. The non-robotics tests are listed for completeness, but only partial results from the KSS were available and are discussed in this thesis. The four main experiment sessions (Slam Test 1 an Countermeasure Test 1-3) were identical such that the same trials were seen in the same order every session.

The main protocol difference between the 6-Hr Baseline and Slam 1 session was the hour of refresher training prior to the 6-Hr Baseline and the additional test blocks in the Slam 1. There were also differences in the testing environment. The lighting in the room was different (discussed in Section 5.3.5) and in the 6-Hr Baseline, subjects were not outfitted with EEG electrodes like in Slam 1. Less equipment was involved in the test setup, with the second set of SSLA-R lights (not connected to robotics cart) absent from the 6-HR Baseline. These differences created an overall less formal test environment in the 6-Hr Baseline than in Slam 1. For some subjects, these differences could have resulted in different performance within the sessions, not related to the slam shift.

5.3.5. Countermeasures

In each of the last 3 main experimental sessions, Slam Countermeasure Test 1-3, one of three countermeasures (caffeine, blue-enriched white light, or both) was applied. The order in which the countermeasures were given was randomized such that each subject received one of three possible orders of the countermeasures. Caffeine was administered hourly in pill form, with a placebo taking its place during the non-caffeine sessions. The caffeine dose was 0.3 mg/kg/hr, beginning one minute after wake time and terminating 2 hours prior to bedtime.

The 6-hr baseline session took place with the room lights on (90 lux white light) and without the SSLM-Rs. All 4 main experiment sessions took place with room lights off and SSLM-Rs on and programmed either to white light or blue-enriched white light depending on the countermeasure being implemented. Figure 15 is included to visually describe the test setup however, in the picture, room lights and SSLM-R lights are on. This combination never occurred in the experiment.

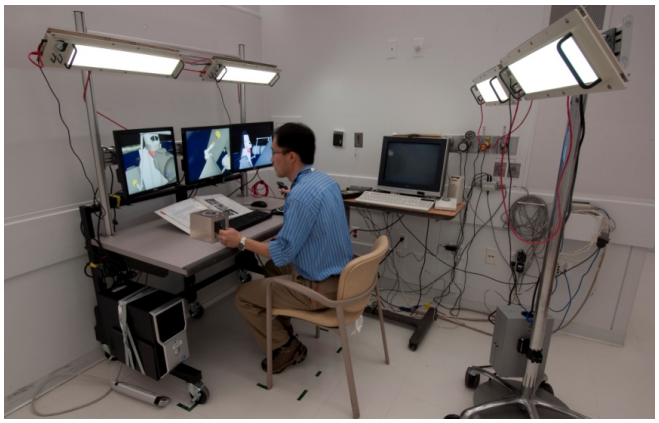


Figure 15: The experimental setup at BWH in the sleep lab, including the RWSS and SSLM-R units placed in front of and behind subject. Room lights and SSLM-R units are on.

The SSLM-R light setting descriptions are given in Table 6. Light intensity (lux) and Irradiance ($\mu W/cm^2$), were measured throughout the session, before and after each block. Measurements were taken at a height of 54 inches at the edge of the desk and 12 inches away from the desk (the chair position range). Light intensity was also measured at the subject's eye level. The two sets of SSLM-R lights were placed 2 meters apart, a similar arrangement of that found in the ISS Destiny module.

Table 6: SSLM-R Light Settings in Study

Measure	Color	SSLM-R white light	SSLM-R blue enriched white light
Color Temperature (K)		4100	6500
Light intensity (lux)		92.02	88.6
Light Intensity	Red	1.803	0
	Green	2.623	1.09
	Blue	0	2.55
	White	15.90.2	17.27

Caffeine, blue light, caffeine+blue light, and placebo (during Slam 1 session) administration was double blind. The code of countermeasure assignments applied will not be broken until after the experiment is complete.

6. Data Processing

Organizing the data from this study was challenging because of the large number of metrics and samples. The experiment includes 20 total hours of robotics per subject, 8 additional hours of tests during robotics blocks, and many additional hours of non-robotics test data. It is of great value to have a system capable of importing, organizing, and outputting this data so that it can be properly analyzed. The foundation of this infrastructure has been developed focusing first on managing the robotics data. In the future, this structure could be expanded to include non-robotics data. A description of the simulation data (Table 7) and hierarchical structure follows.

Table 7: Files, their description, and location output by the simulator

	File	Description
Each Session	Summary	Time, frame, and top level metrics for each trial in the session
	Timesync	Time and frame at start and end of session
Each Trial	Input	Time, frame, X, Y, Z, Roll, Pitch, Yaw inputs
	Joint Angles	Time, frame, 6 Joint angles of arm
	Keystrokes	Time, frame, all keystrokes
	Secondary task	Time, frame, all secondary task prompts, responses, and misses
	States	Time, frame, 10 states (command frame, grapple state, brake state, etc.)
	Target	Time, frame, X, Y, Z, Quaternion of target position
	*Autosequence	Time, frame, brake errors, correct catches, and late catches (*only for autosequence type trials)

Using Matlab, all robotics data is imported and organized into a structure as follows:

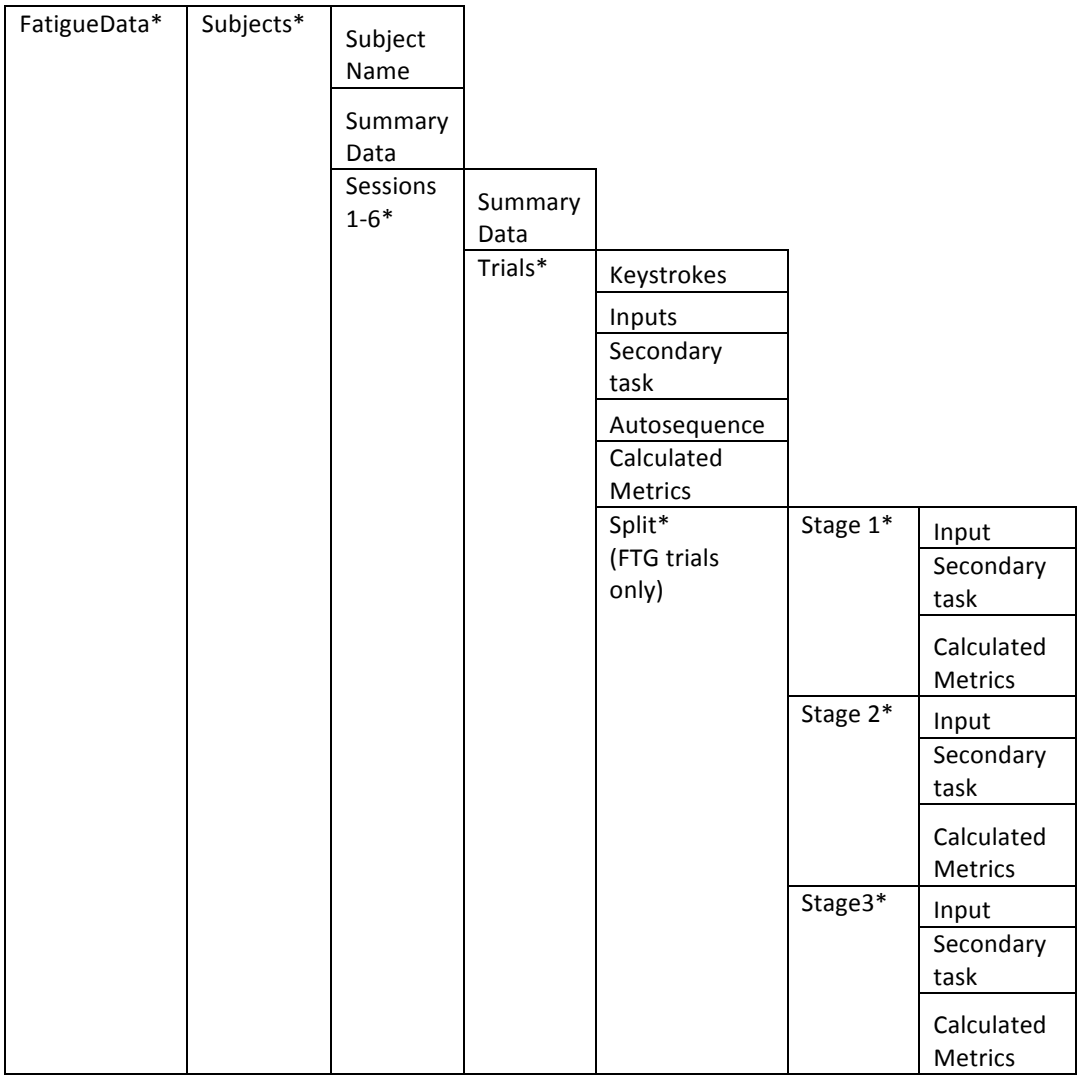


Figure 16: Robotics data structure organization. * denotes sub-structure.

The main advantage organizing the data in this way is that it was particularly easy both to access specific individual pieces of data and to create huge arrays of data for analysis. Using the structure, it is also simple to use the raw data to calculate metrics that were not originally calculated and output by the simulator.

7. Preliminary Results

Preliminary observations and analyses for hypotheses 1 through 4 and 7 are presented in this section. The current status of the subjects who passed the initial recruiting screening questionnaire and had at least one robotics training session at MIT can be seen below.

Table 8: Summary of Subject Screening and Retention

Status	Number of Subjects
Dropped out after at least one robotics session	8
Screened out by MIT for robotics	13
Screened out by BWH for med/psych exams	8
Completed Study	16

To understand the large BWH recruiting effort necessary for this study, we must also look at the numbers of participating subjects (at various degrees) that didn't progress to an MIT training session. Although the study has been recruiting subjects for about 22 months, we have recruiting information for the past year. In the past 7 months (since January 2012), there were 733 inquiries to the BWH recruitment office averaging to about 26 inquiries per week. Roughly 50% of these inquiries did not complete or return the initial screening questionnaire and a large percentage (about 40%) were excluded based on questionnaire responses. The majority of exclusions were due to not meeting the following requirements: specified maximum body mass index, Bachelor's degree, acceptable sleep pattern/duration, absence of night shift work, absence of family or primary history of psychiatric illness. About 20% of the people that passed the initial screening questionnaire, sign the consent form and all necessary paperwork at BWH. Of those, roughly 60% continued on and had at least one training/screening session at MIT.

7.1. SpA as Screening Predictor

This section addresses Hypothesis 1: Subjects SpA test scores will correlate to initial robotics performance.

SpA scores were not used in robotics screening. However, given that Liu et al (2012) found a correlation between SpA scores and astronaut performance in Generic Robotic Training, it was of interest to determine if they were reliable predictors of the screening process. We had previously shown that SpA scores are good predictors of early performance and that they are relatively good at predicting final training evaluations in astronauts. This study presented an opportunity to see if these tests could predict scores on a screening method that was already in place. We had SpA scores for 40[1] of the 47 subjects who completed the 1st training session. Eight of those were screened out due to poor robotics performance on the first day of training. The 40 scores were added to a large database (N=391) of SpA scores (including MIT students, Astronauts, and other subjects from previous studies) and their percentile ranks were found. Because each of the four tests had different scoring scales, each test data set was standardized to z-scores. The average of the four standardized SpA test scores was also ranked in the database (Figure 17). One subject was excluded from analysis because the cause of their release was a language barrier.

[1] 7 sets of scores were missing from the recorded subject notes.

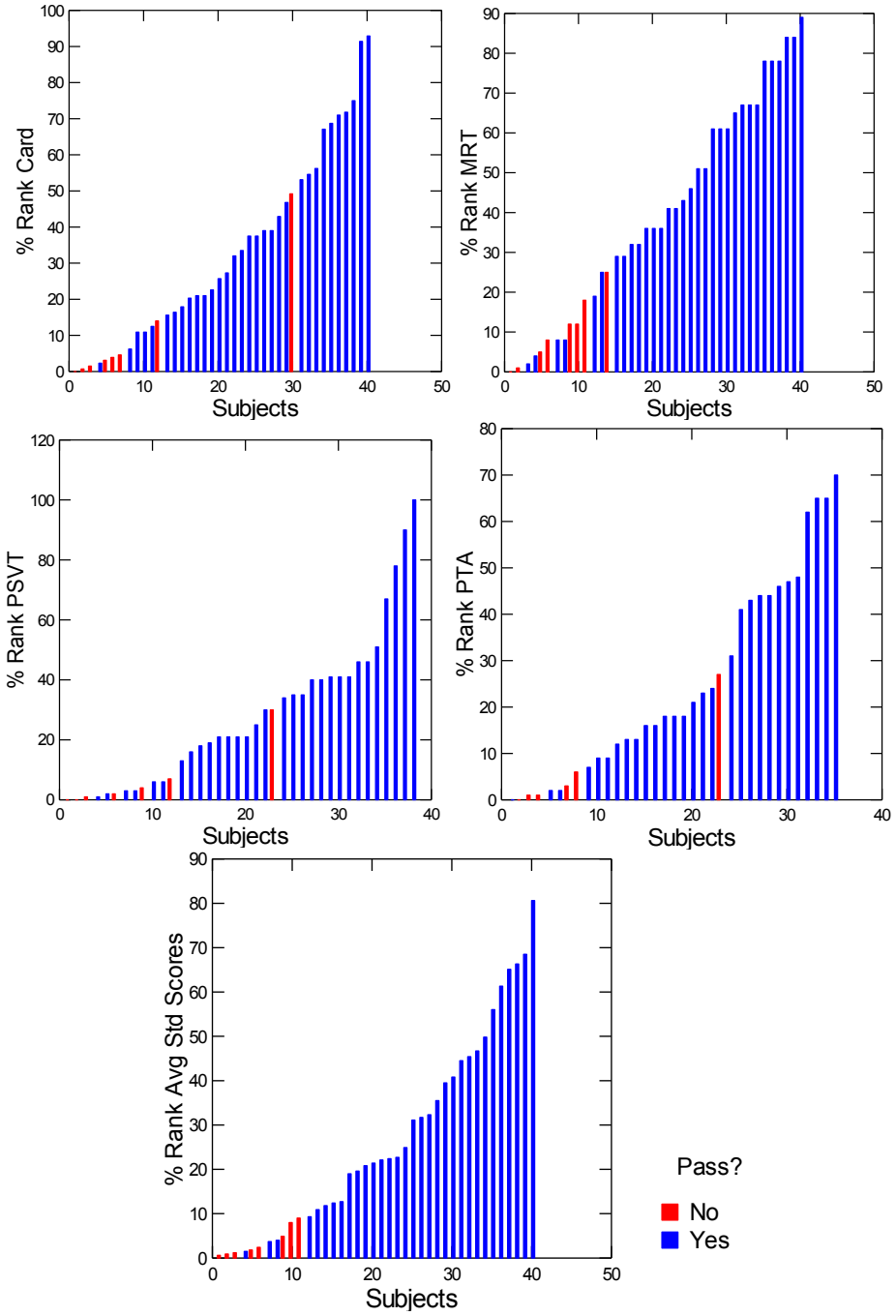


Figure 17: Percent Rank of Fatigue study subjects in SpA Test Data base (N=319) for four separate SpA tests and the average of the four standardized scores. Pass/fail of robotic screening is indicated. Note: Some subjects did not take all 4 tests and subject numbers are not associated across plots. Instead, in each plot, subject scores are ranked from lowest to highest. Also note that there are subjects with 0% Rank in each individual test.

Subjects who did not pass the robotics screening process generally had very low SpA scores for all 4 SpA tests. The converse, however, was not necessarily true. Some subjects with SpA scores comparable to those who failed the robotics screening managed to pass the screening. A contributing factor could be any variability among

trainers' judgments. The trainer pool was small, however, and if the screening decision was not clear to the individual trainer, trainers consulted one another before making a decision. It was also likely that some subjects were able to compensate better for poor spatial abilities by, e.g., the use of strategy, tricks, or rules of thumb.

The average of all 4 SpA standardized test scores separated subjects who passed and those who failed robotics screening better than any individual test. This may suggest that the individual tests are measuring different facets of SpA. Some subjects who may have only one strong spatial skill might still be able to perform the robotics tasks adequately but the pace of learning or ultimate level of performance would be limited. This view is consistent with the high, but imperfect correlation found separately among those scores due to predictor variability.

Following the analysis of Liu, et al (2012), logistic regressions were used to analyze the predictive capability of the SpA test scores or the average, on the robotics screening results. It describes the probability of an event occurring based on predictor values. For the regressions, the dependent variable was the binary screening decision (0: fail, 1: pass) and the independent variable was each of the four SpA test scores, or the average standardized score.

With logistic regression, a threshold probability can be set that defines the number of correct and false predictions. In line with traditional signal detection theory, and using Figure 18C as a reference, the data points to the right of the threshold would be predicted to pass. Data points outlined in green on this side are correct classifications while those in red are wrong classifications, or Type 1 error. To the left of the threshold, points outlined in green are correct rejections while those in red are misses, or Type 2 errors. The threshold in Figure 18C was set at an average score that yields a 50% chance that a subject would pass the robotics screening based only on SpA scores. Moving the threshold to the right would increase the probability that the subject would have passed robotics screening based on their SpA scores, however may also lead to failing subjects who would have otherwise passed. Moving the threshold to the left would decrease the probability of rejecting subjects that would have passed robotics screening but accept a larger portion of subjects that likely would not have passed.

The Receiver Operating Characteristic (ROC) curves are also shown describing how reliably the logistic regression predicts the outcome by showing the % of correct predictions (true positive rate) as a function of the percentage of incorrectly classified top performers (false positive rate) over the range of threshold probabilities. The Area Under the Curve (AUC) gives a quantitative metric of the fit of the logistic regression to the data and provides a basis for comparing models. A model that has no predictive value--equivalent to totally random results--would have an AUC of 0.5. In clinical studies, an AUC less than 0.75 is generally not useful while an AUC above 0.97 is of high value (Fan, 2006). As expected, the ROC curve for the model incorporating the average of the 4 standardized test scores gave the highest AUC value at 0.96 while the MRT had

the highest AUC out of the individual tests at 0.91. All 4 SpA tests and the average had significant logistic model fits to the binary screening data—i.e., the fitted parameters were significantly different from 0-- and AUC values above 0.85 (Table 9).

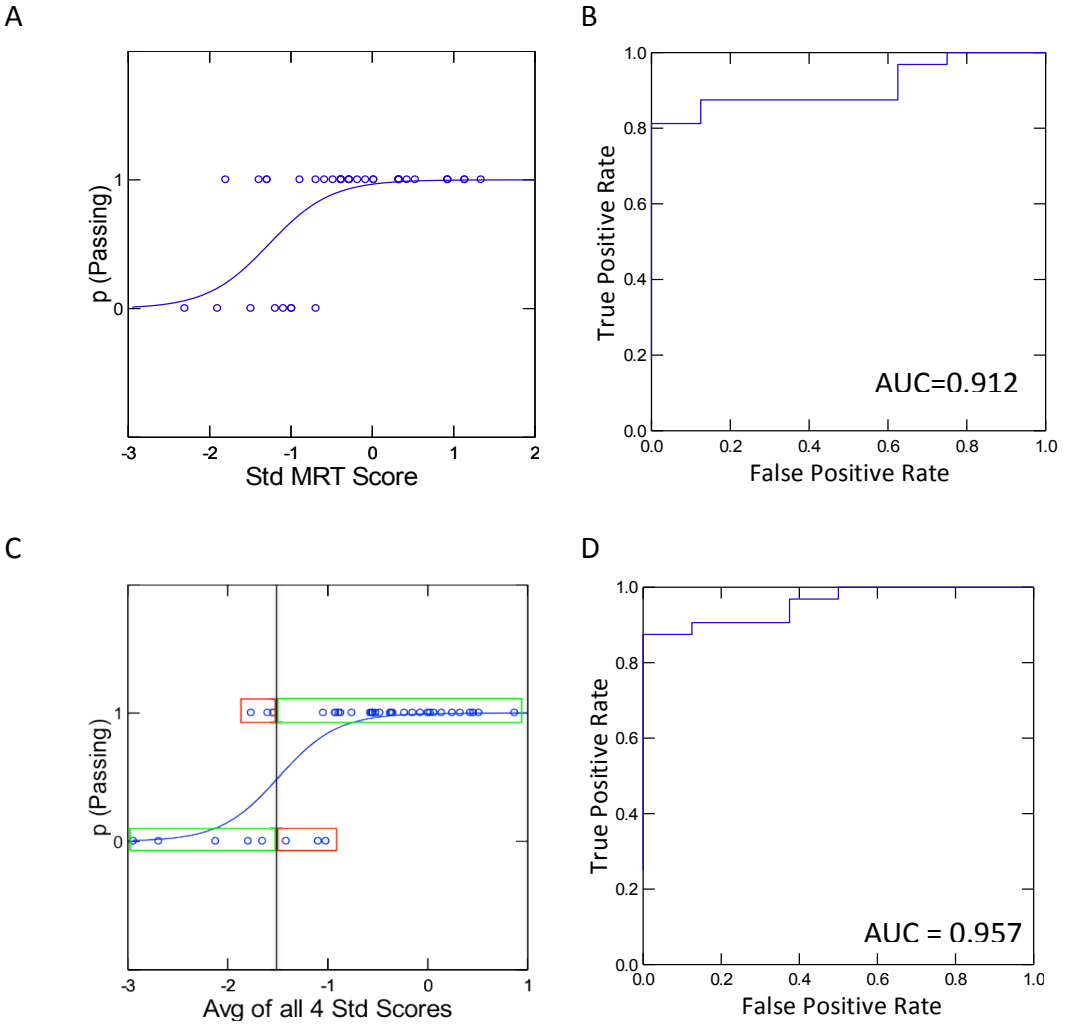


Figure 18: Logistic model fits overlaid on data and ROC curves for MRT (A, B) and average of standardized scores (C, D). Plot C highlights the correct (green) and false (red) predictions based on a set threshold at 50% (black vertical line).

Table 9: Model Fit and AUC values for SpA tests and Average

SpA Test	Overall Model fit p-value	ROC AUC
Card	< .0001	0.88
MRT	< .0001	0.91
PSVT	0.001	0.87
PTA	0.007	0.85
Average	< .0001	0.96

Using this model, it may ultimately be possible to set a threshold that corresponds to an acceptable false positive rate and in future studies, quickly screen subjects without any robotics testing, based only on their SpA scores. If the number of subjects available for recruitment to the study was large enough such that we could afford to screen out potentially usable subjects, then setting a high screening test score threshold could potentially save valuable time for recruiters and trainers.

The AUC of the logistic models generated from the current fatigue study subjects are much higher than those obtained from the astronaut training evaluation data. The two analyses differ greatly in that the astronaut study was predicting relatively small differences in performance after extensive training (+30 hours) while this study is predicting gross performance after 3 hours of training. Because astronauts are trained to a minimum criterion level, there is not much variation in their evaluation scores making it more difficult to accurately predict them. In addition, it is clear (as shown in Figure 19) that the fatigue study subjects had on average lower scores for all 4 SpA tests. For Card and PSVT, the fatigue subject scores spanned a noticeably larger range than the other two groups. Finally the fatigue subjects, although able to achieve comparably high scores at least for Card and PSVT, obtained the absolute lowest scores we have ever recorded in all 4 tests. It is reasonable to conclude that our screening methods really distinguished between subjects who were average or above and those that were extremely poor at robotics. If we had put astronauts, or for that matter other MIT students through the same robotics screening, we likely would not have screened out nearly as many subjects and the SpA scores would therefore not be as useful as a potential screening tool.

Even eliminating the subjects who were screened out due to robotics, the fatigue study group still had lower mean scores than the astronaut or MIT group for all four SpA tests. The fatigue study subjects who passed screening also still exhibited the lowest recorded scores for all tests except MRT, their highest scoring test out of all four.

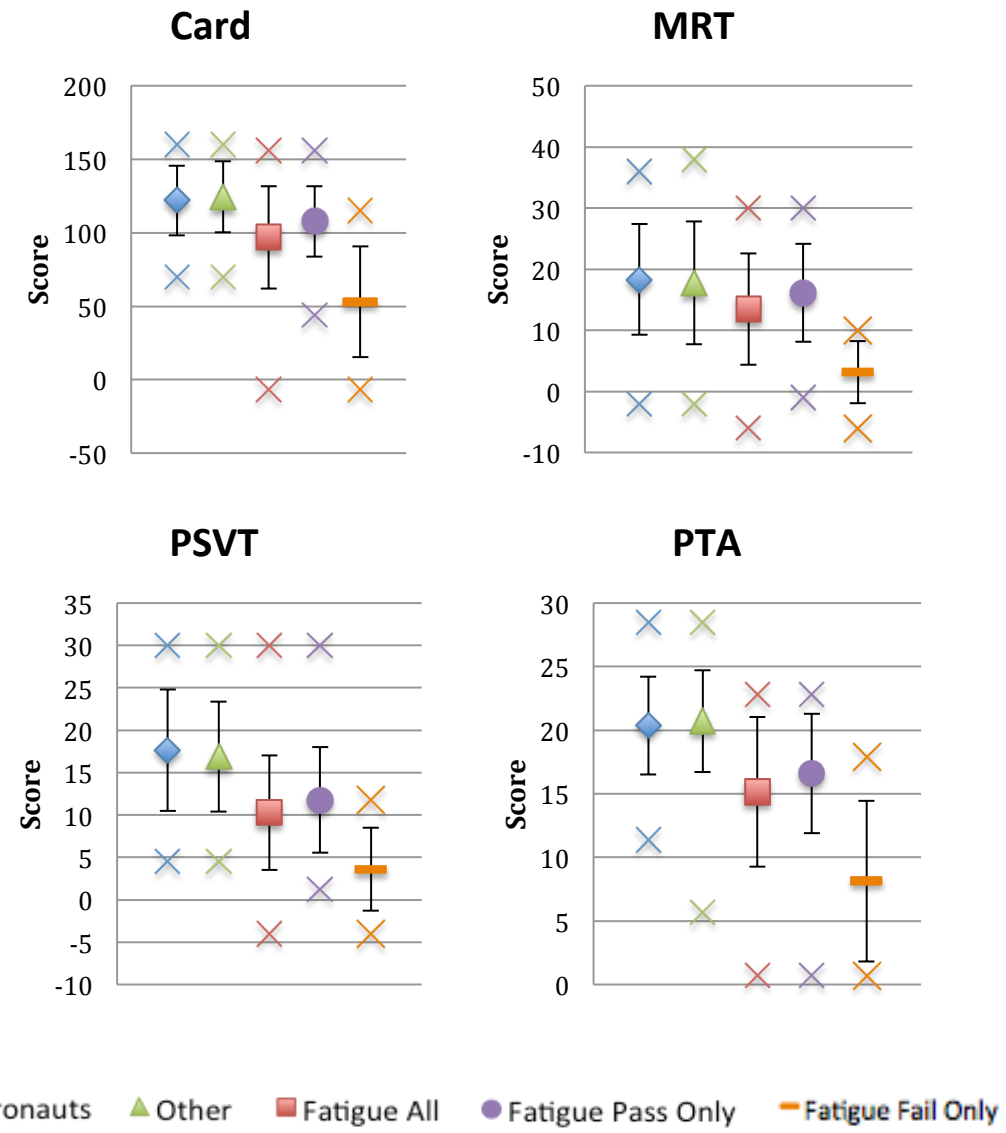


Figure 19: Mean and standard deviation of SpA test scores for astronauts, subjects from other MIT experiments (mainly MIT students), all fatigue study subjects, fatigue study subjects that passed robotics screening, and those who didn't. X's are maximum and minimum scores. $N_{Astronauts}$: 50 for all tests, N_{Other}: 87, 130, 162, 279, $N_{Fatigue\_All}$: 40, 40, 38, 35, $N_{Fatigue\_Pass}$: 32, 32, 31, 29, $N_{Fail\ Only}$: 8,8,7,6 for Card, MRT, PSVT, and PTA respectively.

7.2. Astronaut Training Evaluation and SpA Scores Revisited

In Liu et al. (2012), the average of the four standardized test scores was not evaluated as a predictor of final training performance. Therefore, we re-examined the astronaut data to determine if it was a better predictor. In all Generic Robotics Training categories in which at least one single SpA test was found to have a significant logistic fit (e.g., $p<0.05$, (broken down by training flow, test focus, and test version)), the average of the 4 standardized scores, although also comparably significant, did not have a higher AUC value than the most predictive single test. There were no cases in which significance was found with the average score when it was not with a single SpA test score.

We speculate that for this robotics fatigue study the average of the four SpA tests was more predictive than a single test because we were evaluating gross overall (early) performance on tasks that require a variety of different spatial skills. Perhaps, more than one test is needed to target all of the skills being tested. In contrast, the astronaut training evaluations were broken down into categories, in which the grading is focused on a more specific set of skills, either situational awareness or clearance recognition. The results suggested that when the evaluation targets performance on specific tasks, a single SpA test may be adequate to detect weaknesses and strengths. As previously discussed, there was a large difference between the astronaut group and the subjects in the fatigue study (mean and spread), however this did not seem to be a major factor in the predictive capability of a single SpA score vs. the average. As detailed later in Section 7.5, in this study, a single SpA test score was more predictive than the average SpA score, of robotics task metrics measured in the experimental test sessions, consistent with the astronaut evaluation.

7.3. Primary Robotics Metrics

This section focuses on:

Hypothesis 3: Robotics, cognitive, and sleepiness measures will degrade with:

A. Slam Shift

B. Time in test session

Preliminary analysis of the robotics sessions discussed here includes data from the 6-hr Baseline and Slam 1 test sessions for 16 subjects (7 female). As discussed earlier, in this study it is not possible to definitively separate out a true time-on-task effect from sleep homeostatic and circadian desynchrony effects which are all potentially further confounded with prolonged sleep restriction. In the analysis that follows, the term block effect (change in metric/ block) refers to the combination of these effects of which we believe time-on-task effects are largest. In order to address Hypothesis 3 and 4, the data was organized into two sets, and models were made for each:

Model 1: 6-hr/Slam 1

- Compares data from the entire 6-hr baseline (2 blocks) with the first two blocks in the Slam 1 test session.
- Determines the effect of session (represented the slam shift), the effect of block, and cross effects between session and block on two hours of robotics.
- Note that although the 2nd block from the 6-Hr Baseline differs in detail from the 2nd block in the Slam 1 session, the term block effect is used, referring to the difference in time between the blocks, not the difference in trials between the blocks.

Model 2: Slam 1

- Compares data from across all four blocks of Slam 1 test session only.
- Determines the effect of block on 4 hours of robotics within a 6-hour test session.

Primary robotics metrics were chosen and analyzed for T&C and FTG trials. The secondary task was analyzed separately for T&C, AS, and the three distinct stages of the FTG trials. Each metric was evaluated by examining individual subject performance and the average performance of the whole group.

All statistical analyses were done using mixed hierarchical regressions in which subject was treated as a random effect. Dependent variables were transformed as appropriate in order to achieve equal variance and normality in the model residuals. Additional independent fixed effect variables included gender, the most predictive spatial ability score (or average), and task specific explanatory variables. Individual subject vulnerability to fatigue and Gender and SpA effects are discussed separately in Section 7.4 and 7.5, respectively.

7.3.1. Track and Capture: Primary Measure Results

Out of the available T&C metrics, grapple time, grapple position error, and % bimanual movement were chosen for formal evaluation. Since T&C tasks were performed with deliberate pressure on completion time, grapple time was an appropriate performance measure. Grapple position error can describe how well the subject was able to maintain control in the final moments just before grapple, when the close proximity of the end effector to the payload makes the task more difficult. The % bimanual movement quantified the efficiency of the control inputs and a subject's ability to control both hands (in different ways) simultaneously.

We analyzed group averaged T&C metrics using hierarchical regressions for each dependent variable and the independent fixed effect variables listed in Table 10. For the grapple time metric, the first trial in each block was not included since there were often delays in starting due to subjects making adjustments (of position in chair, of Optalert glasses, etc.) to be comfortable after the break. Only trials with drift and spin of the HTV were included for % bimanual movement models since drift-only trials require very little (even zero) % bimanual movement. T&C trials with collisions or failed grapples were not included in the data set but are discussed separately later, along with % multi-axis movement. Models were fit to the transformed variables (Table 10) however for simplicity, the discussion for each metric will refer to the untransformed variable.

Table 10: T&C 6-Hr/Slam1 and Slam 1 Model Variables

Dependent Variables	**Transform**
Grapple time (s)[2]	Inverse
Grapple Position Error (m)	None
% Bimanual Movement	Fisher[3]
Independent Variable	**Description**
Gender	Categorical
SpA score (or Average)	Continuous
Drift	Categorical: 0 drifting towards arm, 1 drifting away
Spin	Categorical: 0 no spin, 1 pitch up, 2 yaw right
Session	Categorical, 6-hr/Slam1 Model only
Block in Session	Continuous
Session x Block in Session[2]	6-hr/Slam1 Model only

[2]Tests for normality and equal variance show the residuals were not satisfied for either model. Because the data set is very large (up to 768 data points), formal test of normality are difficult to meet since large sample sets give more power to detect non-normality. Residuals were plotted and were deemed to be approximately normal and equally variant by visual inspection.

[3]A typical transformation for percentage and rate variables defined as arcsin(sqrt(% Bimanual/100)).

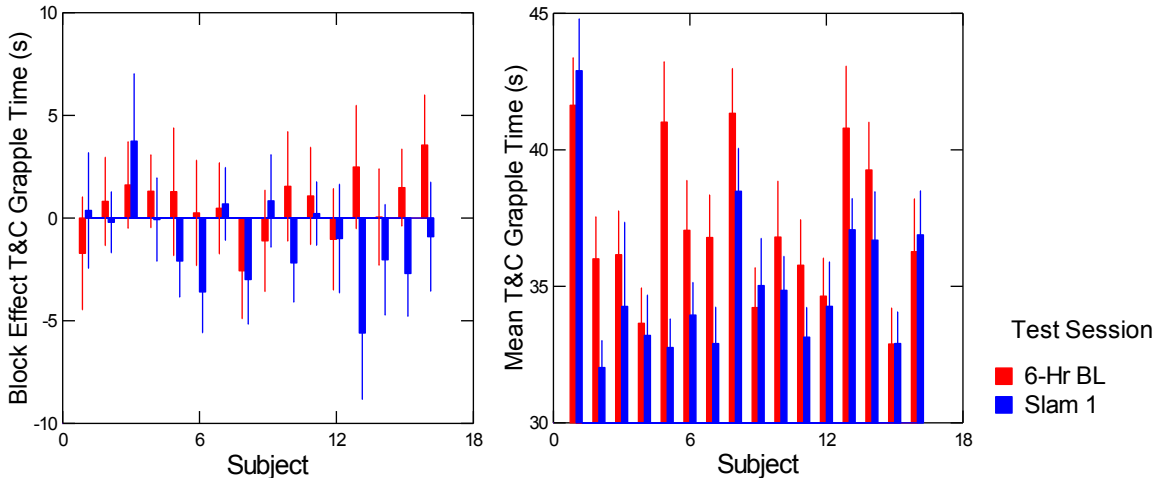


Figure 20: T&C grapple time presented as Left) The difference in average grapple time by subject between the first two blocks in each session, and Right) Individual subject means for first two blocks by session. All error bars are SEM.

Looking at just the 6-Hr Baseline and first two blocks of Slam 1, there were inconsistent block effects on T&C grapple time between the two sessions (Figure 20A). Most subjects had an increase in grapple time in the 6-Hr Baseline (mean block effect: 0.59 s) but a decrease in Slam 1 (mean block effect of -1.10 s). This contributed to an overall higher grapple time in the 6-Hr Baseline (Figure 20B) and a significant cross effect between session and block ($p=0.006$). Since the slam shift was expected to have an adverse effect on performance, it is unlikely that this cross effect was due to the slam shift aspect of session. Refamiliarization to the tasks after a long break before the 6-Hr Baseline was likely the dominant factor in overall higher average times compared to Slam 1. The differences in the test environment between sessions (See Section5.3.4) could have been a factor in subjects maintaining their urgency or motivation to finish the task as quickly as possible throughout the 6-hr Baseline. Similar behavior however, did not occur for any other T&C primary or secondary metric.

No significant effect of block on average grapple time was found in the Slam 1 session, likely due to small and inconsistent block effects for each subject over the session (max block effect of -1.79 s). The magnitude of the block effect between subjects (2.8 s span) did not vary as much as the mean between subjects (span: 32.48 to 40.99 s).

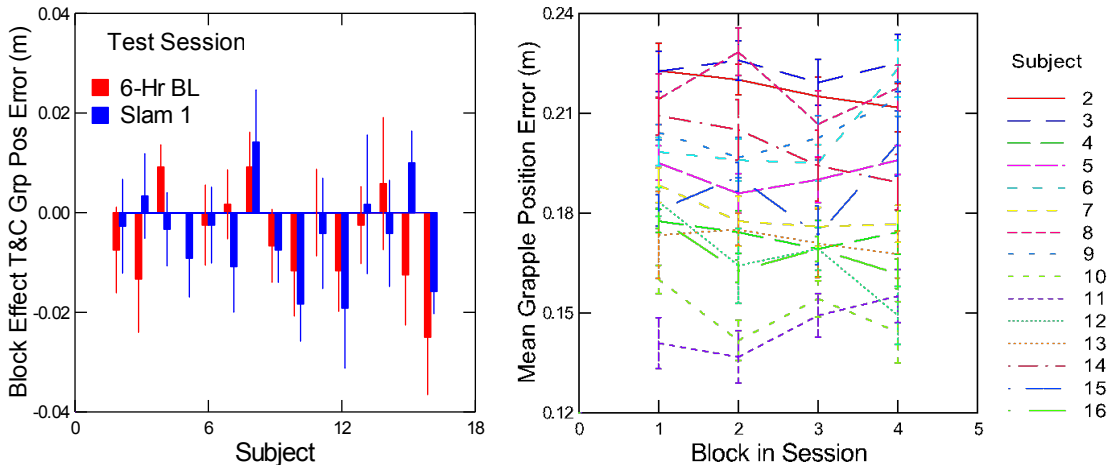


Figure 21: T&C grapple position error presented as Left) The individual difference between the first two blocks in each session, and Right) Individual averages by block for Slam 1 Session only. All error bars are SEM.

A significant block effect was found on the average T&C grapple position error for the 6-Hr BL/Slam1 model (p=0.004) with most subjects (with particular exception of subject 8) decreasing their error over the two blocks (Figure 21A). In Slam 1, no similar block effect was found. This suggests that subjects were initially improving their performance but then became more consistent by the end of Slam 1, possibly due to continued learning. The differences in average position error between subjects (span: 0.15 to 0.22 m) were larger than the average changes in error due to block in Slam 1 (max block effect: -.010m, Figure 21B). In general, all differences in this metric were extremely small.

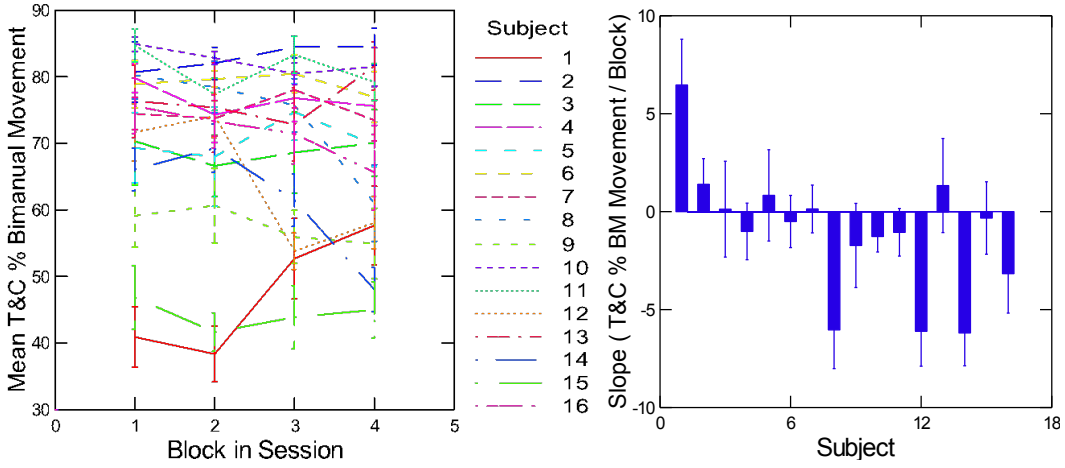


Figure 22: T&C % bimanual movement presented as A) Individual averages by block connected by lines for Slam 1 Session only, and B) Individual slopes representing change in average % bimanual movement per block in Slam 1. All error bars are SEM.

For T&C trials, the % bimanual movement metric is essentially the percentage of movement in rotation, since translational motion towards the target is constant from release of the brake to grapple of the HTV.

In Slam 1, there is a significant decreasing trend in % bimanual movement over the blocks ($p=0.046$) not seen in the 6-hr baseline (Figure 22). Most subjects exhibit decreasing % bimanual movement, with the outstanding exception of subject 1, who increased their % bimanual movement by approximately 20% in Slam 1. This increase suggests that the subject is improving on the task. Ideally, T&C tasks would be completed with close to 100% bimanual movement, which would indicate perfect tracking of the HTV. In this simulation, subjects are not reaching close to 100% bimanual movement, even though many of them perform the task extremely efficiently. One reason is that motion of the HTV is unknown prior to taking the brake off. As soon as the brake is released, subjects automatically translate towards the target in order to not lose time. Tracking in rotation does not begin simultaneously because it takes a moment to identify the nature of the HTV motion in order to begin tracking it.

It is possible to achieve high % bimanual movement with very poor tracking. For example, the operator could make an overcorrection but then immediately compensate, keeping the controller in motion. Realistically, this strategy would be undesirable due to the possibility of inducing arm oscillations, which are particularly hard to recover from when trying to grapple a moving object. Even without arm oscillations, a compensatory control movement strategy makes completing the T&C tasks in our simulation difficult. Subjects learn this during training and trainers emphasize a steady tracking strategy.

Three possible explanations for the decreasing trend in % bimanual movement over Slam 1 are:

1) Subjects were getting worse at steadily tracking the HTV, possibly overcorrecting for HTV motion and then having to wait for it to catch up to the arm position. Unintentional motion of this type is unlikely given that neither grapple time or position error showed any average decline over the session, which we would expect if subjects were in fact struggling to control the arm.
2) Overcorrections in control movements (as in Explanation 1) were done intentionally. It's possible that subjects changed to a predictive impulse control strategy, making shorter, discrete control inputs instead of constantly tracking the HTV. Constant steady tracking takes prolonged concentration whereas an impulse strategy would only take short bouts.
3) As the session went on, subjects became more confident in their ability to successfully track and capture the HTV such that they waited longer to begin rotation tracking after starting translational motion towards the HTV.

The strategy changes in Explanations 2 and 3 could possibly be a response to fatigue, driving the desire to decrease constant mental workload. A closer evaluation of each

subject's raw input data is necessary to fully understand the cause of the trend. The magnitude of the change in % bimanual movement in Slam 1 (max negative block effect: -6.19%) was much smaller than the span between the subject averages (44.3 % to 82.9%).

For T&C trials, the % multi-axis movement metric was dominantly a measure of THC multi-axis control movement because the rotational drift of the HTV was never coupled. The HTV was either not spinning, pitching up, or yawing right. The % multi-axis movement was also subjected to a hierarchical regression, but the fit was unsuccessful, with more variance in the residuals for the lower percentages than for the high percentages. Even though high performance in these T&C trials was associated with high %multi-axis movement, the trials could be successfully completed when the %multi-axis movement was low. Therefore subjects could have scored low in %multi-axis movement because their ability was affected by fatigue or because their strategy employed mostly single axis control. Like the % bimanual movement metric, the % multi-axis movement did on average decrease slightly with block in Slam 1, but did not appear to be effected by session. As discussed in terms of % bimanual movement above, subjects may have been intentionally employing a different control strategy in order to decrease mental workload. Explanation 2 or 3 would also result in a decrease in % multi-axis movement.

No regression was applied to the number of collisions in T&C trials because they occurred so rarely, 6 collisions in 768 trials. Subjects failed to grapple the HTV in 31 out of 768 trials with each subject having at least one failed grapple attempt in the two sessions being compared. In our simulation a failed grapple and recovery occur instantaneously and does not hinder a subsequent successful capture after since the latching does not need to be reset as in the actual operation. In fact, there were no cases in which the subject failed to capture the vehicle. A failed grapple attempt may not always be an indicator that the subject struggled with grappling the payload. It could be an error of commission when intending to respond to the secondary task since both the trigger and secondary task response button are located on the RHC. A closer look at keystroke data could clarify this possibility. Perhaps, if failed grapples had a more evident consequence in the simulation, fewer of them would have occurred. There were no apparent patterns in the occurrence of collisions or failed grapples.

Overall, primary T&C task performance as measured by grapple time, grapple position error, % bimanual movement, number of collisions, number of failed grapple attempts, and % multi-axis movement were apparently not affected by session. Significant block effects were found on average performance for grapple position error (6-Hr BL/Slam 1) and % bimanual movement (Slam 1) however these effects were very small and operationally negligible. In general, differences between subjects were larger than differences due to block.

7.3.2. Fly-to and Grapple: Primary Task Results

Unlike the T&C trials, each FTG trial was unique within a session. This makes isolating the effect of block impossible since the primary robotics performance metrics were trial dependent (some more than others). In the following statistical discussion, we will focus on the metrics that we believe are least affected by trial design, the jerk metric and input reversal rate for translation and rotation, while keeping in mind that trial differences can never be completely accounted for. The following analysis was done for whole FTG trials, not split into their three stages. We are therefore assuming that each subject did not drastically change their control strategy between stages such that they were much smoother in one and jerkier in another.

From observation, the FTG trials in block 3 tended to give subjects the most difficulty and often it took many sessions before a subject was able to complete them successfully. In the 6-Hr Baseline Block 3, only 7 subjects were able to successfully complete the first trial and 8 completed the second trial. In Slam 1, the count increased to 8 and 10. The primary difficulty stemmed from the requirement to cross over the truss while repositioning the payload for final positioning. If the path was not correctly planned, the arm was quite likely to reach a joint hardstop from which could be very difficult to recover. To account for this difficulty, an ad hoc difficulty metric was created based on the number of space station quadrants through which the arm would move. The quadrants are defined by the intersection of the forward-aft (truss) and port-starboard (modules) ISS structures. The variables for the models are described in Table 11.

Table 11: FTG 6-hr/Slam1 and Slam 1 Model Inputs

Dependent Variable	**Transform**
Jerk: Translation	Inverse
Jerk: Rotation	Inverse
Independent Variable	**Description**
Gender	Categorical
SpA score (or Average)	Continuous
Session	Categorical, 6-hr/Slam1 Model only
Block in Session	Continuous
Session x Block in Session	6-hr/Slam1 Model only
Trial Difficulty	Continuous (due to degree of freedom constraints) 1: grapple and berth in one quadrant 2: in two quadrants 3: in three quadrants (crossing truss)

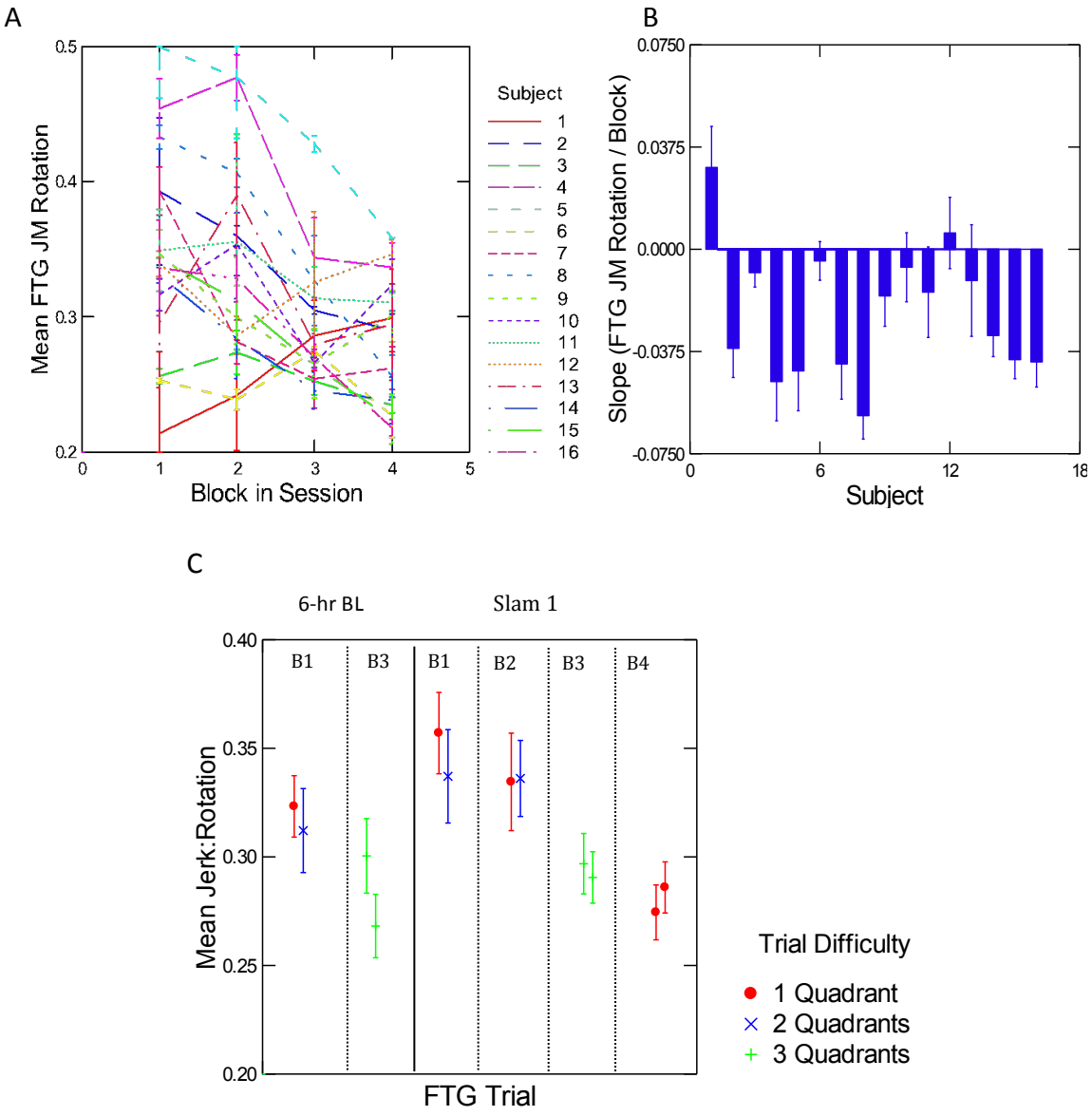


Figure 23: FTG jerk metric for rotation presented as A) Individual averages by block connected by lines for Slam 1 Session only, B) Individual slopes representing change in average jerk per block in Slam 1 only, and C) Averaged over all subjects for each trial. All error bars are SEM

No significant effects of session or block were found for the average $Jerk_{Trans}$ of all the subjects. Upon individual inspection, there appeared to be no consistent effect across subjects. Subject 8 did stand out, having a very steady and large decrease in $Jerk_{Trans}$ over Slam 1 compared to the other subjects. This subject also had the largest decrease in $Jerk_{Rot}$ in Slam 1 (Figure 23B).

For $Jerk_{Rot}$, 13 of the 16 subjects had a higher average in the first two blocks of Slam 1 (mean of all subjects: 0.30) than in the 6-Hr Baseline (mean of all subjects: 0.34). There was a significant block effect in Slam 1 such that $Jerk_{Rot}$ decreased with block ($p<0.001$).

This effect was consistent for all subjects except subjects 1 and 12 (Figure 23A,B). Subject 1 also differed from the group in the T&C trials, showing a large increase in % bimanual movement over block, while the rest of the group showed a decrease or no change (Figure 22A,B). In Slam 1, the difference between subjects average $Jerk_{Rot}$ (span: 0.25 to 0.44) was larger than the block effects (max negative effect = -0.06).

We could not determine whether the decrease in jerk, or smoother rotation inputs were a result of learning, block, or if trial differences not accounted for by the trial difficulty metric were affecting the jerk metric in a coincidently sequential manner. The trial difficulty variable did not correlate to either jerk metric as we expected. If trial differences do not have an effect on jerk, it's possible that there was a significant session or cross effect based on the differences between the blocks in the 6-Hr Baseline and Slam 1 (Figure 23C). Additionally, in Slam 1, the tasks in blocks 2 and 4 are performed for the first time, which could result in increased jerk (e.g., due to more direction reversals resulting from uncertainty about how to move the end effector). Additional variability may have come from the change in emphasis each subject placed on smooth inputs. During training, subjects were educated about the importance of smooth inputs and were encouraged to be as smooth as possible. However the simulation did not include arm dynamics, which could be excited by jerky hand controller inputs, so there are no obvious performance penalties for failing to minimize jerk, perhaps limiting the utility of the metric in this study.

Originally, we thought that the number of input reversals per minute would reveal changes in performance while remaining relatively unaffected by differences in the trial. After inspection of the data, it appears that the trial task does in fact affect the input reversal metric in complex ways and was therefore not included in the analysis. There was large variability between trials and subjects. Some subjects were much stronger in their understanding of the external control mode and therefore their input reversal rate was not as affected when performing new trials for the first time. Some subjects seemed to use a guess and check strategy almost exclusively when they weren't sure which control inputs were correct while others attempted to be more deliberate in their inputs, even at the expense of time. The propensity to reach joint hardstops in the trials in block 3 also contributed to large variability in the input reversal rate metric. Perhaps, subjects would need to be trained to a much higher level of expertise to eliminate trial differences as the dominant effect on the input reversal metric.

The decreasing jerk block effect could be a result of a learning effect. If subjects were getting better at making intended control inputs then they would decrease input reversals, which would increase smoothness. Because the input reversal rate metric appears to be so confounded with trial design, it was hard to draw this conclusion. Jerk could be decreasing due to fatigue effects. Perhaps as subjects got sleepier, they became less engaged in the task and did not make corrective control inputs as quickly as they did when they were more alert. There ability to stay constantly attentive may have diminished.

Overall, for all FTG trial metrics, the effects from session and block are difficult to separate from effects due to trial design, learning from repetition of trial, and general skill improvement. We did not find a statistically significant effect of session on average jerkiness of control inputs nor was there any evidence of an effect when looking at individual performance. There was an effect of block on average $Jerk_{Rot}$, which was consistent across all but two subjects, but the mechanism at play (e.g., block or trial differences) cannot be definitively identified.

7.4. Mental Workload Analysis

This section will focus on Hypothesis 4: Secondary robotics task measures will degrade more than primary robotics measures because subjects will attempt to maintain performance on the primary robotics tasks at the expense of the secondary task.

We analyzed secondary task performance to assess the effect of session and block on mental workload. As expected, the secondary task performance was different for each of the three trial types (Figure 24) due to differences in visual attention and mental workload requirements. Subjects had the shortest average response times in the T&C trials (mean of 1.06 s for all subjects in 6-hr BL). This was expected because for T&C trials, the secondary task message appeared on the same screen the subject uses (almost) exclusively for the main task which promoted shorter response times and fewer missed responses. Additionally, the trials were short, and required only a short burst of attention. Subjects became very practiced at the T&C tasks with performance at nearly the maximum. Thus, they may not have required large amounts of cognitive capacity to perform the task, and could reallocate resources to the secondary task.

The longest response times occurred in the FTG trials (mean of 2.62 s for all subjects in 6-hr BL), which were the most complex trial type involving all of the skills necessary for the other two trial types plus more. Also, since the secondary task message appeared only on the left monitor, it was quite likely that the subject would be focused on a different screen during the FTG trials when the message appears. This results in longer response times and more missed responses.

AS, the vigilance task, had average response times similar to but slightly higher than T&C. AS trials were long and boring (opposite of T&C) monitoring tasks that required only sporadic directed attention. For the majority of an AS trial the secondary task might essentially have functioned as the primary task such that sufficient mental resources were devoted to the task to maintain quick response times.

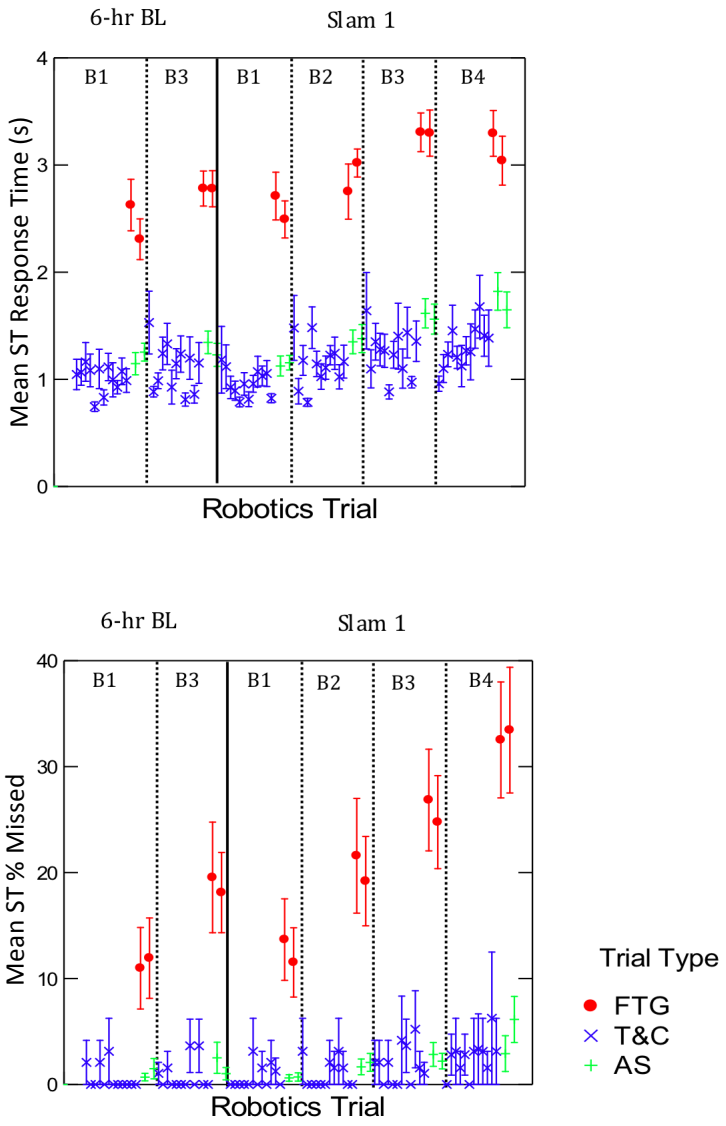


Figure 24: Inverse secondary task response time and missed percentage for all three trial types for 6-hr baseline and Slam 1. Data points are averages for all subjects with SEM.

Due to their length and complexity, subjects had more missed secondary task responses in FTG trials than in the T&C and AS trials. Most T&C and AS trials had zero missed responses however, by the third and fourth blocks of the Slam 1 session, there was a noticeable increase in the number of misses, showing an effect of block on average % missed on even short (T&C) and simple (AS) tasks (Figure 24).

7.4.1. Track and Capture: Secondary task Results

The hierarchical regression for T&C response time included the same independent variables used in the previous primary T&C models (Table 10). T&C response time was inverse transformed for modeling purposes but will be discussed as an untransformed variable.

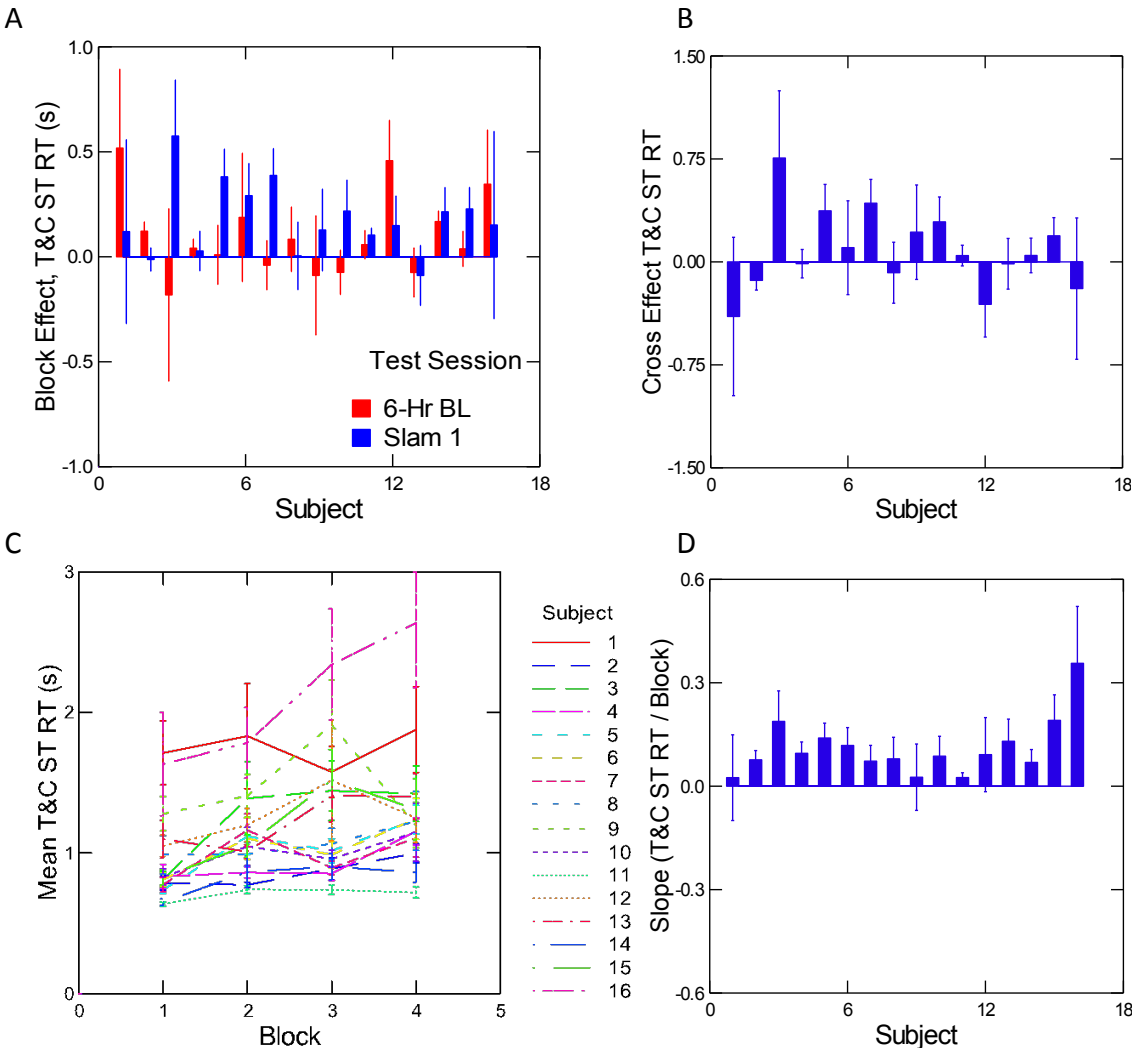


Figure 25: T&C secondary task response time presented as A) The average difference between the first two blocks in each session, B) The difference between block effects in 6-HR BL and Slam 1 for each subject, C) Average RTs by block and subject (Slam 1 Session only), and D) Linear regression model slopes representing the average change in response time per block for each subject (Slam 1 Only). All error bars are SEM.

No significant effect of slam shift was found on the average secondary task response times for T&C. This can be seen in Figure 24(Top) showing no difference between the average response times in the 6-Hr Baseline and the average of the first two blocks in Slam 1. Subject 16 (not plotted) had a noticeably larger difference in response times

between the two sessions (mean difference: .56 s, Slam 1 higher) than the others, which exhibited no difference.

Significant block effects were found in the 6-Hr/Slam 1 model ($p<0.001$) and Slam 1 model ($p<0.001$) such that response times increased throughout both sessions. A significant cross effect between session and block ($p=0.024$) was indicated by the increase in response time between the two blocks in the 6-hr Baseline that was less than in Slam 1 (Avg. increase in 6-hr BL: 0.10 s, Slam 1: 0.33 s, Figure 25A,B). The 30-minute additional test period between blocks in Slam 1 may have increased subject fatigue leading to a larger average response time. The maintained performance in the primary T&C metrics during the first two blocks of Slam 1 suggested that fatigue affected secondary task performance only.

Large inter-subject differences existed in average response time (range: 0.71 to 2.10 s, Figure 25C) and in the size of the block effect (range: 0.03 to 0.36 s, Figure 25D), however in Slam 1, all 16 subjects exhibited increasing response times over the blocks.

7.4.2. Autosequence: Secondary task Results

A main difference between AS trials was the number of clearance violations in each that the subject was expected to identify. Since there was a maximum of only 3 clearance violations in these 10-minute trials, we did not expect the number of violations to affect secondary task performance. With no trial-specific metric, the AS models included the standard independent variables used for all trial types, including gender, SpA score, session, block in session, and the block cross session effect. Response times were log transformed for statistical purposes however discussion will refer to the untransformed response times.

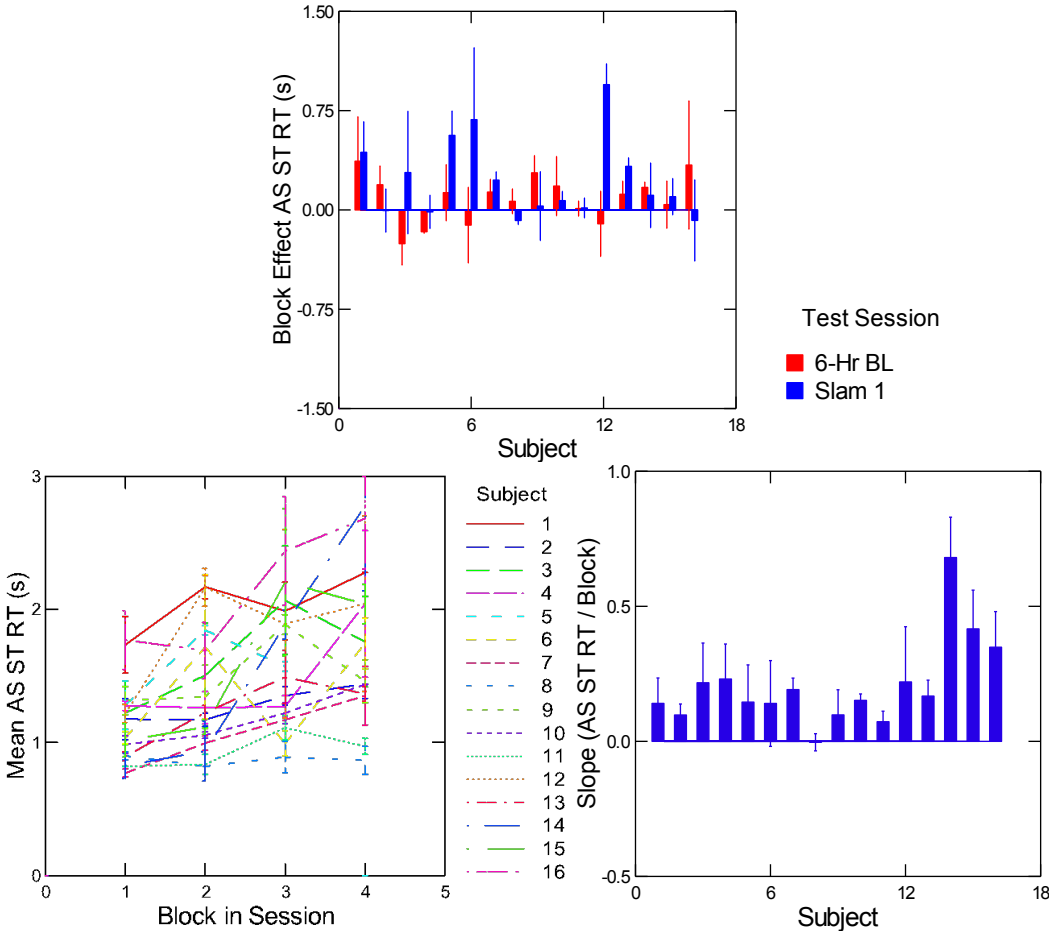


Figure 26: AS secondary task response time presented as A) The individual difference between the first two blocks in each session, B) Individual averages by block for Slam 1 Session only, and C) Individual slopes representing the average change in response time per block in Slam 1. All error bars are SEM.

No significant effect of slam shift was found for average AS response times. This is seen in Figure 24 (Top), showing no difference between 6-Hr BL and 1st two blocks of Slam 1. Additionally, no outstanding differences in session were found for any individual subject.

Significant block effects on average response time were found for both the 6-Hr/Slam 1 model ($p=0.013$) and Slam 1 model ($p<0.001$). It appears though that the average block effect in the 6-Hr Baseline was skewed by a couple of outlier subjects, 5, 6, and 12 (Figure 26A), none of which maintained such high block effects throughout the remainder of Slam 1 (Figure 26B). In fact the average increase in response time was only 0.09 s in the 6-Hr Baseline, compared to 0.59 s in Slam 1. In Slam 1, large inter-subject differences existed in average response time (range: 0.87 to 2.1 s) and in the size of the block effect (range: ~0 to 0.68 s), however all but one subject (8) exhibited an average increasing slope by block in Slam 1. Boredom due to prolonged monotony of the task was likely the strongest factor in increasing response times during AS.

For the majority of the time in AS trials, when the arm was clearly not close to encountering a clearance violation, the secondary task essentially became the primary task. Assuming that subjects were able to maintain performance on the primary tasks in T&C and FTG, but apparently not in AS trials (referring to the secondary task), it may be that primary performance really depends on the nature of the task. Perhaps the fatigue effects hinder the purely cognitive task (AS), but for tasks involving motor actions and complex skills, there is enough of a short term alerting affect, which enables subjects to maintain performance more consistently.

7.4.3. Fly-to Grapple Split: Secondary task Results

As previously discussed, the FTG trials can be split up into three distinct stages, fly-to, grapple, and berth. The average secondary task metrics were calculated for each stage (Figure 27). The version of the simulator used for Subject 1 and the 6-hr Baseline of Subject 5 did not support calculation of average response times for each FTG stage. Therefore, subject 1 was not included in the analysis and subject 5 was only included in the Slam 1 evaluation.

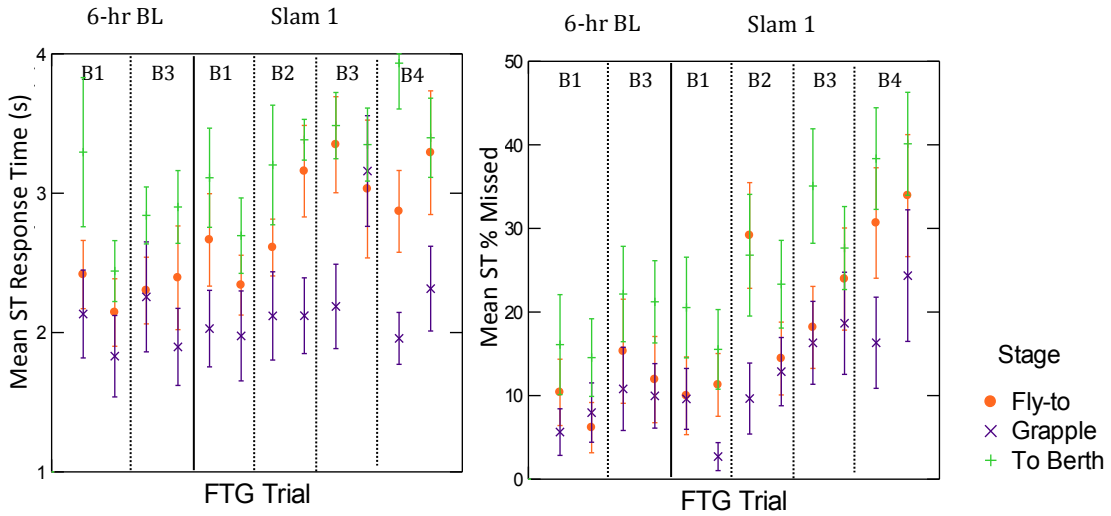


Figure 27: Average secondary task response time and missed percentage for each stage of FTG trials for 6-hr baseline and Slam 1. Data points are averages over all subjects. Error bars represent the SEM.

Both the secondary task response time and % missed varied noticeably by stage (Figure 27). As expected, stage 2 (grapple), consistently had the lowest average response times and % missed of the three stages. Stage 2 was the easiest stage to perform, as it was equivalent to a T&C trial except that the payload has no drift spin. There was also more variability in Stage 2 than in T&Cs since the initial position relative to the grapple fixture (distance and orientation) was dependent on how the arm was moved in Stage 1. Also, the end effector camera view was not always displayed on the same screen as the secondary task message, like in T&Cs. These factors likely contributed to the higher average response time in Stage 2 than in T&C trials (6-hr BL, T&C: 1.06 s, Stage 2: 2.03

s). The quick response times and low number missed percentage (8.6%) in this stage were likely a result of low mental workload and short completion times.

Stage 3, the berthing stage, had the highest response times and highest percent missed (6-Hr BL, 2.87s, 18.5%). This was expected since moving the arm with an attached payload was probably the most challenging of all tasks. It required controlling the robot arm in an external command frame and that constant attention be allocated to clearance monitoring.

Models for stage 1 and 2 of the FTG trials included the same independent variables used in the primary measure models (Table 11) except for the trial difficulty metric, which was kept for Stage 3 only. Response time was log transformed for Stages 1 and 3 and inverse transformed for Stage 2.

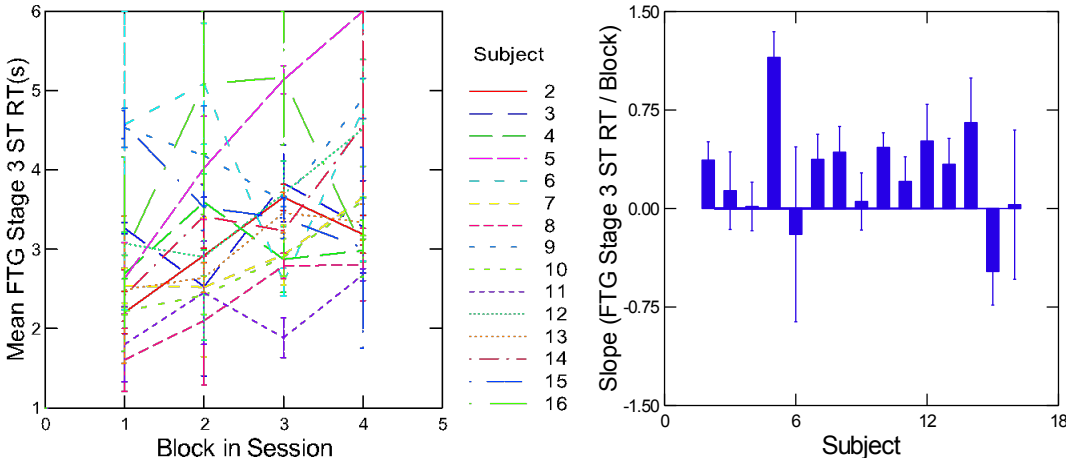


Figure 28: FTG Stage 3 secondary task response time presented as A) Individual averages by block for Slam 1 Session only, and B) Individual slopes representing the average change in response time per block in Slam 1. All error bars are SEM.

There were no significant effects of slam shift on average response time for any FTG stage. There were a couple subjects in each stage that had a large increase in average response time between the sessions, namely subjects 8 and 14 in Stage 1, subjects 8 and 13 in Stage 2, and subjects 6 and 9 in Stage 3.

A significant block effect over Slam 1 was found for the secondary task response times in Stage 3 (0.49 s average block effect, Figure 28A,B) but not in the 6-Hr Baseline suggesting that session durations of more than 2 hours were necessary to see secondary task degradation for this stage of the FTG task. Both T&C and AS tasks showed degradation even within the first two blocks. The difference may have been due to task complexity. Stage 3 required more of a problem solving skill set than T&C and AS which are relatively more cognitively simple. As suggested in the discussion of AS secondary task responses, it seems as though the tasks that required complex skills may have caused a temporary alerting affect not present in more monotonous or learned tasks.

Again, there were large inter-subject differences in average response time (range: 2.20 to 4.45 s) and block effect (positive range: 0.02 s to 1.15s), however all but two subjects had an average increase over the blocks.

7.4.4. Hedge's g Effect Sizes

Hedge's g effect sizes were calculated on the untransformed secondary task data to further quantify the effect of slam shift and block on secondary task responses. For the slam shift calculation, data groups one and two included all data from the 6-hr BL and first two blocks in Slam 1, respectively. For the block effect size calculation, only data from Slam 1 was used such that data groups one and two included all data from Block 1 (began at time-on-task=0), and Block 4 (began at time-on-task = 5 hours), respectively. The results are shown in Table 12 below.

Table 12: Hedge's g effect size for secondary task session and block effects color coded for small, moderate, and large effects

Task Type	Session Effect		Block Effect in Slam 1	
	Response Time	% Missed	Response Time	% Missed
T&C	0.005	-0.018	-0.482	-0.211
FTG Stage 1	-0.350	-0.260	-0.447	-0.941
Stage 2	-0.027	-0.007	-0.121	-0.675
Stage 3	-0.180	-0.132	-0.624	-0.912
AS	-0.021	0.050	-1.130	-0.706

As expected, the effect sizes for the slam shift session analysis were all small. For block effects on response times, the largest effect size was found for the AS task type. In fact, it was comparable to a combined effect size of -1.142 calculated through a meta-analysis for vigilance tasks conducted after 24-30 hours of total sleep deprivation (Philibert, 2005). The large % missed effect sizes are comparable to combined effect sizes of -0.762 for lapses in simple attention tasks after 24-48 hours of sleep deprivation (Lim and Dinges, 2010). Out of the multiple components that make up the block effect, namely time-on-task, sleep homeostat drive, circadian desynchrony, and chronic sleep restriction, we believe that time-on-task likely has the largest effect, contributing the most to these large effect sizes.

In future analysis, hedge's g effect sizes will be particularly useful for comparing block effects with the various countermeasures.

7.4.5. Individual Subject Fatigue Vulnerability

This section will focus on Hypothesis 7: Inter-subject differences in performance will exist due to individual vulnerability to fatigue.

Block effects were found for many metrics on average, although some subjects were clearly more affected than others. Comparing subjects' individual block effects across task type, looking for consistency within an individual will help identify which subjects were particularly vulnerable to fatigue. Because the primary metric effects were small and/or inconclusive, this comparison focused on the secondary task response times. FTG Stages were not included because of the large variability in effects between stages for most individuals.

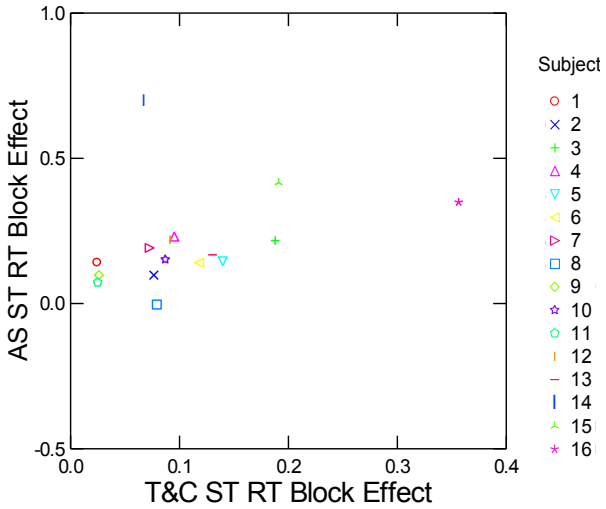
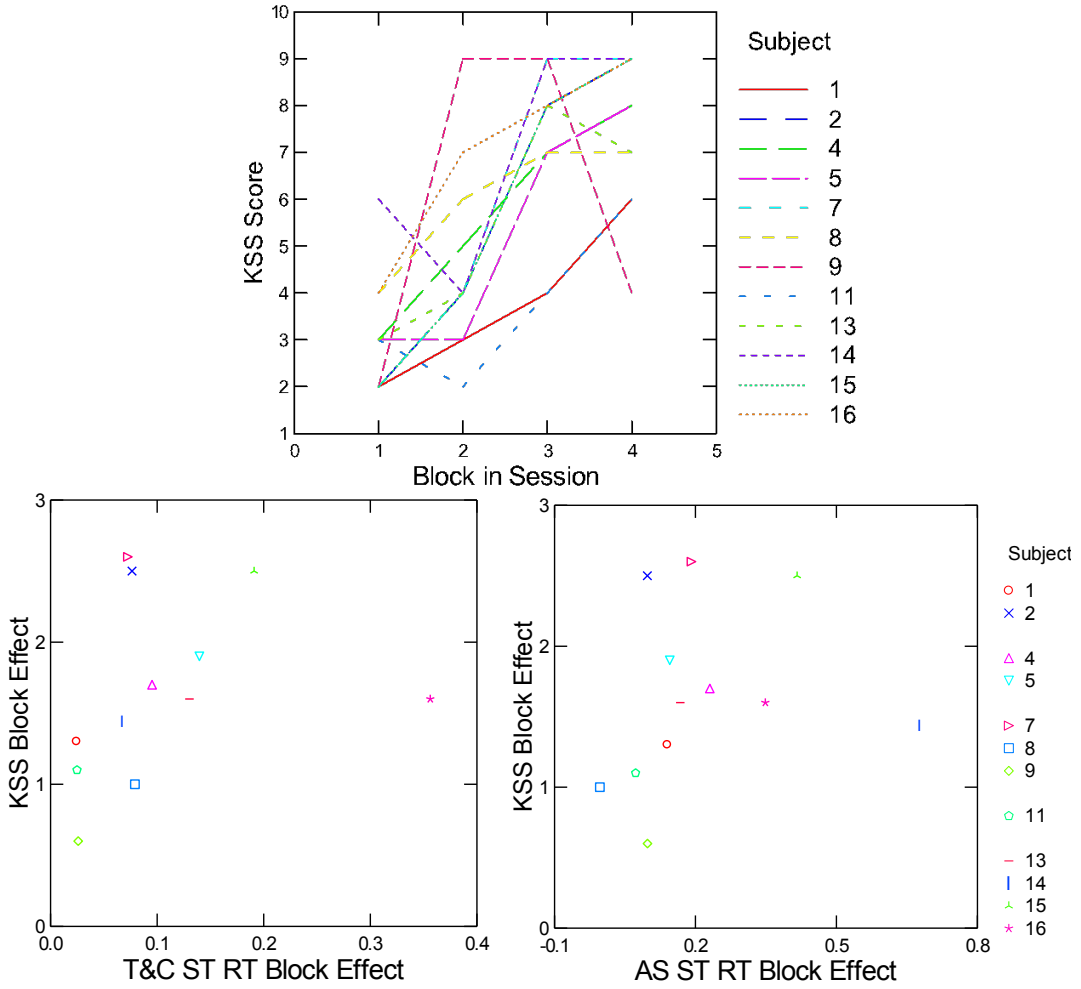


Figure 29: Individual block effects for AS vs. T&C in Slam only.

There was a moderate correlation between block effects in the Slam 1 sessionfor T&C and AS (r=0.348, Figure 29). Subjects 3, 15, and 16 appeared to have the most consistently large block effects for both T&C and AS, while subjects 1, 9, and 11 seemed to have the most consistently small block effects. Subject 16 was also the only subject who showed an appreciable increase in response time after the slam shift during T&C suggesting that this subject may be generally more vulnerable to fatigue than the others.

To better understand the differences between subjects, we compared subjects' self-assesed sleepiness (measured by KSS, Appendix 12.5) with their secondary task response times in T&C and AS. Four subjects have not yet been added to the KSS score database and therefore were not included.



: A) Individual KSS scores by block in Slam 1, B) KSS block effect vs. the normalized AS secondary task response time block effect in Slam 1, and C) KSS block effect vs. the normalized T&C secondary task response time block effect in Slam 1. Some subjects are missing due to a currently incomplete KSS database.

The KSS scores of all subjects increased from block 1 to 4 in the Slam 1 session (Figure 30A). The average KSS score of all subjects increased in each block (Blocks 1-4: 3, 4.6, 7.3, 7.6). Subject 9 showed out of the ordinary KSS behavior from block 3 to 4, in which the score dropped 5 levels from 'very sleepy' to 'neither alert nor sleepy'. Consistent with their subjective self-assessment of sleepiness decreasing only from Block 3 to 4, this subject's average response time in T&C and AS also only decreased from Block 3 to, objectively suggesting a decrease in sleepiness as well.

Subject 16, who exhibited the largest T&C block effect, did not have a similarly large KSS block effect. The same can be said for Subject 14, who had the largest AS block effect. Subjects 1, 9, and 11, had some of the lowest T&C and AS block effects. The block effects on their KSS scores were relatively small as well (Figure 30B,C). Overall, there were only modest correlations between the KSS block effect and secondary task response time block effects for T&C (r=0.30) and AS (r=0.22). There were plausible

explanations for this: The KSS test instructions asked the subjects to rate their sleepiness 5 minutes prior to the current time, however the T&C tasks ended roughly 45 minutes before and one of the two AS tasks ended 25 minutes before. A KSS rating every 1.5 hours was likely not sensitive enough to describe performance changes over the entire block with high accuracy. However, large changes in subjective sleepiness, such as experienced by Subject 9, may create effects strong enough to influence the robotics secondary task response times.

7.5. Spatial Ability and Gender Effects

This section addresses Hypothesis 2: Subjects SpA test scores will correlate positively with final robotics performance.

The following table indicates the variables in which there was a significant SpA effect in the 6-Hr/Slam 1 and Slam 1 models.

Table 13: Effects of SpA Scores in 6-hr/Slam1 Model and Slam 1 Model for T&C, FTG, and AS

Task Type	Variable	Transform	Effect of SpA Score	
			6-hr/Slam 1	Slam 1
T&C	% Bimanual Movement	Fisher	MRT, p=0.015	X
	Secondary task Response Time	Inverse	MRT, p=0.038	X
FTG	Jerk Metric Rotation	Inverse	MRT, p<0.001	MRT, p=0.040
	Stage 1: ST Response Time	Log	MRT, p=0.001	MRT, p=0.016
	Stage 2: ST Response Time	Inverse	X	MRT, p=0.015
	Stage 3: ST Response Time	Log	MRT, p=0.021	MRT, p=0.002
AS	Secondary task Response Time	Log	MRT, p=0.002	MRT, p=0.003

For every model in which a SpA score had a significant effect, MRT was either the only or most significant SpA test. The standardized score average was also tested with very few significant results. It was unexpected that MRT was the only significant predictor for the large majority of the metrics tested. Based on the results of the astronaut evaluation training study (Liu, 2012), we expected that although one test may be better than the rest, others would show some predictive power. It appeared that MRT was the most reliable predictive test out of the four given.

Past research has shown high correlations of SpA tests and gender. Including both gender and SpA scores in the models could have been inappropriate if there were large

correlations between the two. For the 16 subjects in this experiment, MRT, the most predictive test, had no correlation with gender (r=0.156).

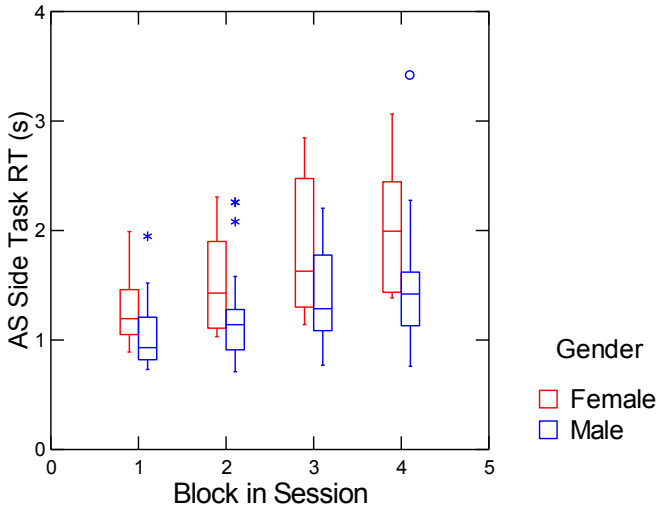


Figure 30: Autosequence secondary task response time by block in Slam 1 session only, split by gender. The center horizontal line marks the median, box edges lie at the first and third quartile of the values, whiskers show the range of values that fall within 3/2 of the interquartile range, asterisks represent outliers that fall within the whiskers, and empty circles are outliers outside the whiskers.

A significant main effect of gender was found only for one task type and one metric, AS secondary task response time in the Slam 1 Model, for which females had significantly higher response times than men (Slam 1 mean: Females= 1.63 s, Males= 1.31 s, p=0.009, Figure 31). Future analysis of data from the remaining sessions will help establish if there is a consistent effect of gender on secondary task performance in this vigilance based task.

8. Conclusions

From preliminary analysis we conclude:

Spatial Abilities:

1) Spatial Ability test scores (most effectively, the average) were predictive of subjects' ability to pass the robotics screening. Subjects who did not pass robotics screening had very low average scores. However, some subjects with comparably low scores did pass. The AUC, or area under the receiver operator characteristic curve was relatively high: 0.96 for the average of four test scores, and 0.85-0.91 for the individual tests. A threshold of one standard deviation below the mean composite SpA score would give an 85-90% accuracy with minimum false positives (i.e., selecting a subject that would have failed robotics screening). Setting the desired threshold would have to be based on the cost of holding a robotics screening session that the subject might fail versus the cost of recruiting subjects (since some low scoring subjects might still pass robotics screening). The Spatial Ability predictors seem to be more selective for the general population and at very early stages of learning that with populations with more homogeneous abilities, e.g. the astronaut population studied by Liu et al (2012).

2) In both the 6-Hr Baseline and Slam shift sessions, for the Track and Capture, Fly-To Grapple, and Autosequence primary and secondary task metrics in which Spatial Ability scores had a significant effect, the Vandenberg Mental Rotation Test (MRT) was the most significant predictor out of all four tests or the average of the four standardized scores.

Primary Robotics Metrics:

3) We did not find a consistent effect of session (representing slam shift which includes circadian and sleep homeostat effects) on the average of any primary robotics task metrics studied. Although some subjects had noticeably different performance between sessions for one or two metrics, none had consistent session effects across all metrics, even within the same task type. It is possible that any effect from the slam shift would only appear after a longer period performing robotics (e.g., after 4-6 hours rather than 2 hours), but unfortunately, the protocol design did not allow such an analysis. A recommendation for future studies is to keep consistent lengths for all test sessions and to increase the length of the test session up to 8 hours. This would ensure enough time to see any late declines in performance while staying operationally analogous. Refamiliarization of the robotics tasks in the 6-Hr Baseline after a break in training, the different testing environment in the 6-Hr Baseline, and the 30-minute test/break period in the Slam 1 session not present in the 6-Hr Baseline could have compromised the slam shift session effect that we had expected

we might see. Regardless of the possible confounds, it is plausible that the interesting nature of the robotics tasks (compared to standard cognitive tests, such as the PVT) was engaging enough such that subjects were able to maintain their primary task performance after the slam shift.

4) Statistically significant block effects (representing a time-on-task effect combined with effects from the sleep homeostat, circadian desynchrony, and prolonged sleep restriction) were found in the slam shift session over approximately 6 hours of testing (in four blocks) for 2 out of the 5 primary metrics evaluated: the % bimanual movement measure in Track and Capture tasks and the $Jerk_{Rot}$ metric in the Fly-To and Grapple tasks. The block effect on $Jerk_{Rot}$ was significant but potentially confounded by differences in trials across and within the blocks. The % bimanual movement change due to block was very small and likely operationally negligible.

Secondary Task Responses

5) As expected, secondary task response times and percentage of missed stimuli differed by trial type, and by stage within the Fly-To Grapples. The shortest response times were found in the Track and Capture trials while the longest were in the Fly-to and Grapple Trials. Within those, Stage 2 had the shortest response times and Stage 3 had the longest. Overall, secondary task response times were fastest in the tasks that were short and relatively intuitive. The longest responses occurred in longer tasks that required more complex skills. The Autosequence trials are neither short nor complex. The average response times for Autosequence trials were longer than in T&C trials but faster than in Stage 2. The low mental workload required of the task likely drives the response times down while the monotony of the task drives them up, resulting in a moderate average response time.

6) There was no session effect on the average secondary task response time on the Track and Capture, Autosequence, or three stages of the Fly-To and Grapple trials. For the Fly-To and Grapple stages, response times were very inconsistent within and between subjects. We believe this could be due to the differences between trials, stages, and strategies employed. Subjects also varied in their level of performance on each FTG task, with some struggling more than others. No individual subjects exhibited a substantial effect of session for the Autosequence trials, and only one subject did for the Track and Capture trials. Overall, this suggests that slam shifting had no measurable effect on mental workload during approximately 2 hours of robotics tasks.

7) Significant block effects on average secondary task response time were found in all three task types corresponding to an increase in response time over the blocks. In Track and Capture and Autosequence trials a significant block effect was found even after only two blocks (in the 6-Hr Baseline), whereas a significant block effect was not established until all four blocks of the first slam shift session were analyzed for Stage 3 of the Fly-To Grapple trials. For Track and Capture and Fly-to and Grapple trials, all subjects, except

for one, had increasing response times over the four block session, Slam 1. The consistency between subjects, and earlier onset of fatigue effects, is likely due to the simple nature of the Track and Capture tasks compared to the Fly-to and Grapples tasks.

8) The effect of block in the 6-hr Slam 1 test session on the secondary task response times was substantial and comparable to effects found from sleep deprivation on simple cognitive tasks. The Hedge's g effect size comparing responses in block 1 to block 4 (approximately 5 hours time-on-task) for response times in Autosequence was -1.163, comparable to combined effect sizes from meta-analyses for vigilance tasks after 24-30 hours of total sleep deprivation. The effect size for percentage of missed stimuli in Stage 1 of the Fly-to and Grapple trials was -0.941, comparable to that for lapses in a simple attention task after 24-48 hours of total sleep deprivation. The effects of block on mental workload are substantial and could be operationally relevant.

Inter-Subject Differences

9) As expected, inter-subject differences were large. The span between the subjects was consistently larger than the block effects for all metrics, primary and secondary.

10) Individual consistency in block effects between task types and measures was moderate. For Track and Capture and Autosequence secondary task response times (the most stable measures), there was a correlation of r= 0.348 between block effects. Consistently large block effects may be an indicator that certain subjects are highly vulnerable to fatigue. In future analysis, finding consistency within subject block effects across all 5 test sessions would help to confirm which subjects are most vulnerable.

11) All subjects (for whom we had KSS scores available) reported getting sleepier with each successive block in the Slam 1 session, as measured by the subjective Karolinska Sleepiness Scale. The sleepiness score block effect had modest correlations with the secondary task response time block effects for T&C (r=0.30) and AS (r=0.20). The correlation supports our hypothesis that sleepiness, due to the circadian shift or sleep homeostat, decreases the availability of mental resources for the secondary tasks. The average change from 3 (alert, normal level) to 7.6 (between 7: sleepy but no effort to keep awake, and 9: very sleepy, great effort to keep awake, fighting sleep) on the Karolinska Sleepiness Scale is considerable, however subjects were still able to maintain primary task performance.

Despite a week of 6-hr sleep restriction, a 9-hr slam shift, up to 6 hours of test duration, and large increases in subjective self-assessed sleepiness, subjects were able to maintain primary task performance on robotics tasks. However a consistent decrement in their responses to a secondary task was found for all three primary task types across session blocks. This time-on-task related effect increased over the un-shifted and slam shifted

sessions and is consistent with a decrease in attentional reserves due to fatigue. Secondary task performance appears to be a more sensitive indicator of mental workload than primary robotics task performance under off-nominal sleep conditions.

To understand the applications of these results to realistic telerobotics operations, we should mention a potentially important difference. In this experiment, the maximum length of any one task was 10 minutes with small breaks between tasks. Actual operations can run for a much longer continuous period of time, for example, when assisting an astronaut on EVA. We did attempt to simulate the long nature of operations with a 6-hr long test session however effects of circadian cycle, sleep homeostat, and time-on-task may be somewhat different under longer uninterrupted periods of intense concentration.

9. Comments and Suggestions for Further Analysis

Some experiment-specific details and general approaches to handling them are discussed below.

As discussed in this thesis, the 6-hr Baseline test consists of blocks 1 and 3 from Main Experiment sessions 1-4. When comparing the 6-hr Baseline to the other sessions, block effects are confounded with trial order for FTG and AS (because those trials are unique). Similarly, since trials are not randomized within a session, block effects within a single session are confounded with trial order. We can attempt to explain trial differences with quantitative traits of the trial (Such as in with FTG trial difficulty described in Section 7.3.2), however we are limited in our ability to confidently assess block effects for metrics that are trial dependent. Although this is a limiting factor in the analysis presented in this thesis, the experiment design is essential for future analysis of countermeasure effectiveness, in which will easily be able to compare trials across sessions without block complicating the analysis.

So that all subjects would have equal robotics session times and equal numbers of tasks, the trials had a fixed duration sufficient for almost all subjects to complete the trial. When a subject finished a trial before the allotted time, he/she had to sit at the workstation and wait until the trial automatically ended. This situation is only relevant for Fly-to and Grapple trials and Track and Capture trials, although the wait time is much less variable for the latter (mean, SD in Slam 1: FTG: 3±1.5 min, T&C: 55±6 s). Subjects occasionally would drift into sleep during these periods and needed to be awakened by the experimenter. In general, we should not forget that subjects experience different periods of idle time between sessions, which could affect sleepiness and subsequent robotics performance. In future analysis, we could compare OptAlert data during the trial, while waiting for the next trial, and during the next trial to look for evidence of microsleeps or eye closure. If the optalert drowsiness rating is consistently higher during the rest time than in the trials, this could strengthen the assertion that subjects are becoming more alert when performing relatively interesting robotics tasks.

The order of the tasks in each of the four robotics blocks is constant throughout the experiment. Therefore, subjects have seen the same trials at least five times by the last main test session. It is the goal of training to help the subjects reach an approximately asymptotic level of performance (i.e., so that they are no longer learning the tasks). However, for a complex skill such as robotics, even four 3-hour training sessions may not be sufficient time for all subjects. It will be important to look for evidence of continued learning (seen by improving performance for each repetition of a trial) when analyzing data from later countermeasure sessions.

There is large variability in task performance within and between subjects. Much of the variability is due to trial differences and subject skill levels however subjects may also differ in their level of motivation and in what they place priority on while doing the tasks. Some subjects may strive to complete the tasks as quickly as possible, while others may focus more on minimizing errors. As subjects get fatigued, some may decrease their effort towards the task while others could have more personal motivation to maintain high performance. We take into account the differences between subject averages by treating subject as a random effect in the models, however this does not account for more complex differences. We likely will not have enough subjects in the data set to explore subject cross effects which could further explain variability. To maintain awareness of inter-subject differences throughout our analysis, we will examine individual subject behavior along with the group averages. Also, we may have to assume that a subject's personal approach to robotics and motivation to succeed does not change drastically over the course of the experiment.

Another source of variability between subjects arises if subjects perform the tasks differently than the way they were trained. For example, one subject consistently switched back and forth between internal and external control modes during Stages 1 and 2 of the FTG trials. During these stages, the arm is being moved large distances around the ISS and no end effector camera views are available. Therefore, according to training, external control mode should be used exclusively. Making personal strategies is part of what makes a complex task different from a simple one. Some variation is expected. We will, however, have to exclude some cases in which personal strategies were used if they are too different from what is expected and cannot be analyzed in a way that is consistent with the other subjects or trials. Some cases may require a more manual, rather than automated analysis to account for these idiosyncratic differences among subjects. Notes taken by the trainer during the session, out of order keystrokes in the keystroke.dat files, and outlier data points in certain metrics may help identify these off-nominal cases.

10. Future work

This Study:

When data collection is completed for the study, the analysis will be expanded to include the three remaining main experiment sessions in which the three countermeasure combinations are applied. The efficacy of the blue-enriched white light countermeasure is of particular interest since it has certain practical advantages (e.g. short half-life after exposure) over commonly used countermeasures like caffeine. This study will be able to assess the effectiveness of each countermeasure. In addition, the results of the large battery of cognitive, sleepiness, and physiological tests and scores will be integrated with the robotics data to create a more complete description of the state of the subjects during the robotics sessions.

We hypothesize that overall performance on robotics (primary and secondary measures) and the additional tests will improve when the countermeasures are present. We still expect to see block effects in each session, primarily for the secondary task in the group of robotics metrics, since we assume time-on-task fatigue to be independent of the sleep related mechanisms. We also expect that performance on the additional non-robotics tests will degrade with each successive block. Including physiological data from EEG or Optalert will provide continuous data to correlate with the robotics performance metrics and provide a more detailed view of the time course of fatigue effects. For example, Optalert and EEG data could give physiological evidence that Subject 9 was in fact more alert in Block 4 than Block 3 of Slam 1, as seen in that subject's KSS score and secondary task response times.

Areas for Future Research:

During the analysis, trends were found indicating effects that perhaps cannot be validated completely with this experiment but that may warrant future study. Further study into these areas would aid in gaining a more comprehensive understanding of fatigue effects on telerobotics performance.

1) Effects of Fatigue on Jerk:
Smoothness of controller inputs is very important in actual ISS robotics operations because of arm dynamics. It could be valuable to study the effects of fatigue on input jerk with a simulation that includes arm dynamics and identifies a jerk threshold that is realistically acceptable. This would be an interesting way to study the effects of fatigue on mental workload and motor control.

2) Cross effects of gender and time-on-task:
There was evidence from preliminary analysis that for all trial types, the effect of time-on-task may be different for males and females (i.e., there may be significant cross-effects of gender and block) on secondary task response times. The response times of females seem to decrease at a faster rate than those of males. An experiment specifically focused on this effect could promote an understanding of fatigue with a stronger physiological basis.

3) Effects of idle time on subsequent task performance:
We found evidence that the amount of time subjects spent waiting after completion of the FTG trial had a significant effect on the average secondary task response time in the subsequent AS trial such that longer idle times corresponded to faster subsequent response times. However, the amount of idle time is not a controlled independent variable and cannot be treated as one. An experiment designed to test this interesting effect could be operationally relevant in terms of deciding when breaks should be scheduled and how long a period is needed to maintain alertness and/or performance.

4) Learning while fatigued:
During training and during the experiment test sessions, subjects tended to struggle with particularly hard and complex trials. Some of these hard trials were seen for the first time in the experiment test sessions, so that subjects had to learn the task for the first time while under fatigued conditions. It would be interesting to directly evaluate the differences between subjects' ability to learn when fatigued vs. when well rested. A good understanding of this could be particularly insightful for when off-nominal robotics operations occur on orbit, requiring astronauts to learn new tasks on the spot. Looking even further into the future, an understanding of learning capability and retention of those learned skills under various conditions is essential for successful long duration space flight missions to Mars.

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12. Appendix

12.1. Phone/Email Screening Questionnaire for Healthy Volunteers

DATE:_____ RECRUITER:_____

WHERE DID YOU HEAR ABOUT THE STUDY?_____

CURRENT OCCUPATION (IF STUDENT, WHERE)?_____

AGE/DOB:_____ HEIGHT:_____ WEIGHT: _____

HAVE YOU EVER DONE A RESEARCH STUDY BEFORE?
IF SO, WHEN AND WHAT KIND?

DO YOU HAVE ANY MEDICAL ILLNESSES OR PROBLEMS ?
NO [ ] YES [ ]
IF YES,
EXPLAIN:_____

ARE YOU CURRENTLY TAKING ANY MEDICATION, USING INHALERS, PATCHES, HORMONE REPLACEMENTS, (BIRTH CONTROL, FOR WOMEN): NO [ ] YES [ ]
If yes: Type:_____ Started:_____Finished:_____

DO YOU CURRENTLY SMOKE CIGARETTES? Yes [ ] No [ ]

If yes, how many per day or per week? ---_____

Do you currently use any chewing tobacco, cigars, or nicotine patches? Yes [ ] No [ ]

HAVE YOU EVER TAKEN PRESCRIBED ANTI-ACNE MEDS:
Oral Retin-A NO [ ] YES [ ] _____
Accutane NO [ ] YES [ ] _____
Tetracycline NO [ ] YES [ ] Oral { } Topical { }
If yes, how long ago did you take it? ----------_____
For how long? -----_____

HAVE YOU TRAVELED OUTSIDE THE EASTERN STANDARD TIME ZONE WITHIN THE PAST 3 MONTHS?

If so, where?

How many Time Zones (time difference in hours)?
Date Left: Date Returned: Eligible starting:

DO YOU HAVE ANY PLANS TO TRAVEL IN THE NEXT FEW MONTHS?
Where/when_____

HAVE YOU EVER WORKED THE NIGHT SHIFT (For example, 11PM to 7AM)? NO [ ] YES [ ]

*Night work is defined as working anytime during the hours of 1:00am and 6:00am. Anything in the last 3 years should be explained in detail:

Date started: Date finished: Hours of shift: Number of days a week: Type of Work:

HAVE YOU EVER HAD OR DO YOU NOW HAVE:

No	Yes	
[ ]	[ ]	heart disease or a heart murmur
[ ]	[ ]	thyroid disease
[ ]	[ ]	lung disease
[ ]	[ ]	high blood pressure
[ ]	[ ]	kidney disease
[ ]	[ ]	diabetes
[ ]	[ ]	visual or hearing impairment
[ ]	[ ]	hepatitis
[ ]	[ ]	eye injuries
[ ]	[ ]	hepatitis vaccination
[ ]	[ ]	color blindness
[ ]	[ ]	asthma (what type of inhaler?)
[ ]	[ ]	stomach or intestine disease (ulcer)
[ ]	[ ]	psychiatric care
[ ]	[ ]	neurological disease (stroke, seizures)
[ ]	[ ]	mental illness in family
[ ]	[ ]	surgery **
[ ]	[ ]	attempted suicide
[ ]	[ ]	anesthesia (type)
[ ]	[ ]	accidents/ head injuries/loss of consciousness (if yes, how long unconscious for and when?)

**********FOR WOMEN**********

Last menses:_____
Prior menses:_____
Do you have a regular menstrual cycle?

Average length of cycle:_____
Have you ever taken birth control?
If so, when?_____
Type:_____
Was it tricyclic Yes [ ] No [ ]

HOW MANY TIMES PER DAY OR PER WEEK DO YOU HAVE THE FOLLOWING?

CAFFEINE Coffee:
Tea:
Chocolate:
Cappuccino/Espresso/Latte:
Caffeinated soft drinks:

ALCOHOL
Alcoholic drinks (which kind, how many times per week, how many drinks per time?):

MEDICATION Antihistamines (medications for allergy):
Sedatives (anti-anxiety agents such as valium):
Aspirin, Tylenol, other pain relievers:
Antacids:
Health food supplements/remedies (melatonin, herbal ecstasy, ginseng):

DO YOU CURRENTLY OR HAVE YOU EVER USED THE FOLLOWING (if so -- WHEN WAS THE MOST RECENT TIME?; for all drugs besides marijuana –HOW MANY TIMES IN LIFE?):

Marijuana:
Sleeping Pills:
Cocaine:
LSD, mushrooms:
Amphetamines (uppers):
Steroids like DHEA or andro:
Ecstasy:

Can you stop during and 3 weeks prior to the study?

DO YOU HAVE ANY PROBLEMS WITH SLEEP? IF SO, WHAT KIND OF PROBLEMS AND HOW FREQUENTLY?:

USUAL BEDTIME ON WEEKDAYS?
USUAL BEDTIME ON WEEKENDS?
USUAL WAKETIME ON WEEKDAYS?

USUAL WAKETIME ON WEEKENDS?

Would you be able to keep regular 8-hour sleeping schedule?

Target bedtime:_____ Target waketime:_____

WHEN WAS THE LAST TIME YOU STAYED UP ALL NIGHT (or much later than usual)?

FIRST NAME:_____ LAST NAME:_____

*Any personal and identifying information asked during this phone screen will need to be stored in the Division of Sleep Medicine Database. Do you give us permission to enter contact information in our Database?
_____
*If you are found ineligible, or are uninterested in this particular study, would you like to be informed about other studies in the future?
_____

PHONE #:
(DAY)_____(EVENING)_____

EMAIL:_____

ADDRESS:_____

Do you have a Bachelor's Degree or higher from a four-year institution?
_____

9 or 13 DAY SPACE RESEARCH STUDY

"Validation of assessment tests and countermeasures for detecting and mitigating changes in cognitive function during robotics operations"

INFORMATION FOR INTERESTED SUBJECTS

Subject Coordinator: Peter Dearborn

Study Phone Line: (617-525-8904)

PURPOSE

The purpose of this study is to see if you can take part in a research

study that looks at how light and caffeine affect the daily rhythms of the body and the body's response to not getting enough sleep. Many functions of the body change with the time of day. This includes alertness and performance, the release of hormones, body temperature, and the sleep-wake cycle.

The information presented here is subject to change but will always be consistent with the information provided in the research consent form available from your coordinator. Be sure to ask the coordinator for clarification of any of the information presented below and in the consent form.

OVERVIEW

During this study, you will live in a special isolation suite in the sleep laboratory. The suite is shielded from any external time cues that may tell you the time of the day. There are no windows, radios, televisions, clocks or other information that tell you the time of day and you may not wear a watch or timepiece. This is an inpatient study, so all of your time will be spent in your suite. You cannot leave the suite until the end of the XX day period unless you decide to withdraw from the study.

We will ask you to remain in the suite for the whole research study. Throughout the research study, we will observe you on a closed circuit television and listen to you through an audio/intercom system to ensure your safety in the suite. We will not record you on video or audiotape. Laboratory and hospital staff will enter the room often to perform duties related to the study or for maintenance of the suite or to make sure everything in the suite is working correctly.

During your stay, you cannot receive visitors or make or receive telephone calls. We will schedule your daily activities (eating, sleeping, etc.) in a regular manner. You may not drink any alcoholic beverages, caffeinated drinks, or smoke while you are taking part in the study.

PRESTUDY SCREENING:

In order for us to determine if you are eligible for the study you will need to go through a screening process. This consists of multiple visits to my office to:

- Fill in paperwork (take three to four hours)

- Have a physical, an EKG and lab work (a blood and urine sample)

- We will have to contact your PCP to obtain any major medical

records of treatments/non-routine visits.

·Meet with our psychologist for a routine assessment

· Meet with our ophthalmologist for an eye exam

· Attend up to 4 study training sessions at the BWH or at MIT to help you get used to the simulator tests that we will use in the study (each session is about 3 hours)

·Meet with the Doctor that runs the study to discuss in-study procedures/rights of a volunteer

After these are completed (or while you are working on them) we will need you to keep a regulated 8-hour sleeping schedule for up to 3 weeks immediately prior to you starting the study. You will be able to pick your own 8-hours but they must stay the same over the 3 weeks.

Following at least two weeks of this 8-hour sleep schedule, we will ask you to restrict your sleep to 6 hours for the week leading up to admission to the lab. You keep track by calling into a voice-mail system every night and every morning at the times you go to sleep and the times you wake up. As the final week prior to admission is starting and you are restricting your sleep to 6 hours per night, you will be given the wrist activity recorder mentioned in the paragraph above. Your admission to the study is directly related to how well you maintain (or try to maintain) this schedule. Once you begin keeping your 8 hour sleep schedule, you must begin to refrain from all prohibited substances (see below for details).

During the weeks you keep the 8-hour sleep schedule (at least two weeks), you will get training in the robotics simulator task you will be performing during the study. During the robotics simulation task you will learn to fly the robotic arm that is used at the International Space Station via two joy-sticks and perform different maneuvers with it. There will be up to four training sessions in total, two per week, each of them lasting up to 3 hrs. The training will either happen at the BWH or at the MIT site. Your study co-coordinator will schedule them for you and provide information on the location. It is important that you understand that the robotic simulator task training has to be completed during the weeks you keep the 8-hr sleep schedule, i.e. if we can't manage to schedule them during this time due to time conflicts, this might delay your admission to the study.

PROHIBITED SUBSTANCES DURING SCREENING:

The following substances are prohibited throughout the course of the

study, from the time of the screening evaluation until the completion of the inpatient stay.

- Alcohol
- Caffeine (frequently found in coffee, tea, soft drinks, dark and white chocolate, etc.)
- Nicotine (tobacco products of any kind)
- Prescription or non-prescription (over-the-counter) drugs
- Recreation/street drugs
- Other foreign substances

**If in doubt about a particular substance, ask before taking.

There are no other options to these steps, except to not do the study.

DURING THE STUDY:

*Electroencephalogram: Every night your sleep will be monitored with an EEG, recording your brain waves. Just before you go to sleep, you will be asked to wash your face, with special soap and cleanse the skin with an alcohol swab. Small electrodes will be placed on the skin of the scalp, face chin, and some are held in place with special glue that will shampoo out.

*Blood Drawings: During your stay in the lab, you will have an IV catheter that will draw small amounts of blood at various times. This is for hormonal analysis. The total blood lost over the entire length of the study is 2 pints. A very small amount of Heparin (an anti coagulant) will run through the IV to prevent clotting in the tube.

*Urine Samples: Throughout the entire study, urine will be collected.

*Saliva Samples: During certain portions of the study, saliva is collected by asking you to spit in a small test tube.

*Body position**:** We may measure your body position with a sensor worn on the skin or clothing on your chest during sleep.

*Special tasks**:** We will ask you to perform a series of simulated space teleoperation tasks using a Robotic Work Station simulator. These tasks may occur over long periods of time during the study.

*Blood pressure: We will measure your blood pressure by a small blood

pressure monitor and cuff. The blood pressure cuff is worn on the arm. We will measure your blood pressure at least once every day during the research study.

*Caffeine: Throughout the course of this study, you will receive either capsules that contain caffeine (about the same as 3-4 cups of coffee per day) or capsules that contain placebo. The placebo capsules look exactly like the caffeine capsules, but contain no caffeine. You and the study doctor will not know if you are getting caffeine capsules or placebo capsules, but we can find out that information if we need it. This is called double-blinded.

*Light: We will expose you to bright light at certain times during the study. We do this to see how light and/or caffeine or both together can help people to perform complex tasks when they are tired.

*Eye Movement Recordings: We will monitor your eye and eyelid movements using a pair of glasses called Optalert.

COGNITIVE PERFORMANCE BATTERY:

During the study, you will perform several performance tests. The tests are presented on a computer. You respond to these tests by using a trackball, the keys on the computer keyboard, or a two-button response pad. The performance tests are of several types, testing for reaction time, memory, hand-eye coordination, math and your mood at that time.

In addition to the performance tests, you will also do the robotics simulator task you got trained in prior to admission. The maneuvers during the task will be similar to the ones during your training session but not identical. The robotics simulator task may occur over long periods of time during which you will have to remain seated.

Most people are surprised at the frequency and the repetition of computer testing, so please realize that this will take up a lot of your time.

IN-STUDY LAB ENVIRONMENT

Time Isolation Restrictions: Again this study involves spending X days and X nights living in a lab. That means you cannot leave the room. You will not know what time of day it is. This is so that your knowledge of what time of day it is does not effect how you are feeling at any particular

time. For example, if we ask you if you are sleepy and you know that it is 11pm, you are more likely to say that you are sleepy than if we asked you at 11am. As there are no time cues allowed during the study, there are no windows in the suites. In addition, no watch, clocks, TVs, radios, visits or phone calls are allowed in order to maintain a time free environment.

PAYMENT:

Payment begins once you have completed the paperwork and begun your regular sleep-wake schedule. When this commences, you are paid $25.00/ week for call-ins. This increases to $50.00/ week when you receive the actiwatch. Please know that at any time you may be screened out. If this happens, then you will be paid for what you have completed.

Payment is broken as such:

Screening:

1. $25.00 for the physical examination

2. $25.00 for each week of regular sleep-wake schedule maintenance (for up to 4 weeks)

3. $25.00 for each week of wearing the wrist actigraphy device (for monitoring your activity and light levels) prior to the research study (for up to 4 weeks)

- $25.00 for returning the actigraphy device.
- $30 per session for completing the pre-study training sessions (up to 6)

The total amount of money that you can receive from taking part in the entire screening process is $370.

In-study:

- $100 per day for coming to the laboratory to complete the study, resulting in a maximum of $900 for a 9 day study and a maximum of $1300 for a 13-day study.
- $60/day bonus for completing the study and for returning the actigraphy device

The maximum amount of money that you can receive from participating in this study is up to $2510 for the 13 day and up to $1870 for the 9 day.

Please note that whether one receives the 13 day or 9 day condition is

randomized and cannot be chosen ahead of time.

Payment is in the form of one check about 4 weeks after the study. If the entire study is not completed for any reason, subjects are paid for their participation up through their last day, but none of the $60/day completion bonus is paid. Also, there is no monetary compensation paid to any person whose blood and/or urine tests indicate use of drugs, alcohol, caffeine, nicotine, non approved prescription or over the counter drugs, recreation/street drugs, illicit drugs or any other foreign substances.

OTHER BENEFITS

You will not benefit from taking part in these screening tests. What we learn by doing this study may help astronauts and other people in the future who must do complicated tasks while tired.
There is also the chance that the pre-study screening or various blood and urine samples taken during the study may reveal some medical abnormality. This information will be conveyed to you at once, together with a recommendation to a local clinic or physician.

There are no lingering effects of this study, although it may take your body a day or two to adjust to its normal schedule after sleeping less or at different hours than usual (similar to if you had jet lag).

12.2. Experiment Consent Form

Partners HealthCare System
Research Consent Form

Subject Identification

General Template
Version Date: February 2010

Protocol Title: Validation of assessment tests and countermeasures for detecting and mitigating changes in cognitive function during robotics operations

Principal Investigator: Steven W. Lockley, Ph.D.

Site Principal Investigator:

Description of Subject Population: Healthy adults aged 26-55 -- Research

About this consent form

Please read this form carefully. It tells you important information about a research study. A member of our research team will also talk to you about taking part in this research study. People who agree to take part in research studies are called "subjects." This term will be used throughout this consent form.

Partners HealthCare System is made up of Partners hospitals, health care providers, and researchers. In the rest of this consent form, we refer to the Partners system simply as "Partners."

If you have any questions about the research or about this form, please ask us. Taking part in this research study is up to you. If you decide to take part in this research study, you must sign this form to show that you want to take part. We will give you a signed copy of this form to keep.

Why is this research study being done?

We are doing this research study to see how light and caffeine affect the daily rhythms of the body and the body's response to sleep. Many functions of the body change with the time of day. This includes alertness and performance, the release of hormones, body temperature, and the sleep-wake cycle.

Subject Population: Healthy adults aged 26-55 - Research
IRB Protocol No.: 2009P-001154 **Sponsor Protocol No.:** N/A
Consent Form Valid Date: 03/21/2012 **IRB Amendment No.**: N/A **Sponsor Amendment No.**: N/A
IRB Expiration Date: 02/13/2013 **IRB Amendment Approval Date:** N/A

In this research study, we want to examine how light and caffeine can affect these rhythms. This study may help us to understand how light and/or caffeine may be used to help astronauts and others who need to complete complex mental tasks when they are tired.

We are asking you to take part in this research study because you are a healthy adult between the ages of 26 and 55.

About 28 subjects will take part in this research study at Brigham and Women's Hospital (BWH). We expect that about 24 subjects will complete the entire study.

How long will I take part in this research study?

You will take part in this study for either 9 or 13 days depending on when you are enrolled. During this time, we will ask you to make one study visit to the BWH when you start your study. After you finish your study we might ask you to make another visit to the BWH for a post study ophthalmology exam if we cannot schedule it on the day of your discharge. You will also have either 8 or 12 overnight stays in the General Clinical Research Center at the Brigham and Women's Hospital in Boston. We will tell you the number of days during the separate screening process.

What will happen in this research study?

During this study, you will live in a special isolation suite in the sleep laboratory. The suite is shielded from any external time cues that may tell you the time of the day. There are no windows, radios, televisions, clocks or other information that tell you the time of day and you may not wear a watch or timepiece.

We will ask you to remain in the suite for the whole research study. Throughout the research study, we will observe you on a closed circuit television and listen to you through an audio/intercom system to ensure your safety in the suite. We will not record you on video or audiotape. Laboratory and hospital staff will enter the room often to perform duties related to the study or for maintenance of the suite or to make sure everything in the suite is working correctly.

During your stay, you cannot receive visitors or make or receive telephone calls. We will schedule your daily activities (eating, sleeping, etc.) in a regular manner. You may not drink any alcoholic beverages, caffeinated drinks, or smoke while you are taking part in the study.

Over the course of the research study, we will be recording information about some or all of the following body functions while you are awake or asleep:

1. **Sleep and wakefulness**: During some or all of the time that you are awake or asleep, we will record your brain wave signals (electroencephalographic, EEG), eye movement signals (electroencephalographic, EOG), muscle activity signals (electromyographic, EMG), and heart beat activity (electrocardiographic, EKG).

   For EEG, EOG, and EMG recordings you will wash your face with special soap and we will clean your skin with an alcohol swab. We will place small electrodes, some of which will be held in place by a special glue, on the skin of your scalp, face and chin. We will also place small electrodes on and around your chest to record EKG activity.

2. **Rest-activity**: We will record actigraphy (rest-activity cycles) throughout the research study through an activity monitor worn around your wrist. The actigraphy device is the size of a wrist-watch. This device should not cause any discomfort. We may also ask you to wear a sensor for measuring light levels in the room. The sensor is mounted on a pair of glasses or a wristband. This device will also not be uncomfortable to wear.

3. **Body position:** We may measure your body position with a sensor worn on the skin or clothing on your chest during sleep.

4. **Performance and mood**: We will do frequent testing either by a computer or by pencil and paper tests to measure different types of performance (addition, thought processes, memory, concentration, reaction time, etc.). We may also measure how you feel (mood, sleepiness, sleep quality, etc.). We may do the same tests many times a day.

5. **Special tasks:** We will ask you to perform a series of simulated space teleoperation tasks using a Robotic Work Station simulator. These are the same tasks you completed during the screening process, before you were enrolled in the study. The tasks will be similar to the "fly-to and align in pre-dock grapple" tasks performed by astronauts using the teleoperation systems on the International Space Station. These tasks may occur over long periods of time during the study.

6. **Urine**: We will ask you frequently to provide urine samples for laboratory testing. We will collect your urine samples in a urinal or bedpan.

7. **Saliva**: We will ask you frequently to provide saliva samples, so we can check your hormone levels. You will do this by spitting into a small test tube.

8. **Blood**: We will draw your blood continuously during the research study. We want to measure the amount of hormones and other signals (chemicals) in your bloodstream. We will put a very thin plastic tube called an intravenous (IV) catheter into a vein in your forearm. This allows us to draw blood without putting a new needle in your vein every time. We will give you a new IV every few days; to make sure you do not develop an infection.
   At certain times during the study, we will collect small blood samples through the IV every 10-60 minutes to measure your hormonal levels. We may insert a second IV catheter into your other arm, to make sure we can draw enough samples. If this is necessary, we will remove one of the two IV catheters at the end of that study day.

   We will draw a total of about 32 ounces about (4 cups) during the whole course of this research study. By comparison, the Red Cross allows you to donate (2 cups or 16 ounces) of blood every 8 weeks. A sterile salt solution with small amounts of heparin (a blood-thinning drug) will run through the IV line between blood samples, to prevent your blood from clotting in the IV.

9. **Blood pressure**: We will measure your blood pressure by a small blood pressure monitor and cuff. The blood pressure cuff is worn on the arm. We will measure your blood pressure at least once every day during the research study.

10. **Caffeine**: Throughout the course of this study, you will receive either capsules that contain caffeine (about the same as 3-4 cups of coffee per day) or capsules that contain placebo. The placebo capsules look exactly like the caffeine capsules, but contain no caffeine. You and the study doctor will not know if you are getting caffeine capsules or placebo capsules, but we can find out that information if we need it. This is called double-blinded.

11. **Light**: We will expose you to bright light at certain times during the study. We do this to see how light and/or caffeine or both together can help people to perform complex tasks when they are tired.

12. **Eye Movements**: We will monitor your eye and eye movements using a pair of glasses. These glasses measure how alert or drowsy you are. You will wear these glasses during the robotic and cognitive tests.

Storage and use of study information and specimens

We will use the samples and study information that we collect from you for research on sleep and daily rhythms of the body. All of the samples and information that are collected are coded so that they cannot be linked directly to your name or other identifiers. The key to this code is stored in a location that is secure and separate from your medical and research study records.

We will store the coded blood, saliva, and urine specimens at BWH until testing them for levels of hormones and signals. Your samples may go to a company or institution outside the BWH for testing. If your specimens are sent outside of the BWH, we will send no information that could link the specimens to your name.

Because scientific research is an ongoing process, we may store some of your blood, saliva, and urine samples for many years for future analysis related to sleep research. For example, if a new hormone is discovered that promotes sleep, we may want to test for this hormone in your stored samples.

We will collect and store your blood, urine, and saliva samples. You cannot take part in the research study if you decide **before the** study **begins that** you do not want us to use or store your samples.

After you begin the study, you have the right to withdraw the use of your information data and/or samples at any time during or after the research study. If you withdraw your permission for us to use and store your samples, you will have to withdraw from the study at that time. We won't be able to withdraw information or samples that have already been used or shared with others.

If you want to withdraw your permission for us to use your information and/or specimens for this research, please contact the study doctor in writing. The address to use in this case is:

Dr. Steven Lockley,
Brigham and Women's Hospital,
Division of Sleep Medicine, 221 Longwood Avenue,
Boston, Ma 02115.

Blood and urine tests

We expect that you will go without the use of all drugs or medications (prescription or non-prescription).You cannot use these items from the time of the screening evaluation until you have completed the research study. For **at least 3 weeks** before the research study, you must stop using over-the-counter drugs, prescription drugs, and non-prescription drugs. This includes caffeine, nicotine, street drugs (such as marijuana or cocaine), anti-histamines, and sleeping pills. If you are taking prescription medication(s), the doctor who prescribed them must agree that you can stop taking them for the study.

There are many sources of caffeine, including coffee, tea, most sodas, and energy drinks, foods, chocolate, and medications. We will give you a listing of foods, drinks and medications that contain caffeine that you should avoid taking.

Throughout the research study, we will collect small samples of blood and urine from time to time. We will test for the presence of any over-the-counter drugs, prescription drugs, non-prescription drugs, or recreational/street drugs.

If we discover any drugs, medications, or other foreign substances are detected in your blood or urine, you won't receive any money for taking part in this research study. This includes any and all payment for parts of the study that may have taken place before your use of such drugs.

If you are female, we will test your urine at the start of the study, to see if you are pregnant. If you are pregnant, you will stop taking part in the study.

Stopping the Research Study

You have the right to stop taking part in the research study at any time. We also reserve the right to end the research study at any time. We may end your taking part in the research study:

1) for health reasons (for example, if you become ill during the study or are pregnant);

2) for issues of study compliance (for example, if drugs are found in your blood or urine, or if you are unable to comply with procedures of the research study);

3) for scientific reasons (for example, if data cannot be collected properly);

4) for administrative reasons.

What are the risks and possible discomforts from being in this research study?

Risks of Having an IV

You will likely experience some discomfort or bruising when the intravenous (IV) catheter goes into your forearm vein. Once inserted, the catheter shouldn't be painful. To help keep the venipuncture site clean, we may shave some of your forearm hair before putting in the IV catheter.

Occasionally, there is a black and blue mark that may last a couple of weeks where the needle enters the vein. Rarely, a small scar may remain permanently at the venipuncture site. There is also the slight possibility of fainting during or after the procedure. You may experience contact dermatitis (skin rash) from the tape used to hold the IV catheter to your arm.

Risks of Heparin (Used to Keep Blood Flowing Through the IV)

Rarely, you may experience side effects from the use of heparin, such as bleeding, allergic reaction, or heparin induced thrombocytopenia (HIT). HIT is a reversible condition associated with the use of heparin. With HIT, the number of platelets in your blood decreases significantly, below normal levels. Platelets are small particles normally circulating in your bloodstream that prevent bleeding.

HIT is occasionally associated with abnormal blood clotting. Such episodes of blood clotting have been associated with blood clots in the arms and legs, heart attacks, and stroke.

Since the earliest sign of HIT is a drop in the number of platelets, we will take regular blood samples from you to check for such changes. If the number of platelets in your bloodstream drops below normal levels, we will perform follow-up tests to confirm HIT. Also, we will stop the heparin immediately, let the study doctor know, and tell you.

If you do have HIT, you will stop taking part in this research study. You will receive the necessary medical treatment and care at the hospital, and the doctor will decide when you are healthy enough to return home safely.

Other IV Complications

There is a rare possibility that you may develop a small blood clot, inflammation, or local infection around the vein where the catheter goes into the vein. In rare cases a larger infection may spread through the bloodstream as a result of the IV catheter. We can treat infections with antibiotics.

Occasionally, you may experience mild discomfort from the tube in your forearm vein. If this happens, we will either move it or remove it entirely, and will ask your permission before putting a new IV into your vein.

Risks of Blood Loss Due to Study Sampling

The total amount of blood drawn over the course of the study (about 2 pints) is twice as much as the amount normally drawn during blood donation. There may be a small drop in the number of red blood cells (hematocrit). We will keep close track of your red blood cell count throughout the study. Study blood drawing will stop if your hematocrit falls below safe levels.

If your levels of hematocrit or hemoglobin (which carries oxygen in the blood) become too low, you may become anemic. Anemia means there is a reduction in the amount of oxygen you are able to carry in the blood due to a drop in red blood cells. Symptoms of anemia include muscle tiredness, weakness, and a lack of energy.

To reduce the risk of anemia, we will ask you to take an iron pill before, during and after the study. The iron pills may cause upset stomach, constipation, and/or a change in the color of your stool.

Risks of EEG, EKG, EOG, EMG, etc.

Measuring the brain electrical activity (EEG), heart beat (EKG), eye movements (EOG), muscle activity (EMG), respiration, rest-activity (actigraphy), body position, and skin temperature involve no risks. The EEG, EKG, EOG, EMG and actigraphy monitoring devices meet hospital standards for electrical safety.

The tape and special paste used to attach the electrodes or sensors may cause some minor discomfort or skin irritation. The glue used to hold electrodes to the scalp may leave a flaky patch for several days. You may experience some skin irritation from the sticky EKG pads. We will change their placement if this occurs.

Risks of Weight Loss

You may experience weight loss over the course of your study (up to about five pounds). Usually, this weight loss is due to a loss of body water; the salt content in the study diet may be lower compared to your regular diet. However, it is also possible that you may experience a modest loss in actual body mass (muscle and/or fat).

Risks of Changes in Your Sleep/Wake Cycle

You will probably become sleepy during some parts of the study when you are asked to remain awake. This experience is similar to that of a shift-worker who works the night shift. There may be times during these parts of the study when we will ask you not to read or do things that are making you feel sleepy. During such times, we may ask you to talk or interact with a study technician, to help you stay awake.

If you feel that you are unable to remain awake during any part of the research study, you are free to withdraw from this study and then go to sleep. If this happens, the study doctor will take you out of the study. Before you go home, you can sleep until you feel well-rested.

Risk of Developing Jet Lag

At the end of the study, you may find that you are no longer going to sleep and waking up at the same time that you did before the study started. It may take you several days to readjust to the regular routine that you had before starting the research study. This is similar to jet lag, which affects millions of people annually who travel rapidly across time zones.

Commonly reported symptoms include upset stomach and/or digestive disorders, insomnia (cannot fall or stay asleep), irritability, or excessive daytime sleepiness. These symptoms may last for up to 1-2 weeks, although most people report readjustment after only a few days.

Risks of Living in Dim Light

During the research study, the lights may remain dim for long periods of time. You may find it difficult to read or perform other activities that require brighter lighting. You may also find it difficult to stay awake continuously in dim light or darkness.

During other parts of the research study, you may be exposed to very bright light. You may experience a glare from the bright light, or irritation of your eyes. The bright white light is high for indoor light, but is equal to the type of light you would normally experience at dawn or dusk.

The artificial light includes a small amount of ultraviolet light, similar to the amount you would be exposed to by looking up at a blue sky just after dawn. As an added precaution, a) we may ask that you wear safety glasses that block ultraviolet light during each exposure to white light, or b) window glass will be used to shield the lighting fixtures used for the light exposure, which also blocks most ultraviolet light.

Special Risks for Women Taking Birth Control Pills

If you are a woman currently taking birth control pills, you will be able to continue taking these during the study. However, in order to maintain a time-free environment, the investigator will determine and inform you of when during the study you are to take your pills. The timing of when you take your pills during the research study will be irregular. After the research study, your protection from pregnancy with birth control pills may be temporarily ineffective. Therefore, in addition to taking your birth control pills, you should use barrier methods of contraception (such as a diaphragm or condoms) until your next menstrual period.

Risks for Monitoring Eye Movements

The Optalert glasses are a commercially available product and are safe and cause no known risk due to malfunction. The device is designed to measure alertness/drowsiness via a small infra-red diode attached to the pair of glasses. The glasses have been certified by the Biomedical Engineering of the BWH and are in accordance with all safety standards.

Other Study Risks

Side effects of taking caffeine may include: irritability, sleeplessness, nervousness and occasional rapid heart beat. You will receive capsules that contain about equal to 3-4 cups of coffee per day. We expect the side effects to be no greater than that experienced when drinking 3-4 cups/day. If you develop symptoms of rapid or irregular heart beat, then we won't give you any more caffeine capsules until a study doctor examines you.

During your time in the laboratory you won't have the opportunity to receive visitors (such as family or friends). You also won't be able to make or receive telephone calls. However, you will be able to send and receive mail/audio tapes via the study staff, although their delivery may be delayed in order to maintain a time-free environment.

You may experience discomfort providing answers to sensitive, personal questions (such as questions about your prior drug use and/or illnesses) asked by the physician or the Investigators of the research study. The information that you give becomes part of the research record.

You may experience harm related to a breach in confidentiality of information collected about illegal activities.

In addition to the risks or discomforts listed above, there may be other risks or discomforts that aren't known at this time.

What are the possible benefits from being in this research study?

There will be no direct benefit to you for taking part in the study.

We hope that the information gained from the results of the study will help us better understand how caffeine and light exposure can help astronauts and others who need to perform complex tasks when tired.

Can I still get medical care within Partners if I don't take part in this research study, or if I stop taking part?

Yes. Your decision won't change the medical care you get within Partners now or in the future. There will be no penalty, and you won't lose any benefits you receive now or have a right to receive.

Taking part in this research study is up to you. You can decide not to take part. If you decide to take part now, you can change your mind and drop out later. We will tell you if we learn new information that could make you change your mind about taking part in this research study.

What should I do if I want to stop taking part in the study?

If you take part in this research study, and want to drop out, you should tell us. We will make sure that you stop the study safely. We will also talk to you about follow-up care, if needed.

It is possible that we will have to ask you to drop out before you finish the study. If this happens, we will tell you why. We will also help arrange other care for you, if needed.

Will I be paid to take part in this research study?

Yes. We will pay you for your time as follows:

1. $100 per day for coming to the laboratory to complete the study, resulting in a maximum of $900 for a 9 day study and a maximum of $1300 for a 13-day study.
2. $60/day bonus for completing the study and for returning the sleep log.

The maximum amount of money that you can receive from participating in this study is $2510 for the 13 day study and $1870 for the 9 day study. If the entire study is not completed for any reason, subjects are paid for their participation up through their last day, but none of the $60/day completion bonus is paid. Also, there is no monetary compensation paid to any person whose blood and/or urine tests indicate use of drugs, alcohol, caffeine, nicotine, non approved prescription or over the counter drugs, recreation/street drugs, illicit drugs or any other foreign substances.

What will I have to pay for if I take part in this research study?

Study funds will cover all costs of the screening visits, procedures, tests, and equipment.

Costs for any ongoing or routine medical care you would receive apart from this study will be billed to you or to your insurance company in the usual way. You will be responsible for any deductibles or co-payments required by your insurer.

What happens if I am injured as a result of taking part in this research study?

We will offer you the care needed to treat any injury that directly results from taking part in this research study. We reserve the right to bill your insurance company or other third parties, if appropriate, for the care you get for the injury. We will try to have these costs paid for, but you may be responsible for some of them. For example, if the care is billed to your insurer, you will be responsible for payment of any deductibles and co-payments required by your insurer.

Injuries sometimes happen in research even when no one is at fault. There are no plans to pay you or give you other compensation for an injury, should one occur. However, you are not giving up any of your legal rights by signing this form.

If you think you have been injured or have experienced a medical problem as a result of taking part in this research study, tell the person in charge of this study as soon as possible. The researcher's name and phone number are listed in the next section of this consent form.

If I have questions or concerns about this research study, whom can I call?

You can call us with your questions or concerns. Our telephone numbers are listed below. Ask questions as often as you want.

Steven W. Lockley, Ph.D. is the person in charge of this research study. You can call him at 617-732-4977 during office hours [10:00am – 6:00pm, Monday-Friday]. You can also call Erin Evans Ph.D. at 617-525-6710 or Melanie Rueger at 617-525-8827 with questions about this

research study. These doctors can also be reached 24 hours a day by calling the page operator at Brigham and Women's Hospital on 617-732-6660 and asking for one of them to be paged.

Elizabeth Klerman , M.D., Ph.D. is the doctor on call for medical concerns. She can be called at 617-732-8145 or paged at 617-732-5700 x32090.

If you have questions about the scheduling of appointments or study visits, call the research coordinator at 617-732-4311 between 9:00am and 5:00pm, Monday-Friday.

In addition to the Partners Human Research Committee office (listed below), you can also talk to the MIT Human Research Committee office.
You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143B, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 6787.

If you want to speak with someone **not** directly involved in this research study, please contact the Partners Human Research Committee office. You can call them at 617-424-4100.

You can talk to them about:
- Your rights as a research subject
- Your concerns about the research
- A complaint about the research

Also, if you feel pressured to take part in this research study, or to continue with it, they want to know and can help.

If I take part in this research study, how will you protect my privacy?

During this research, identifiable information about your health will be collected. In the rest of this section, we refer to this information simply as "health information." In general, under federal law, health information is private. However, there are exceptions to this rule, and you should know who may be able to see, use, and share your health information for research and why they may need to do so.

In this study, we may collect health information about you from:

- Past, present, and future medical records
- Research procedures, including research office visits, tests, interviews, and questionnaires

Who may see, use, and share your identifiable health information and why they may need to do so:

- Partners research staff involved in this study
- The sponsor(s) of this study, and the people or groups it hires to help perform this research
- Other researchers and medical centers that are part of this study and their ethics boards
- A group that oversees the data (study information) and safety of this research
- Non-research staff within Partners who need this information to do their jobs (such as for treatment, payment (billing), or health care operations)
- The Partners ethics board that oversees the research and the Partners research quality improvement programs.
- People from organizations that provide independent accreditation and oversight of hospitals and research
- People or organizations that we hire to do work for us, such as data storage companies, insurers, and lawyers
- Federal and state agencies (such as the Food and Drug Administration, the Department of Health and Human Services, the National Institutes of Health, and other US or foreign government bodies that oversee or review research)
- Public health and safety authorities (for example, if we learn information that could mean harm to you or others, we may need to report this, as required by law)
- Other: Current investigators, trainees, research assistants, employees and consultants that continue to collarborate on this research project after leaving partners as well our collarborators at MIT (PI: Charles M. Oman and colleagues) in order to schedule the pre-study robotics training sessions.

Some people or groups who get your health information might not have to follow the same privacy rules that we follow. We share your health information only when we must, and we ask anyone who receives it from us to protect your privacy. However, once your information is shared outside Partners, we cannot promise that it will remain private.

Because research is an ongoing process, we cannot give you an exact date when we will either destroy or stop using or sharing your health information.

The results of this research study may be published in a medical book or journal, or used to teach others. However, your name or other identifying information **will not** be used for these purposes without your specific permission.

Your Privacy Rights

You have the right **not** to sign this form that allows us to use and share your health information for research; however, if you don't sign it, you can't take part in this research study.

You have the right to withdraw your permission for us to use or share your health information for this research study. If you want to withdraw your permission, you must notify the person in charge of this research study in writing. Once permission is withdrawn, you cannot continue to take part in the study.

If you withdraw your permission, we will not be able to take back information that has already been used or shared with others.

You have the right to see and get a copy of your health information that is used or shared for treatment or for payment. To ask for this information, please contact the person in charge of this research study. You may only get such information after the research is finished.

Informed Consent and Authorization

Statement of Study Doctor or Person Obtaining Consent

- I have explained the research to the study subject.
- I have answered all questions about this research study to the best of my ability.

_____ _____

Study Doctor or Person Obtaining Consent Date/Time

Statement of Person Giving Informed Consent and Authorization

- I have read this consent form.
- This research study has been explained to me, including risks and possible benefits (if any), other possible treatments or procedures, and other important things about the study.
- I have had the opportunity to ask questions.
- I understand the information given to me.

Signature of Subject:

I give my consent to take part in this research study and agree to allow my health information to be used and shared as described above.

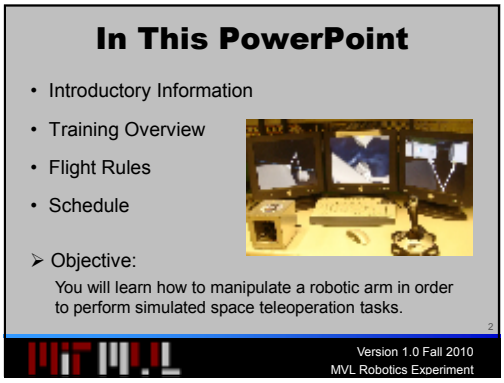
Subject _____ Date/Time _____

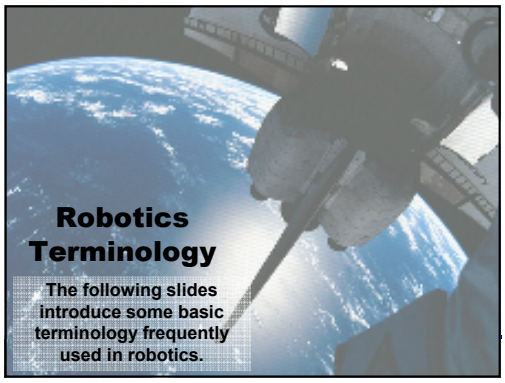
Consent Form Version: 05/05/2011

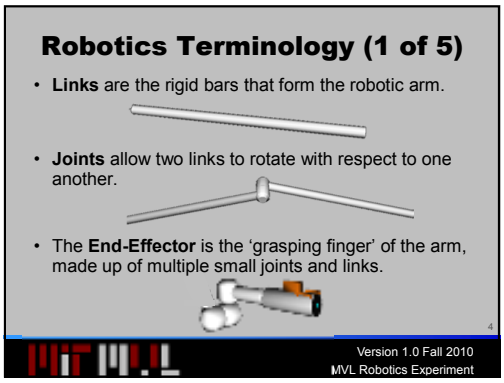
Subject Population: Healthy adults aged 26-55 - Research		
IRB Protocol No.: 2009P-001154	**Sponsor Protocol No.:** N/A	
Consent Form Valid Date: 03/21/2012	**IRB Amendment No.**: N/A	**Sponsor Amendment No.**: N/A
IRB Expiration Date: 02/13/2013	**IRB Amendment Approval Date:** N/A	

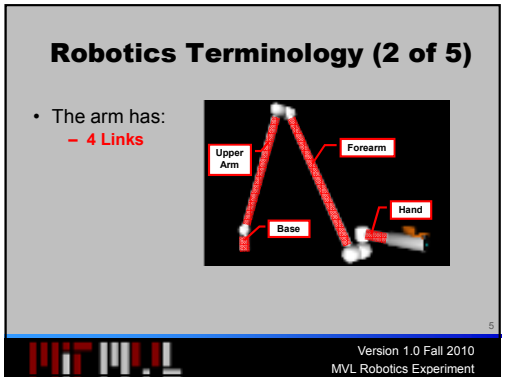
12.3. Training Slides

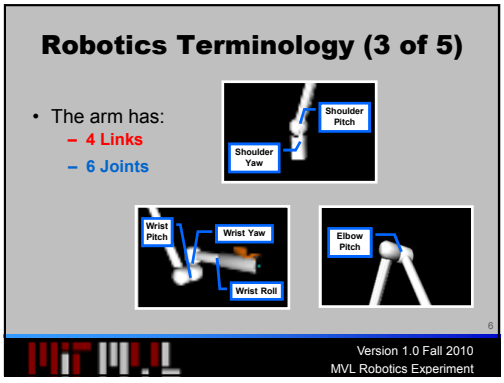
General Training Slides











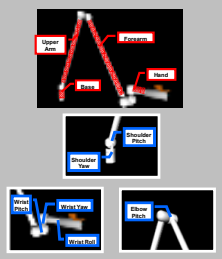
Robotics Terminology (4 of 5)

- The arm has:
  - **4 Links**
  - **6 Joints**
  - and a brake that may be toggled on/off by pressing '**b**'.

BRAKE ON

Brake indicator in lower right corner of screen disappears when brake is off.

The brake must be off in order for the arm to move.



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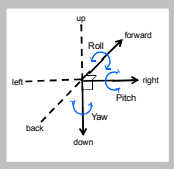
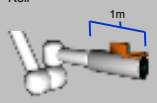
Robotics Terminology (5 of 5)



- The arm's joints allow it to move 6 ways in 3-D space
  - Left/right
  - Up/down
  - Forward/backward
  - Pitch
  - Yaw
  - Roll

- The arm is 17m long when fully extended, and the end-effector is 1m long.



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Robotics Terminology Recap

- The arm is made up of 4 links and 6 joints.
- The brake should be applied whenever the arm is not in motion.
  - Press '**b**' to toggle the brake on/off.

BRAKE ON

- The end-effector may move left/right, up/down, forward/backward or may pitch, yaw, or roll.
- The arm is 17m long when fully extended, and the end-effector is 1m long.

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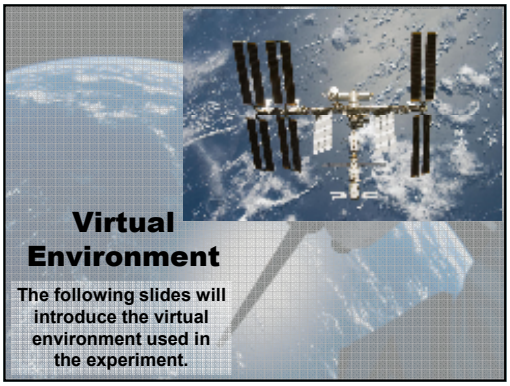
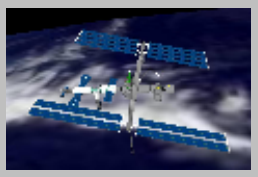


Virtual Environment

The following slides will introduce the virtual environment used in the experiment.

Virtual Environment



International Space Station (ISS)

- Components
  - Modules
  - Truss & Solar Arrays
  - Robotic Arm

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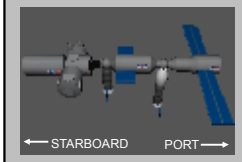
International Space Station

- **Modules**
  - The habitable space of the station.
  - Located on the port/starboard axis of the ISS in this simulation.



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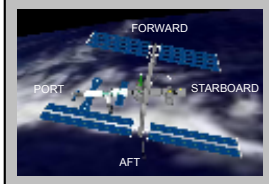
International Space Station



- **Truss and Solar Arrays**
  - The truss is mounted at the starboard end of the modules in this simulation, oriented along the forward/ aft axis of the ISS.
  - The large solar arrays are mounted on the truss.

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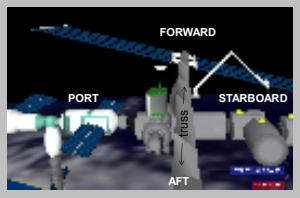
International Space Station

Anatomy of the Truss



- A useful cue for determining which side of the truss you are looking at is the Z1 truss (green box) with the Ku-band antenna (white dish).
- Note that the Z1 is located on the port side of the truss in this simulation.

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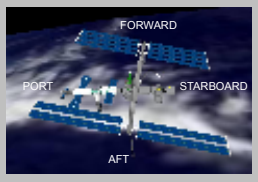
Virtual Environment Recap



- ISS components include modules, the truss and solar arrays, and the robotic arm.
- In this simulation:
  - -The modules are located on the port/starboard axis of the ISS.
  - -The truss is oriented along the forward/aft axis.
  - -The Z1 truss with the Ku-band antenna is located on the port side of the truss.

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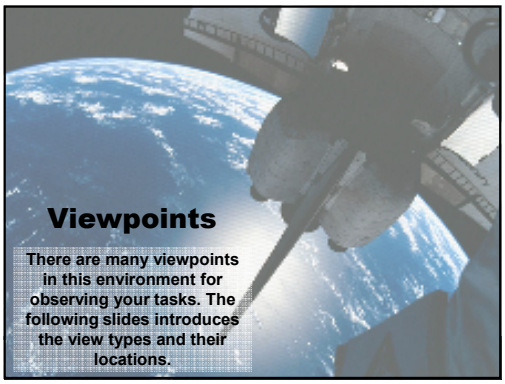

Views

- There are 3 general view types:

1) **Big Picture** - whole arm and work area

2) **Clearance** - arm/payload (what the arm may be carrying) with respect to structure, so as to avoid collisions

3) **Task**- often an end-effector or intuitive view, used to provide a more detailed image of the current task. The end-effector view includes cross-hairs centered on the screen in order to allow for accurate alignment over objects.

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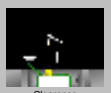
Views


Big picture


Clearance


Task

- It is important to monitor all three views in order to fly safely and accurately.
- Views in this simulation may come from cameras floating in space.
- End-effector motion may appear different depending on the camera view.
- You will learn later how to change camera views on each of the monitors.

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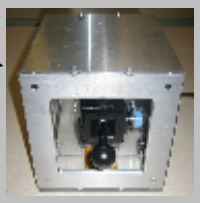
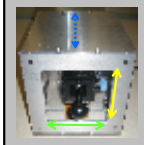
Hand Controllers

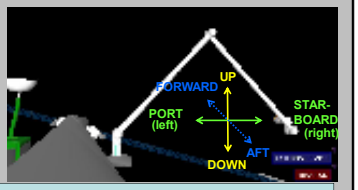
- Translational Hand Controller

With your left hand you will control the translational hand controller, which **moves the tip of the end-effector.** The arm's software calculates how all of the joints must rotate to make the movement.



Try It Out - Translation





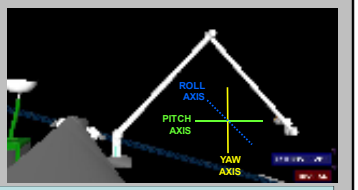
- Press '**b**' to disengage the brake.
- Move the controller left/right, up/down, and in/out.
  - Notice that the orientation of the end-effector does not change when you use the translational hand controller.
  - Watch all of the joints to ensure they do not collide with other objects.
- When done, press '**b**' to engage the brake.
  - Remember to always use the brake when not actively moving the arm.

Hand Controllers

- Rotational Hand Controller

With your right hand you control the rotational hand controller, which **rotates the arm around the tip of the end-effector;** it does not move the position of the tip.

Try It Out - Rotation

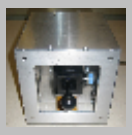


- Type 'Shift+r' to reset the arm's position. Press '**b**' to disengage the brake.
- Push right to roll around the end-effector tip; push left to return to the starting position.
- Twist to input yaw and push forward and backward to input pitch.
- Engage the brake when finished.

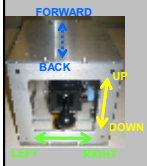
Hand Controllers

- It is important to make smooth movements with the hand controllers. Quick motions could damage a robotic arm.

- It is often desirable to move in more than one axis at once. This is called multi-axis control and increases the efficiency of the movement.



Hand Controllers Recap



- Left hand controls translation, moving the tip of the end-effector.
- Right hand controls rotation, rotating the arm about the tip of the end-effector.
- Make smooth movements with the hand controllers.
- Move in more than one axis at a time.
- Always use the brake when not paying attention to or actively controlling the arm.
- Monitor all views while controlling the arm; do not focus solely on the end-effector.

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Arm Limitations

There are two types of limitations on the arm's movement:

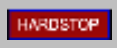
(1) Joint Limits

(2) Singularities.

The following slides explain these limitations and let you see what happens when you encounter them.

Joint Limits

- It's very important that you pay attention to what each of the arm's joints is doing, not just to where the end-effector is going.
- The arm joints have a finite range of motion:
  - A **hard-stop** is the limit on how far a joint can rotate.
  - This notice is displayed on the screen when you encounter a hard-stop:



  - Move in the reverse direction to free the arm.

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Try It Out – Hardstops

- Press 'Shift+r' to reset the arm.
- Disengage the brake.
- Push the rotational hand controller to the right and hold it there, (roll input).
  - Watch the arm rotate around the end-effector until it hits the hardstop.
  - Notice the warning displayed on the screen.
- Push the controller in the opposite direction, left, to recover and return to the starting position.
- Engage the brake.

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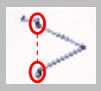
Singularities

The arm also has kinematic limitations, known as **singularities**.
At a singularity, some directions of motion are not possible.

1) Elbow Pitch joint at 0° or 180°

2) Wrist Yaw joint at 90°



3) Wrist Over Shoulder
(limits translational movement)

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Try It Out – Singularities

- These steps will let you see what happens when you reach the elbow pitch singularity:
  - Press 'Shift+r' to reset the arm.
  - Disengage the brake.
  - Push the translational hand controller to the right and hold it there.
    - Watch the arm move until it reaches the singularity.

  - Push the controller to the left to recover and return to the starting position.
  - Engage the brake.

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Arm Limitations Recap

- Joints have a finite range of motion; a **hard-stop** is the limit on how far a joint can rotate.

- The arm has three kinematic limitations, known as **singularities**:
  1) Elbow Pitch joint at 0° or 180°
  2) Wrist Yaw joint at 90°
  3) Wrist over Shoulder

- Monitor all three views and pay attention to what each of the arm's joints is doing, not just to where the end-effector is going.
- If you encounter a hardstop or singularity, reverse direction to free the arm.
- Pressing 'Shift+r' will reset the arm, but be aware that during the experiment, resetting the arm will hurt your score.

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Practice

- Now that you are aware of the limitations of the arm, you will have up to 4 minutes to gain some hands-on experience.

Try it out:

- Use both hand controllers at once and move the arm intentionally.
- Keep the arm in view at all times and discover how the arm responds to various controller inputs.
- Focus on making smooth motions.
- Practice multi-axis movement.
- Remember to monitor all three views.
- If you encounter a hardstop or singularity, reverse direction to free the arm.
- Pressing 'Shift+r' will reset the arm, but be aware that during the experiment, resetting the arm will hurt your score.
- Press 'b' to turn on the brake when you're finished.

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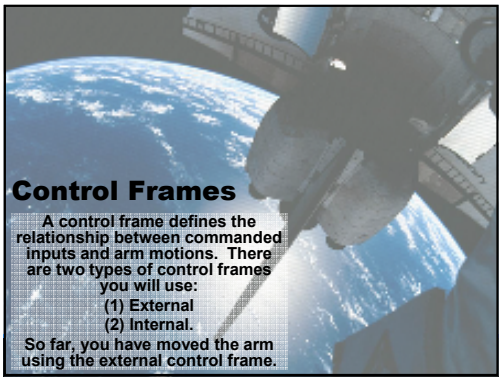
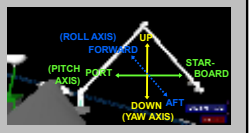


Control Frames

A control frame defines the relationship between commanded inputs and arm motions. There are two types of control frames you will use:
(1) External
(2) Internal.
So far, you have moved the arm using the external control frame.

External Control Frame

- An *external* frame is fixed with respect to the environment.
  - Directions are permanently aligned with the ISS.
  - Forward and aft are along the truss.
  - Port and starboard are along the core modules.
  - Up and down are above and below the station.



- Generally you will use an external frame when making large arm movements.
- Recall:
  - The Z1 truss with the Ku-band antenna is located on the port side of the truss. When attempting to orient yourself in the external frame, it may be useful to imagine yourself in the environment, facing forward along the forward/aft axis.

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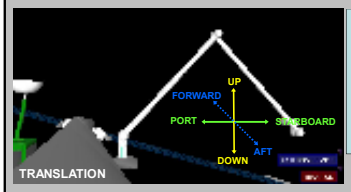
Try it Out – Translation, External Control Frame



- Press 'Shift+r' to reset the arm.
- Make left/right, up/down, and forward/aft movements with the translational hand controller.
- Did you remember to engage the brake?

- Motion may not be intuitive, depending on the camera views.

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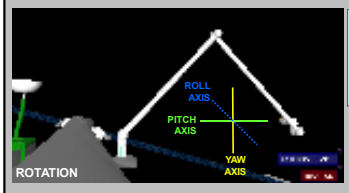
Try it Out – Rotation, External Control Frame



- Press 'Shift+r'.
- Make positive and negative pitch, yaw, and roll movements with the rotational controller.

- Remember that the controller causes rotation about a single axis – in external control, rotations are linked to axes, not specific joints.
- Did you press 'b' when done?

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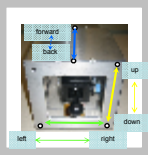
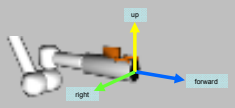
Internal Control Frame

- An *internal* frame is fixed to the tip of the end-effector.
- Generally you use an internal frame for small movements at the end stage of grappling tasks (aligning to grab objects).





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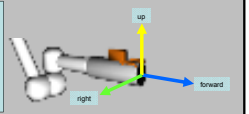
Try it Out - Translation Internal Control Frame

- Press 'Shift+r' to reset the arm.
- Press 'i' to switch to the internal control frame.
  - Note that the frame indicator in the lower right corner of the left monitor has changed to "internal".



- Make left/right, up/down, and forward/backward movements with the translational hand controller.
  - Motion is intuitive through the end-effector camera view.

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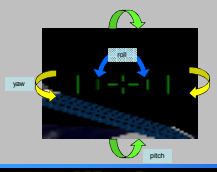
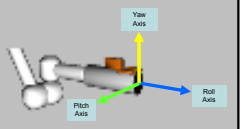
Try it Out - Rotation Internal Control Frame

- In the internal control frame, hand controller inputs produce the same end effector motion regardless of end effector orientation.





- Use the rotational controller to become familiar with pitch, yaw and roll in the internal control frame.
  - Motion is intuitive through the end-effector view.

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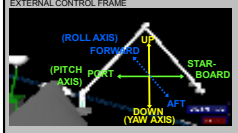
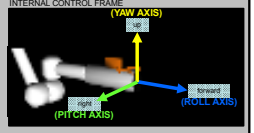
Control Frame Recap

- The *external frame* is fixed with respect to the ISS.
  - -Use the external frame when making large arm movements.
- The *internal frame* is fixed to the tip of the end-effector.
  - -Use the internal frame for small movements and alignment.

EXTERNAL CONTROL FRAME



INTERNAL CONTROL FRAME



- Press '**e**' to switch into the external control frame.
- Press '**i**' to switch into the internal control frame.

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Quick Review

The following slide reviews some important concepts. If there is something you do not understand, feel free to ask the experimenter questions or re-read the slides on that material.

Review of Important Concepts

- Camera Viewpoints
  - The ISS environment has **multiple viewpoints**.
  - It is important to monitor big picture, clearance, and task views.
- Hand Controllers
  - **Translational** (box)
  - **Rotational** (joystick)
  - Use both at the same time, and move in multiple axes simultaneously whenever possible.
- Arm Limitations
  - **Hardstops** are the limit on how far a joint can rotate.
  - The arm's configuration includes three types of **singularities**.
- Control Frame
  - **External** control frame axes are fixed to the ISS.
  - **Internal** control frame axes are fixed to the tip of the end-effector.

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Training Overview

- The training will allow you to practice tasks similar to those you will perform during the experiment.
- Over the course of today and the next 2 training sessions, you will become familiar with controlling the arm in the ISS environment and will practice several other types of tasks.
- During training, you will receive feedback on metrics such as:
  - Time to task completion
  - Number of collisions
  - Final position and alignment
  - Coordination of multi-axis movement
  - Number of resets of the arm position ('Shift+r')
  - Adherence to flight rules, described in the next section

Flight Rules

- Overall clearance limitation: 0.6m between any part of the arm and ISS structure
  - The following warning will be shown on the screen when any part of the arm comes within this limit:

  - Look for the cause of the clearance violation and move away to remove the warning.
  - Remember that you can use the length of the end-effector as a distance cue.

- You must avoid collisions between the arm and obstacles or between links of the arm (self-collision)
  - If a collision occurs, this warning will be displayed on the screen:

Keep in Mind

- Cameras
  - Use all of your viewpoints, observe clearances, monitor the task.
- Frames
  - Think carefully about how to move the arm in the external or internal control frame.
- Joints
  - Be aware of joint angle limits and arm singularities.

Strategies (Slide 1 of 3)

- Collision/Clearance Limit Avoidance
  - Monitor both the elbow and the end-effector's position and clearance.
  - Check all of the camera views for potential clearance concerns.
- Reducing Task-Time
  - Move in more than one direction at once and perform both rotational and translational movements together in order to finish the task more quickly.
  - Look for the shortest workable path between the start position and the target and follow that line as best you can.

Strategies (Slide 2 of 3)

- Moving the Arm
  - Plan ahead. Before you start working, think about the movements required for the best route and how to avoid obstacles.
    - i.e. Where will the elbow be if you move the end-effector toward the port side? Will it be too close to a nearby object?
    - When you begin moving the arm, make sure it is doing what you expected. If not, think about what happened and why before moving again.
  - Verbalize what you are doing or planning to do while you are working.
    - e.g. "I'm pulling the translational hand controller back; I expect the arm to move away from the base. The elbow is going to get closer to the truss, but it won't violate the clearance limit."
    - If what you are planning to do does not make sense, you may be able to realize it in advance through hearing yourself say it out loud.

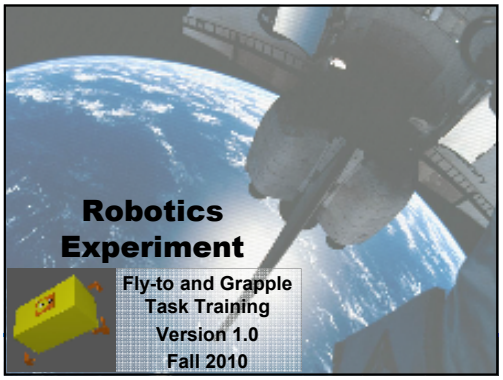
Strategies (Slide 3 of 3)

- Arm Alignment
  - Use the edges of fixed objects such as the targets or the trusses to determine when the end effector is vertical or horizontal with respect to a feature.
  - Look at all of your views when you are trying to align the arm with a grapple fixture. In most situations, you CANNOT get all of the information you need from a single view.
- Distance Estimation
  - Remember that the last component of the end-effector is 1m long. Use it as a guide to ensure that you do not violate the clearance limit and to position the end-effector correctly.

- Maneuvering
  - If you reach a hard-stop or singularity or collide with another object, try to move in the opposite direction. If you cannot escape, reset the arm to its original position by pressing 'Shift+r'. Be aware that resets will count against your overall performance score.

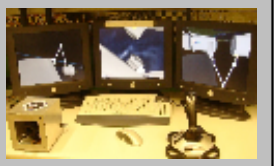
Training Schedule

- Session 1:
  - ☑ Training Slides
  - ☐ Task Training: fly-to and grapple
  - ☐ Advanced Task Training
- Session 2:
  - ☐ Quick Review
  - ☐ Task Training: HTV capture
- Session 3:
  - ☐ Quick Review
  - ☐ Task Training: auto-sequence



In This PowerPoint

- Fly-To and Grapple Task
  - Objectives
  - Stages
  - Strategies
  - Quick Review
- Training Overview
- Hands-on Training
- Schedule Review
- Advanced Task Training



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Objectives

- Training Objective:
  - You will learn how to move the arm from one location to another near a target, called a fly-to.
  - You will maneuver the arm into pre-grapple position.
  - You will learn how to grapple (grab onto) the target.
- Fly-to and Grapple Task Objectives:
  - Fly-to and grapple maneuvers are used to pick up objects, including nodes, cargo, and astronauts, and to move them from one location to another.
  - The operator moves the arm from the starting position to the pre-grapple position, then grapples the target.
  - The operator monitors the arm while flying to ensure there are no clearance violations or collisions.

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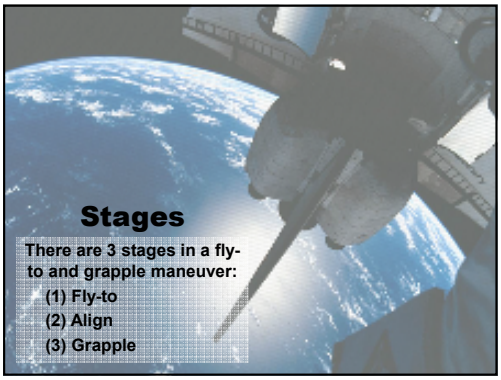
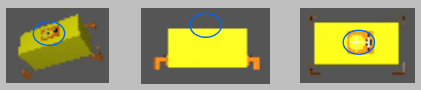


Stage 1: Fly-to

- For your practice trials, the targets in the environment are yellow boxes with the same **grapple fixture** that will be used on nodes in the experiment.



- During a fly-to, you will use both hand controllers to position the end-effector roughly 2 meters above the grapple fixture on the target.
- Recall that the length of the end-effector is 1 meter.

You should complete the fly-to with the small circle with the small pin appearing above the large circle with the large pin.

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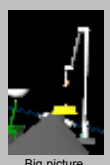
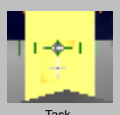
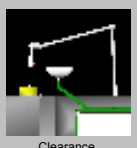
Stage 2: Pre-grapple Alignment

- Once you are above the target, you need to align the end-effector into pre-grapple position. This is often easiest in the internal control frame.
- In pre-grapple position, the end-effector is 1.5 meters above the target and perpendicular to the target, as shown:


Big picture


Task


Clearance

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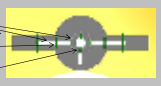
Stage 3: Grapple

- Once you have achieved pre-grapple alignment, carefully move the end-effector until it is in the grapple envelope, just touching the pin.

- You are in the **grapple envelope** when the following conditions are met:
  - The white dot is in the white circle.
  - The long white line is within 5 degrees of horizontal.
  - The inner green lines are just inside the edge of the large gray circle.
  - The crosshairs are centered in the gray circle.



- When in the envelope, you will pull the trigger on the joystick to grapple.

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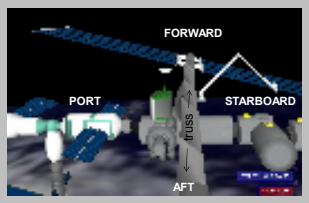
Strategies

The following slides introduce techniques that may help improve your performance in fly-to and grapple tasks.

Fly-to Techniques

- Large arm motions should be made in the external command frame.
- Monitor all views to fly safely and efficiently.
- Recall: The Z1 with the Ku-band antenna is located on the port side of the truss in this simulation.



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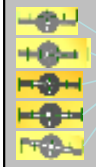
Alignment Techniques

- Work in the Internal Command Frame.
- To significantly slow the rate of motion of the arm, press "**v**" to apply vernier rate when within 2m of a target. You will have finer control of translation and rotation, allowing for easier (and safer) alignment and grappling.
- How to correct alignment errors:



Error	*Technique 1*	*Technique 2*
Center of crosshairs above center of gray circle	Translate down	Pitch down
Center of crosshairs right of center of gray circle	Translate left	Yaw left
Dot high in white ring	Pitch down	Translate up
Dot left in white ring	Yaw right	Translate left
Roll error	Crosshair lines centered in white bar (make sure vertical line on white bar is pointing down)	

Note: If you input a translation you may need a rotation to align the target, as the translational and rotational cues are coupled (i.e., pitch down and translate up)

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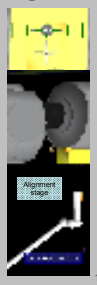
Quick Review

The following slide reviews some important concepts. If you do not understand something, feel free to ask the experimenter questions or re-read the slides on that material.

Review of Important Concepts

- Objective
  - Fly-to and grapple maneuvers are used to pick up objects, including nodes, cargo, and astronauts, and to move them from one location to another.
- Grapple Tolerance
  - White dot in white circle
  - White line level within 5 deg
  - Inner green lines on edge of large gray circle
  - Crosshairs centered in circle

- Stages
  - 1: Fly-to
    EXTERNAL COMMAND FRAME
    End-effector goal is 2m above the target.
  - 2: Align
    INTERNAL COMMAND FRAME
    End-effector goal is 1.5m above and perpendicular to the target.
  - 3: Grapple
    INTERNAL COMMAND FRAME
    VERNIER RATE
    Enter grapple envelope, just touching the grapple pin, and pull the trigger.



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Training Overview

Now that you know how to perform a fly-to and grapple, the following slide will tell you more about what you will be doing in the experiment and then you will have a chance to try it yourself.

Training Overview

- Training
  - The training will allow you to practice tasks similar to those you will encounter during the experiment.
  - Over the course of this training session, you will become familiar with performing fly-to and grapple maneuvers.
- Metrics
  - Your performance will be evaluated by and you will receive feedback on:
    - Time to task completion
    - Number of collisions
    - Pulling the trigger only when in the envelope
    - Coordination of multi-axis movement
    - Number of resets of the arm position ('Shift+r')
    - Adherence to flight rules

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Hands-on Training

There are 12 unique scenarios in which targets will be placed. Your cameras will be selected for you.

Please review these slides as needed and proceed with the training simulation when ready.

Training Schedule

- Session 1:
  - ☑ Training Slides
  - ☑ Task Training: fly-to and grapple
  - ❑ Advanced Task Training
- Session 2:
  - ❑ Quick Review
  - ❑ Task Training: HTV capture
- Session 3:
  - ❑ Quick Review
  - ❑ Task Training: auto-sequence

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Training

Try it out:

- Now complete your 12 trials.

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Advanced Task Training

During the experiment, you will be responsible for switching **command frames**, applying **vernier rate**, and changing **camera views**. You will grapple objects other than the target boxes and will move them to other locations. The following slides outline the procedure that you must follow. You will then have the opportunity to practice more complex tasks.

Switching Command Frames

- Scenarios will begin in the External Command Frame, with axes fixed to the ISS.
- Final alignment and grappling should be performed in the Internal Command Frame.

Recall:

  - Press '**i**' to switch to the Internal Command Frame.
  - Press '**e**' to switch to the External Command Frame.

- Loaded fly-tos, carrying a payload grappled to the end-effector, should be made in the External Command Frame.

Applying Vernier Rate

- To slow the rate of motion of the arm, apply vernier rate.

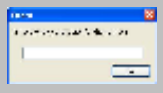
Recall:

- Press '**v**' to toggle between course rates and vernier rates.

- Vernier rate should be used during the grapple stage and for fine alignment, as well as when operating within 1.5m of structure or payloads.

Changing Camera Views

- It is important to maintain big picture, task, and clearance views.
- You will be provided with a list of camera views to use for each stage of each scenario.
  - Press '**F1**', '**F2**', or '**F3**' to change the views on monitors 1, 2, or 3, from left to right, respectively.
  - Input the desired camera view when prompted.



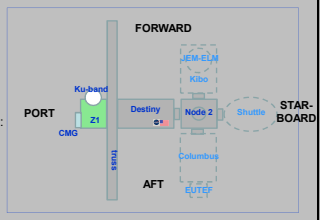
Task Procedure

- You will be given scenario sheets that include:
  1) Task Description – a statement of your objective
  2) Final Placement – images of the final position and orientation of the payload as viewed with the appropriate cameras
  3) Cameras – a table that indicates what cameras you should have on each monitor during each stage of the task
- When referring to the scenario sheet, be sure to engage the brake.

- When you are satisfied with your final placement, press 'Shift+d' to indicate that you are done.

Helpful Hints

- The grapple fixture will have a consistent appearance.
- The following schematic may be useful to help determine final placements:



Review of Important Concepts

- Command Frames
  - Use the internal frame for final alignment and grappling. ('**i**')
  - Use the external frame for large arm motions. ('**e**')
- Rate of Motion
  - Apply vernier rate during the grapple stage and for fine alignment, as well as when operating within 1.5m of structure or payloads. ('**v**')
- Cameras
  - Maintain big picture, task, and clearance views by changing the monitors as instructed on the scenario sheets. ('**F1**', '**F2**', '**F3**')
- Task Procedure
  - Refer to scenario sheets for:
    1. *Task Description*
    2. *Final Placement*
    3. *Cameras*

Hands-on Advanced Task Training

Now you have the opportunity to practice more complex tasks using the same format that you will see during the in-patient study. The experimenter will provide you with printouts of the scenario specifics and is available to provide guidance as needed.

Advanced Task Training

Try it out:

- Now complete your hands-on trials.

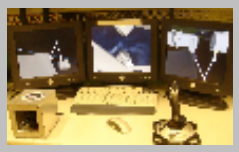
Training Schedule

- Session 1: COMPLETE
  - ☑ Training Slides
  - ☑ Task Training: fly-to and grapple
  - ☑ Advanced Task Training
- Session 2:
  - ❑ Quick Review
  - ❑ Task Training: HTV capture
- Session 3:
  - ❑ Quick Review
  - ❑ Task Training: auto-sequence

Track and Capture Training

In This PowerPoint

- Track and Capture Task
  - Description
  - Procedure
  - Strategies
- Hands-on Training
- Schedule Review



Description

- Training:
  - You will learn how to grapple a moving target, the H-II Transfer Vehicle (HTV), an unmanned resupply vehicle.
  - You will start approximately in pre-grapple position and will have 90 seconds in each scenario in which to approach, maintain alignment with, and latch onto the pin.
- Track and Capture Task:
  - Track and capture is used when a robotics operator aboard the ISS must grapple a free-flying vehicle.
  - The free-flying vehicle may be drifting or spinning in relation to the ISS.

The Start

- Scenarios will load with the proper camera views selected for you:

Clearance | Task | Big Picture

- The brake will be engaged.
- The arm will be in position as of having just finished a fly-to, roughly perpendicular and approximately 2m from the grapple fixture on the HTV.
- The initial command frame will be internal.
- The initial rate will be vernier.

The Procedure

- You will have 90 seconds in which to grapple the HTV.
- Using the techniques that you learned for fly-to and grapple, coordinate translation and rotation such that you maintain proper alignment over the grapple fixture as you approach.

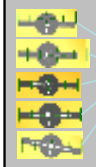
- When in the grapple envelope, pull the trigger to latch onto the HTV.

Strategies

The following slides review techniques that may help improve your performance in track and capture tasks.

Alignment Techniques

- Internal Command Frame
- Vernier Rate
- Correcting Alignment Errors:



Error	*Technique 1*	*Technique 2*
Center of crosshairs above center of black circle	Translate down	Pitch down
Center of crosshairs right of center of black circle	Translate left	Yaw left
Dot high in white ring	Pitch down	Translate up
Dot left in white ring	Yaw right	Translate left
Roll error	Crosshair lines centered in white bar (make sure vertical line on white bar is pointing down)	

Remember: If you input a translation, you may need a rotation to align the target, as the translational and rotational cues are coupled (e.g. pitch down and translate up)

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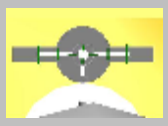
The Grapple Envelope

- You are in the grapple envelope when the following conditions are met:



  - The white dot is in the white circle.
  - The long white line is within 5 degrees of level.
  - The inner green lines are just inside the edge of the large gray circle.
  - The crosshairs are centered in the gray circle.

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Hands-on Training

There are 6 scenarios in which the HTV will have some combination of spin and drift. Your 90 seconds will begin and the HTV will start moving when you release the brake.

Please review these slides as needed and proceed with the training simulation when ready.

HTV Training

Try it out:

- Now complete your 6 trials.

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Training Schedule

- Session 1:
  - ☑ Training Slides
  - ☑ Task Training: fly-to and grapple
  - ☑ Advanced Task Training
- Session 2:
  - ☑ Quick Review
  - ☑ Task Training: track and capture
- Session 3:
  - ❑ Quick Review
  - ❑ Task Training: auto-sequence

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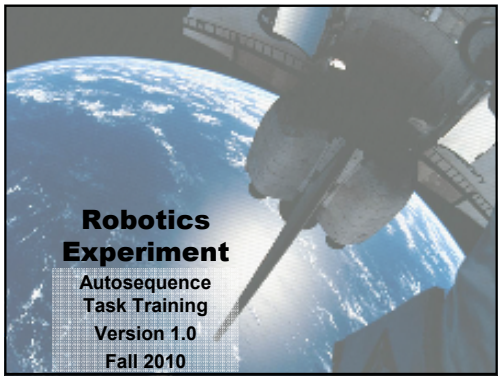

In This PowerPoint

- Autosequence Task Training
- Training Overview
- Flight Rules
- Schedule

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Objectives

- Training Objective:
  - You will learn how to make an autosequence command to move the arm from one location to another.
  - You will practice monitoring the arm while it is moving automatically.
- Autosequence Task Objectives:
  - Autosequence movements are used to move the arm across long distances to prevent physical fatigue for the operator.
  - The operator selects a movement file or inputs predetermined joint angles as directed by ground control.
  - The operator monitors the arm as it is moving to ensure there are no clearance violations or collisions. The operator can stop the arm if necessary.

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Metrics

- During the experiment, your performance will be evaluated based on:
  - Correct initial inputs, both for mode selection and for inputs within each mode (explained on the next slide)
  - Number of collisions or clearance violations missed
  - Number of collisions or clearance violations correctly prevented
  - Number of times the brake is incorrectly applied

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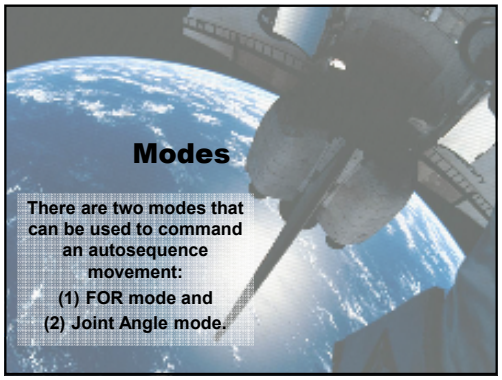

Modes

Read this first:

- In **FOR mode** (Frame Of Reference), the operator selects the movement file from a list of prerecorded files.
- In **Joint Angle mode**, the operator types the destination joint angles into the fields.

Now try it out:

- Type 'A' (Shift+'a') to bring up the autosequence menu. Click on the menu to access the input fields.
- Switch between FOR and Joint Angle in the "Select Mode" drop down menu. Each mode is highlighted when it is selected.

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Steps

There are 3 steps in commanding an autosequence movement:
(1) Selection,
(2) Verification, and
(3) Monitoring.

Step 1: Selection

Read this first:

- To begin, use the Procedure printout (in this case the directions below) to identify which autosequence movement you will be selecting.
- Type 'A' (Shift+'a') to bring up the menu. Choose the specified mode type (FOR or Joint Angle).
- Then:
  - For FOR mode, select the appropriate file from the drop down menu.
  - For Joint Angle mode, enter the numbers listed for the destination joint angles.

Now try it out:

➢ Type 'A' (Shift+'a') to bring up the autosequence menu. Choose FOR mode, then select Option 1. Proceed to the next slide before continuing.

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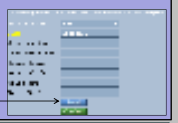
Step 2: Verification

Read this first:

- Once you have chosen a mode and either selected an option or entered the destination joint angles, you must verify that the information has been entered correctly.
- Before clicking 'Load', compare the selected option or numbers on the screen with those on the printout to make sure they match.
- Next, you will click 'Load'. Click 'Yes' if you have entered the information correctly. If the Ground Control Center notices any errors, you will be notified and prompted to correct them. If there are no errors, click 'Ok' to continue.



Now try it out:

➢ Make sure you have FOR mode selected, with Option 1 selected below it. Click on 'Load'. Click 'Yes' if you have checked your inputs. Then click 'OK' when Ground Control verifies your inputs. **Wait** to click 'Confirm' until the next slide.

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Step 3: Monitoring

Read this first:

- Once you and the Ground agree on the inputs, turn off the brake by pressing 'b' and click on 'Confirm'.
- Once you have verified the selection, it is important to monitor the movement of the arm for any unexpected movements or clearance violations.

- Over long movements, it is important to stay vigilant. If the arm gets within **1.5 meters** of any structure, press 'b' to turn on the brake and stop the arm. Follow directions from the ground to continue.
- While the arm is moving, you will see this message:
- When the arm finishes moving, you will see this message:

Now try it out:

➢ Press 'b' to turn off the brake, then click 'Confirm'. Watch carefully as the arm moves. Monitor the clearance of all parts of the arm, and press 'b' if you see any problems. Proceed to the next slide when you see the 'BRAKE ON' message above.

- Remember that the minimum clearance distance is 0.6m and that the end-effector is 1m long.

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Practice

- Now you will try commanding an autosequence movement using Joint Angle inputs.

Try it out:

- Type 'A' (Shift+'a') to bring up the autosequence menu, and click on the menu.
- Step 1: Select Joint Angle mode. Enter the following Joint Angles:
  - Shoulder Yaw: -45.5
  - Shoulder Pitch: 76.0
  - Elbow Pitch: -134.7
  - Wrist Pitch: 27.0
  - Wrist Yaw: 24.4
  - Wrist Roll: 60.5
- Step 2: Verify that the numbers you typed match those above. Click 'Load'. If ground control agrees with your inputs, press 'b' to turn off the brakes, then click 'Confirm' to start movement.
- Step 3: Monitor the arm's movement as it progresses through the autosequence. Press 'b' to apply the brakes if you see any imminent clearance violations.

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Quick Review

The following slide reviews some important concepts. If there is something you do not understand, feel free to ask the experimenter questions or re-read the slides on that material.

Review of Important Concepts

- Objective
  - Autosequence movements are used to move the arm across long distances to prevent physical fatigue for the operator.
- Modes
  - **FOR**: Select a pre-recorded file.
  - **Joint Angle**: Input the destination angles of each joint individually.
- Steps
  - Step 1: Selection
    - Choose the mode, then select the file or input the destination.
  - Step 2: Verification
    - Check your inputs on your own, then verify with the Ground Control Center.
  - Step 3: Monitoring
    - Watch for any clearance violations while the arm is moving. Press 'b' to stop the arm.

Training Review

- Training
  - During this training you practiced tasks similar to those you will encounter in the experiment. You will have the chance to practice 2 more trials at the end of this training.
  - Over the course of this training session, you became familiar with commanding autosequence movements using both modes.
  - You also practiced monitoring the arm's progress as it moved.
- Metrics
  - During the experiment, your performance will be evaluated based on:
    - Correct initial inputs, both for mode selection and for inputs within each mode
    - Number of collisions or clearance violations missed
    - Number of collisions or clearance violations correctly prevented
    - Number of times the brake is incorrectly applied

Flight Rules Review

- Overall clearance limitation: 0.6m between the arm and all obstacles
  - Remember that you can use the length of the end-effector as a distance cue.

- You must avoid collisions between the arm and obstacles or with itself
  - If a collision occurs, this warning will be displayed on the screen:

- Once you press 'b' once correctly, do not press it again until the arm has moved away from the structure.

Strategies

- Collision/Clearance Violation Avoidance
  - Monitor both the elbow and the end-effector's position and clearance.
  - Keep checking all of the camera views for potential clearance concerns.
  - Press 'b' if a clearance concern is imminent.
- Improving Performance
  - Double check your inputs in the menu carefully before clicking 'Load'.
  - Staying vigilant during long arm movements can be challenging, but it is important to monitor the movements carefully to prevent collisions.

Practice

- Now you will practice commanding another autosequence movement using an FOR input. This time, you will use the procedure sheet.

Try it out:

- Follow the instructions on the procedure sheet to command FOR mode, Option 2.
- If you need a reference, the specific steps are shown below.
  - Type 'A' (Shift+'a') to bring up the autosequence menu, and click on the menu.
  - Step 1: Select FOR mode. Select Option 2.
  - Step 2: Verify that FOR mode is selected, with Option 2 selected below it. Click 'Load'. If ground control agrees with your inputs, press 'b' to turn off the brakes, then click 'Confirm' to start movement.
  - Step 3: Monitor the arm's movement as it progresses through the autosequence. Press 'b' to apply the brakes if you see any imminent clearance violations.

Practice

- Finally, you will practice commanding another autosequence movement using Joint Angle inputs. Again, you will use the procedure sheet.

Try it out:

- Follow the instructions on the procedure printout to command the Joint Angles below:
  - Shoulder Yaw: -88.0
  - Shoulder Pitch: 79.9
  - Elbow Pitch: -133.8
  - Wrist Pitch: 53.9
  - Wrist Yaw: 88.0
  - Wrist Roll: 90.0
- If you need a reference, the specific steps are shown below.
  - Type 'A' (Shift+a) to bring up the autosequence menu, and click on the menu.
  - Step 1: Select Joint Angle mode. Enter the following Joint Angles:
    - Shoulder Yaw: -88.0
    - Shoulder Pitch: 79.9
    - Elbow Pitch: -133.8
    - Wrist Pitch: 53.9
    - Wrist Yaw: 88.0
    - Wrist Roll: 90.0
  - Step 2: Verify that the numbers you typed match those above. Click 'Load'. If ground control agrees with your inputs, press 'b' to turn off the brakes, then click 'Confirm' to start movement.
  - Step 3: Monitor the arm's movement as it progresses through the autosequence. Press 'b' to apply the brakes if you see any imminent clearance violations.

Training Schedule

- Session 1:
  - ☑ Training Slides
  - ☑ Task Training: fly-to and grapple
  - ☑ Advanced Task Training
- Session 2:
  - ☑ Quick Review
  - ☑ Task Training: HTV capture
- Session 3:
  - ☑ Quick Review
  - ☑ Task Training: autosequence

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Side Task Slides

The Side Task

- At varying intervals, a notification will pop up on the left monitor (Monitor 1), indicating a communication from the ground. The notification will flash between yellow and green.

- When you see this notification, you should indicate that you have seen it by pressing the side button on the left side of the Rotational Hand Controller.

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Side Task Strategies

- Responding to the notification is your secondary priority.
  - This means that if you are too busy doing the robotics task, it is ok to miss a response.
  - You should scan over to the left monitor if you have extra time to see if the notification is there.
- If you are able to respond to the notification, do so as quickly as possible.

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More Information

- The side task will be present during all types of tasks.
- Don't worry if you are able to pay more attention to it during some tasks and less during others.
- Remember, press the left side button on the Rotational Hand Controller to dismiss the notification.

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Review All Slides

Robotics Terminology Recap

- The arm is made up of 4 links and 6 joints.
- The brake should be applied whenever the arm is not in motion.
  - Press '**b**' to toggle the brake on/off.

- The end-effector may move left/right, up/down, forward/backward or may pitch, yaw, or roll.
- The arm is 17m long when fully extended, and the end-effector is 1m long.

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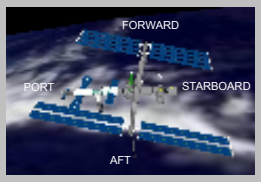
Virtual Environment Recap



- ISS components include modules, the truss and solar arrays, and the robotic arm.
- In this simulation:
  - -The modules are located on the port/starboard axis of the ISS.
  - -The truss is oriented along the forward/ aft axis.
  - -The Z1 truss with the Ku-band antenna is located on the port side of the truss.

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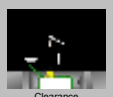
Views Recap


Big picture


Clearance


Task

- It is important to monitor all three views in order to fly safely and accurately.
- Views in this simulation may come from cameras floating in space.
- End-effector motion may appear different depending on the camera view.

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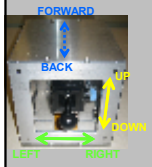
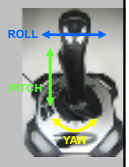
Hand Controllers Recap



- Left hand controls translation, moving the tip of the end-effector.
- Right hand controls rotation, rotating the arm about the tip of the end-effector.
- Make smooth movements with the hand controllers.
- Move in more than one axis at a time.



- Always use the brake when not paying attention to or actively controlling the arm.
- Monitor all views while controlling the arm; do not focus solely on the end-effector.

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Arm Limitations Recap

- Joints have a finite range of motion; a **hard-stop** is the limit on how far a joint can rotate.

- The arm has three kinematic limitations, known as **singularities**:
  1) Elbow Pitch joint at 0° or 180°
  2) Wrist Yaw joint at 90°
  3) Wrist Over Shoulder

- Monitor all three views and pay attention to what each of the arm's joints is doing, not just to where the end-effector is going.
- If you encounter a hardstop or singularity, reverse direction to free the arm.
- Pressing 'Shift+r' will reset the arm, but be aware that during the experiment, resetting the arm will hurt your score.

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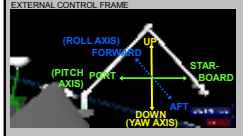
Control Frame Recap

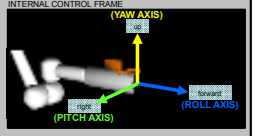
• The *external frame* is fixed with respect to the ISS.
-Use the external frame when making large arm movements.

• The *internal frame* is fixed to the tip of the end-effector.
-Use the internal frame for small movements and alignment.

EXTERNAL CONTROL FRAME



INTERNAL CONTROL FRAME



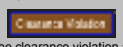
- Press '**e**' to switch into the external control frame.
- Press '**i**' to switch into the internal control frame.

Review of Important Concepts

- Camera Viewpoints
  - The ISS environment has **multiple viewpoints**.
  - It is important to monitor big picture, clearance, and task views.
- Hand Controllers
  - **Translational** (box)
  - **Rotational** (joystick)
  - Use both at the same time, and move in multiple axes simultaneously whenever possible.
- Arm Limitations
  - **Hardstops** are the limit on how far a joint can rotate.
  - The arm's configuration includes three types of **singularities**.
- Control Frame
  - **External** control frame axes are fixed to the ISS.
  - **Internal** control frame axes are fixed to the tip of the end-effector.

Flight Rules Review

- Overall clearance limitation: 0.6m between any part of the arm and ISS structure
  - The following warning will be shown on the screen when any part of the arm comes within this limit:



  - Look for the cause of the clearance violation and move away to remove the warning.
  - Remember that you can use the length of the end-effector as a distance cue.

- You must avoid collisions between the arm and obstacles or between links of the arm (self-collision)
  - If a collision occurs, this warning will be displayed on the screen:

Strategies Recap (Slide 1 of 3)

- Collision/Clearance Limit Avoidance
  - Monitor both the elbow and the end-effector's position and clearance.
  - Check all of the camera views for potential clearance concerns.
- Reducing Task-Time
  - Move in more than one direction at once and perform both rotational and translational movements together in order to finish the task more quickly.
  - Look for the shortest workable path between the start position and the target and follow that line as best you can.

Strategies Recap (Slide 2 of 3)

- Moving the Arm
  - Plan ahead. Before you start working, think about the movements required for the best route and how to avoid obstacles.
    - i.e. Where will the elbow be if you move the end-effector toward the port side? Will it be too close to a nearby object?
    - When you begin moving the arm, make sure it is doing what you expected. If not, think about what happened and why before moving again.
  - Verbalize what you are doing or planning to do while you are working.
    - e.g. "I'm pulling the translational hand controller back; I expect the arm to move away from the base. The elbow is going to get closer to the truss, but it won't violate the clearance limit."
    - If what you are planning to do does not make sense, you may be able to realize it in advance through hearing yourself say it out loud.

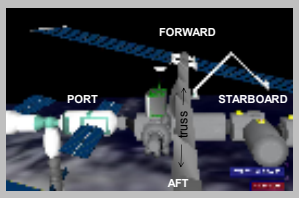
Strategies Recap (Slide 3 of 3)

- Arm Alignment
  - Use the edges of fixed objects such as the targets or the trusses to determine when the end effector is vertical or horizontal with respect to a feature.
  - Look at all of your views when you are trying to align the arm with a grapple fixture. In most situations, you CANNOT get all of the information you need from a single view.
- Distance Estimation
  - Remember that the last component of the end-effector is 1m long. Use it as a guide to ensure that you do not violate the clearance limit and to position the end-effector correctly.

- Maneuvering
  - If you reach a hard-stop or singularity or collide with another object, try to move in the opposite direction. If you cannot escape, reset the arm to its original position by pressing 'Shift+r'. Be aware that resets will count against your overall performance score.

Fly-to Techniques

- Large arm motions should be made in the external command frame.
- Monitor all views to fly safely and efficiently.
- Recall: The Z1 with the Ku-band antenna is located on the port side of the truss in this simulation.



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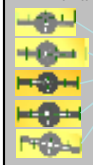
Alignment Techniques

- Work in the Internal Command Frame.
- To significantly slow the rate of motion of the arm, press "**v**" to apply vernier rate when within 2m of a target. You will have finer control of translation and rotation, allowing for easier (and safer) alignment and grappling.
- How to correct alignment errors:



Error	*Technique 1*	*Technique 2*
Center of crosshairs above center of gray circle	Translate down	Pitch down
Center of crosshairs right of center of gray circle	Translate left	Yaw left
Dot high in white ring	Pitch down	Translate up
Dot left in white ring	Yaw right	Translate left
Roll error	Crosshair lines centered in white bar (make sure vertical line on white bar is pointing down)	

Note: If you input a translation you may need a rotation to align the target, as the translational and rotational cues are coupled (i.e., pitch down and translate up)

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Review of Important Concepts

- Objective
  - Fly-to and grapple maneuvers are used to pick up objects, including nodes, cargo, and astronauts, and to move them from one location to another.
- Grapple Tolerance
  - White dot in white circle
  - White line level within 5 deg
  - Inner green lines on edge of large gray circle
  - Crosshairs centered in circle

- Stages
  - 1: Fly-to
    EXTERNAL COMMAND FRAME
    End-effector goal is 2m above the target.
  - 2: Align
    INTERNAL COMMAND FRAME
    End-effector goal is 1.5m above and perpendicular to the target.
  - 3: Grapple
    INTERNAL COMMAND FRAME
    VERNIER RATE
    Enter grapple envelope, just touching the grapple pin, and pull the trigger.

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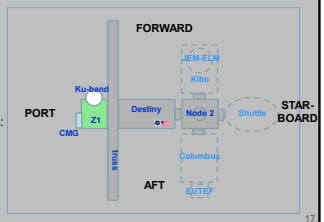
Helpful Hints

- The grapple fixture will have a consistent appearance.
- The following schematic may be useful to help determine final placements:



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Review of Important Concepts

- Command Frames
  - Use the internal frame for final alignment and grappling. ('**i**')
  - Use the external frame for large arm motions. ('**e**')
- Rate of Motion
  - Apply vernier rate during the grapple stage and for fine alignment, as well as when operating within 1.5m of structure or payloads. ('**v**')
- Cameras
  - Maintain big picture, task, and clearance views by changing the monitors as instructed on the scenario sheets. ('**F1**', '**F2**', '**F3**')
- Task Procedure
  - Refer to scenario sheets for:
    1. *Task Description*
    2. *Final Placement*
    3. *Cameras*

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The Start

- Scenarios will load with the proper camera views selected for you:

Clearance | Task | Big Picture

- The brake will be engaged.
- The arm will be in position as of having just finished a fly-to, roughly perpendicular and approximately 2m from the grapple fixture on the HTV.
- The initial command frame will be internal.
- The initial rate will be vernier.

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The Procedure

- You will have 90 seconds in which to grapple the HTV.
- Using the techniques that you learned for fly-to and grapple, coordinate translation and rotation such that you maintain proper alignment over the grapple fixture as you approach.

- When in the grapple envelope, pull the trigger to latch onto the HTV.

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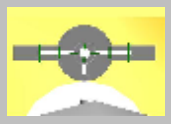
The Grapple Envelope

- You are in the grapple envelope when the following conditions are met:



  - The white dot is in the white circle.
  - The long white line is within 5 degrees of level.
  - The inner green lines are just inside the edge of the large gray circle.
  - The crosshairs are centered in the gray circle.

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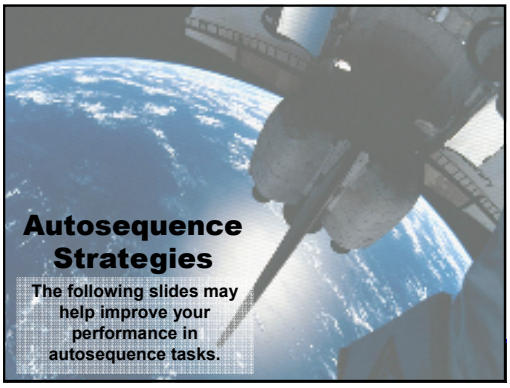

Autosequence Procedure

- Type 'A' (Shift+'a') to bring up the autosequence menu. Click on the menu to access the input fields.

SELECTION

- Select FOR or Joint Angle mode as instructed on the procedure sheet.
- Select the correct option if in FOR mode or input the destination angles as written on the procedure sheet.

VERIFICATION

- Compare the selected option or numbers on the screen with those on the printout to make sure they match, and then click 'Load'.
- Click 'Yes' if you have entered the information correctly. If the Ground Control Center notices any errors, you will be notified and prompted to correct them. If there are no errors, click 'Ok' to continue.
- Once you and the Ground agree on the inputs, click on 'Confirm'.

MONTIORING

- Monitor the movement of the arm for any clearance violations.
- If the arm gets within **1.5 meters** of any structure, press 'b' to turn on the brake and stop the arm. Follow directions from the ground to continue.

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Review of Important Concepts

- Objective
  - Autosequence movements are used to move the arm across long distances to prevent physical fatigue for the operator.
- Modes
  - **FOR**: Select a pre-recorded file.
  - **Joint Angle**: Input the destination angles of each joint individually.
- Steps
  - Step 1: Selection
    - Choose the mode, then select the file or input the destination.
  - Step 2: Verification
    - Check your inputs on your own, then verify with the Ground Control Center.
  - Step 3: Monitoring
    - Watch for any clearance violations while the arm is moving. Press 'b' to stop the arm.

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12.4. Experiment Task Sheets

Complete 12 Track-and-Capture Tasks before proceeding.

Grapple Scenario

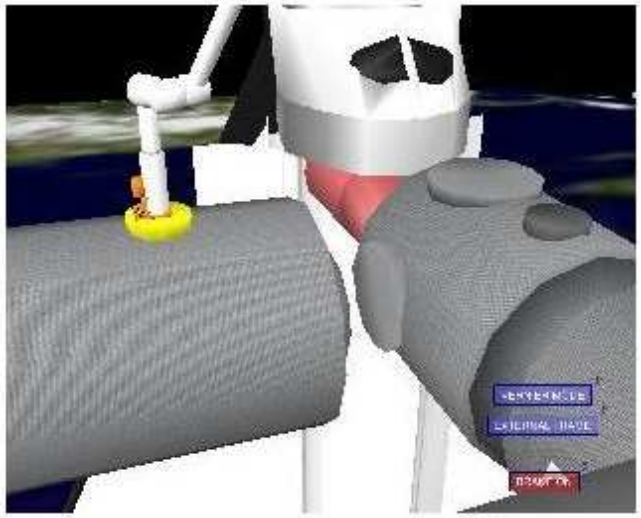
Task description:

Fly-to and grapple the Kibo module, which starts on the port-side position, forward of the Shuttle. After grappling the module, move it to 1 meter from the forward berthing position on Node (within 2 meters and 10 degrees of the illustrated final placement).

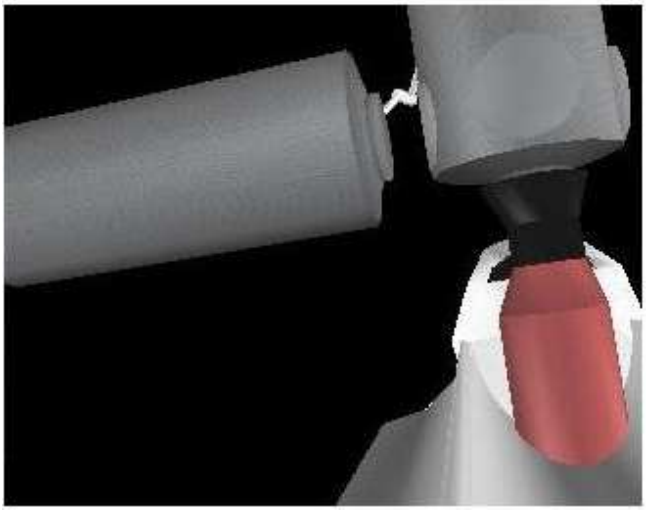
Camera views to use:

	Monitor #1	**Monitor #2**	**Monitor #3**
Initial cameras; fly-to to pre-grapple position	Cam “4”	Cam “1”	Cam “5”
During align and grapple	Cam “0”	Cam “9”	
After grapple, move to Node 2 berth	Cam “4”	Cam “27”	

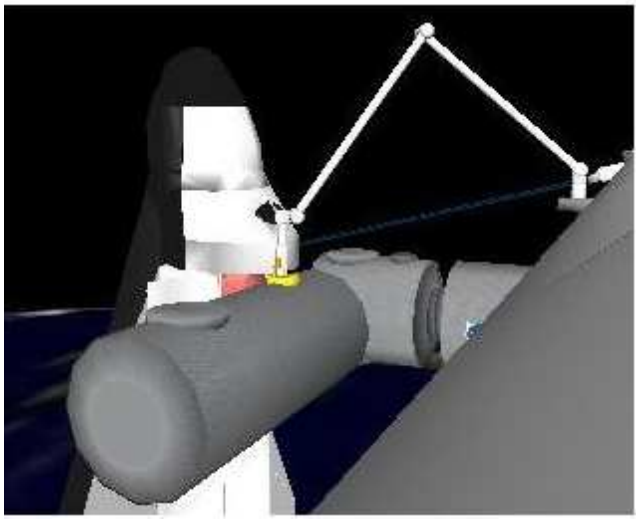
Final placement:



Monitor 1



Monitor 2



Monitor 3

Autosequence Scenario

Task description:

Move from the end position of berthing the Kibo module to the starting position for flying-to and grappling the JEM-ELM module by way of inspecting the truss. Monitor the arm's movement for any clearance violations, and stop the arm if necessary.

Command mode:

Joint Angle

Joint Angles:

Shoulder Yaw	80.2
Shoulder Pitch	18.2
Elbow Pitch	-57.9
Wrist Pitch	-50.6
Wrist Yaw	85.9
Wrist Roll	99.4

Camera views to use:

	Monitor #1	**Monitor #2**	**Monitor #3**
Initial cameras	Cam "4"	Cam "0"	Cam "8"
Immediately after start		Cam "13"	
When arm goes off top right of left monitor	Cam "25"		

Grapple Scenario

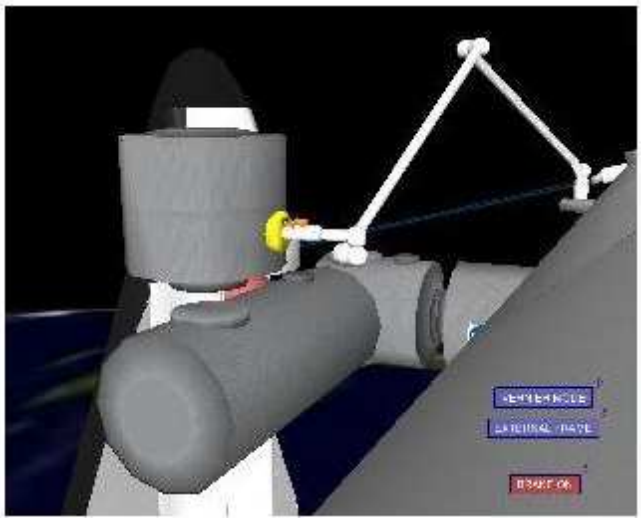
Task description:

Fly-to and grapple the JEM-ELM module, which starts on the starboard-side position, aft of the Shuttle. After grappling the module, move it over the Destiny module to 1 meter from the berthing position over the forward-zenith hatch of Kibo (within 2 meters and 10 degrees of the illustrated final placement).

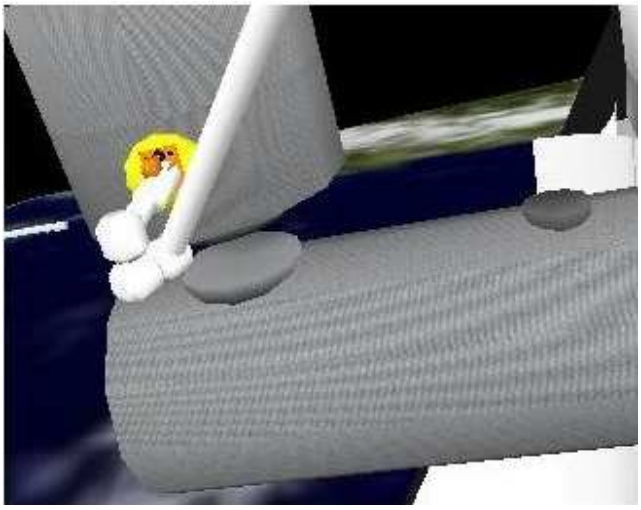
Camera views to use:

	Monitor #1	Monitor #2	Monitor #3
Initial cameras; fly-to to pre-grapple position	Cam “6”	Cam “7”	Cam “8”
During grapple	Cam “0”		
After grapple, move to Kibo	Cam “5”	Cam “28”	
Over Kibo		Cam “12”	

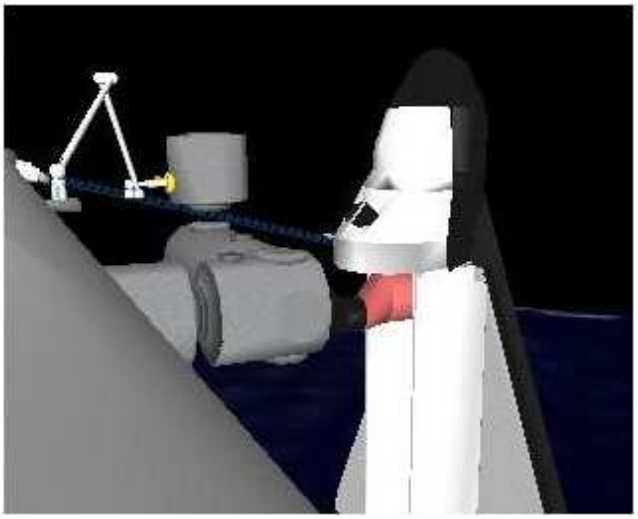
Final placement:



Monitor 1



Monitor 2



Monitor 3

Autosequence Scenario

Task description:

Fly over to the truss, then go below to inspect for damage. Monitor the arm's movement for any clearance violations, and stop the arm if necessary.

Command mode:

FOR

Option:

Option 1

Camera views to use:

	Monitor #1	Monitor #2	Monitor #3
Initial cameras	Cam "8"	Cam "11"	Cam "12"
When end effector goes off the upper right of the right monitor			Cam "25"
When the end effector goes behind the truss on the left monitor	Cam "26"		

Complete 12 Track-and-Capture Tasks before proceeding.

Grapple Scenario

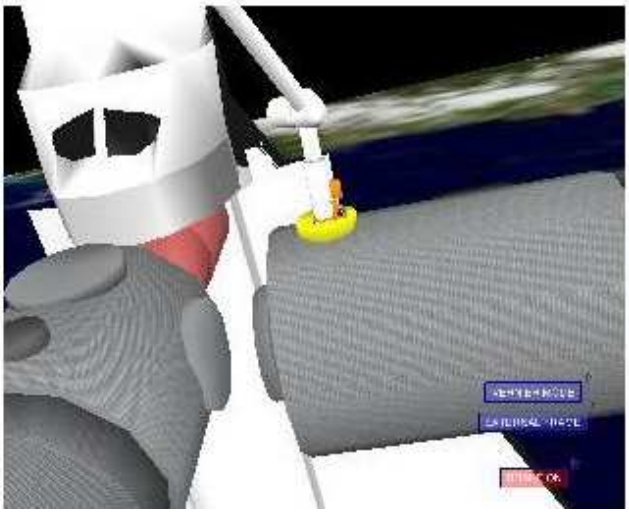
Task description:

Fly-to and grapple the Columbus module, which starts on the starboard-side position, aft of the Shuttle. After grappling the module, move it to the aft berthing position on Node2 (within 2 meters and 10 degrees of the illustrated final placement).

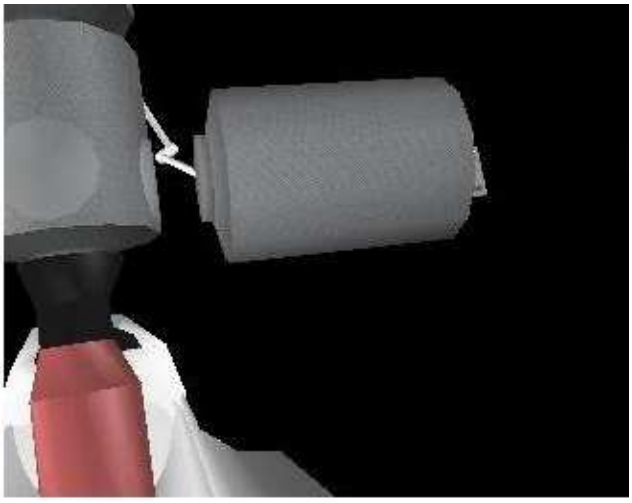
Camera views to use:

	Monitor #1	Monitor #2	Monitor #3
Initial cameras; fly-to to pre-grapple position	Cam “6”	Cam “1”	Cam “8”
During align and grapple	Cam “0”	Cam “7”	
After grapple, move to Node2 berth	Cam “29”	Cam “28”	

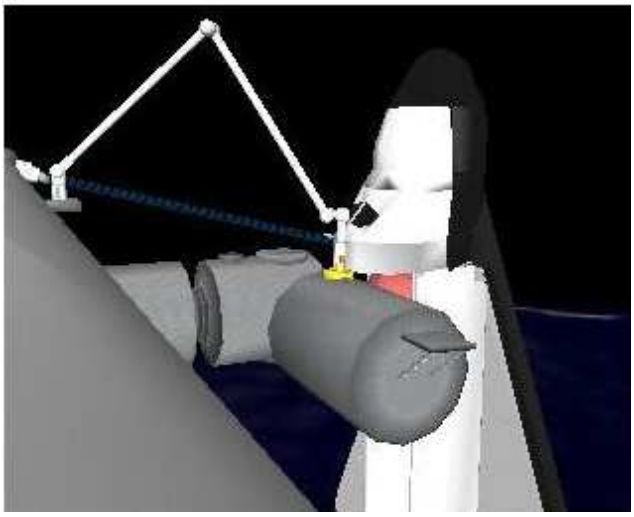
Final placement:



Monitor 1



Monitor 2



Monitor 3

Autosequence Scenario

Task description:

Move from the berthed Columbus module towards the EuTEF pallet. Monitor the arm's movement for any clearance violations, and stop the arm if necessary.

Command mode:

FOR

Option:

Option 2

Camera views to use:

	Monitor #1	Monitor #2	Monitor #3
Initial cameras	Cam "13"	Cam "4"	Cam "8"
When the end effector goes off the top off the center monitor		Cam "20"	

Grapple Scenario

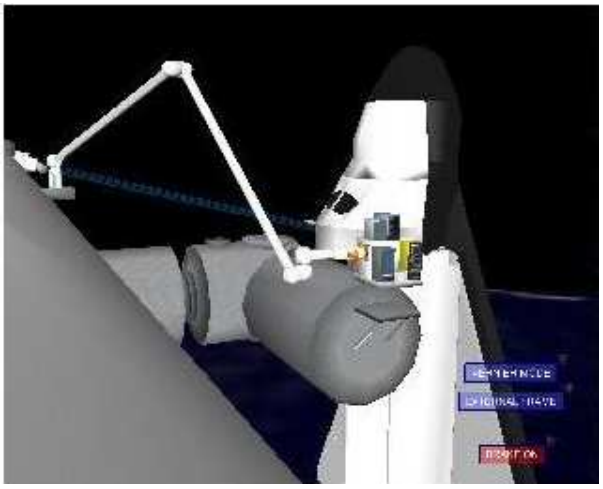
Task description:

Fly-to and grapple the EuTEF pallet, which starts on the port-side position, forward of the Shuttle. After grappling the pallet, move it over the Destiny module to 1 meter above the platform at the aft end of Columbus (within 2 meters and 10 degrees of the illustrated final placement).

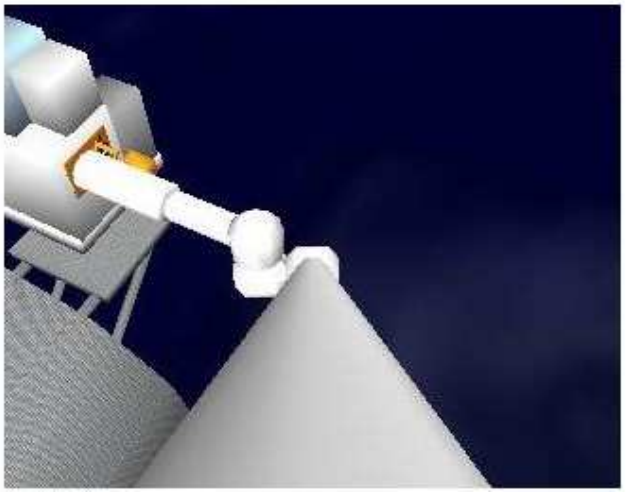
Camera views to use:

	Monitor #1	Monitor #2	Monitor #3
Initial cameras; fly-to to pre-grapple position	Cam “4”	Cam “1”	Cam “5”
During grapple	Cam “0”	Cam “9”	
After grapple, move over Destiny	Cam “4”	Cam “27”	
During move over Columbus	Cam “8”	Cam “28”	
Near berth		Cam “1”	Cam “14”

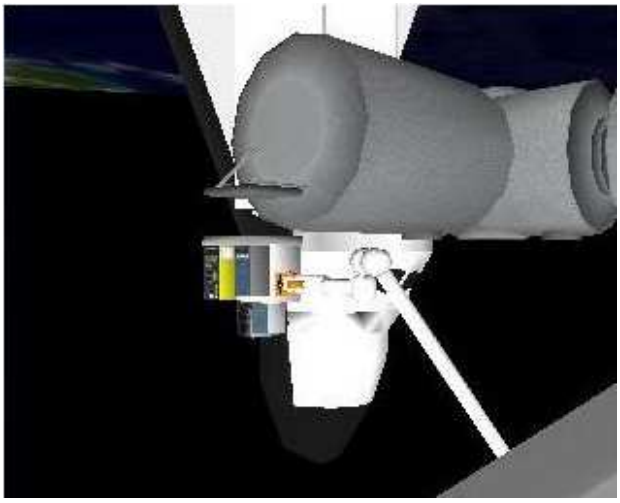
Final placement:



Monitor 1



Monitor 2



Monitor 3

Autosequence Scenario

Task description:

Inspect the EuTEF and its installation point from different angles. Monitor the arm's movement for any clearance violations, and stop the arm if necessary.

Command mode:

Joint Angle

Joint Angles:

Shoulder Yaw	32.5
Shoulder Pitch	7.3
Elbow Pitch	-47.3
Wrist Pitch	13.4
Wrist Yaw	153.8
Wrist Roll	22.5

Camera views to use:

	Monitor #1	**Monitor #2**	**Monitor #3**
Initial cameras	Cam "8"	Cam "6"	Cam "14"
When end effector becomes hidden by object (EuTEF pallet) in right monitor			Cam "1"

Complete 12 Track-and-Capture Tasks before proceeding.

Grapple Scenario

Task description:

Fly-to and grapple the footrest with the astronaut, which starts on the starboard-side position, forward of the Shuttle. After grappling, move the astronaut over the truss to the port side of the Z1 truss, above and port of the CMG (within 2 meters and 10 degrees of the illustrated final placement).

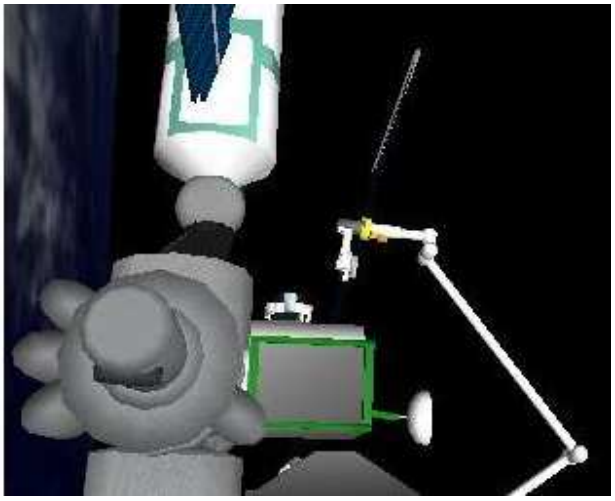
Camera views to use:

	Monitor #1	Monitor #2	Monitor #3
Initial cameras; fly-to	Cam “4”	Cam “1”	Cam “5”
Near pre-grapple position	Cam “0”	Cam “9”	
After grapple	Cam “15”	Cam “27”	
During move		Cam “16”	Cam “30”

Final placement:

Monitor 1

Monitor 2



Monitor 3

Autosequence Scenario

Task description:

Move from the zenith of the CMG towards the Shuttle. Monitor the arm's movement for any clearance violations, and stop the arm if necessary.

Command mode:

Joint Angle

Joint Angles:

Shoulder Yaw	-35.7
Shoulder Pitch	22.6
Elbow Pitch	-115.0
Wrist Pitch	65.0
Wrist Yaw	41.2
Wrist Roll	13.1

Camera views to use:

	Monitor #1	**Monitor #2**	**Monitor #3**
Initial cameras	Cam "15"	Cam "16"	Cam "17"
When end effector passes in front of white dish			Cam "42"
When end effector begins to become hidden by truss	Cam "43"		
When majority of arm goes off left of center monitor		Cam "44"	

Grapple Scenario

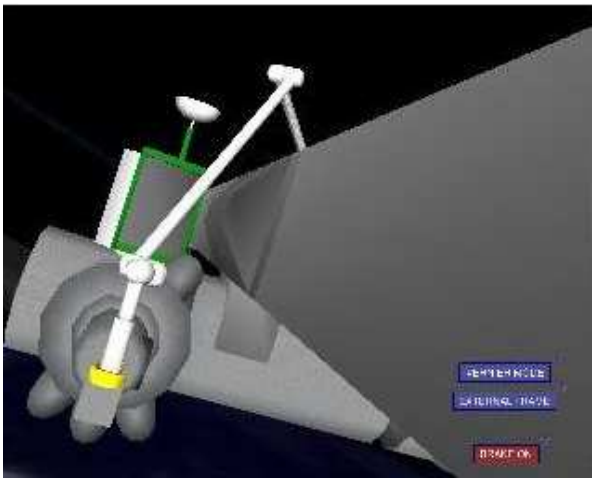
Task description:

Fly-to and grapple the footrest with the astronaut, which starts on the starboard-side position, forward of the Shuttle. After grappling, move it over the Destiny module and truss to the port side of the main truss near the airlock aft of the Z1 truss (within 2 meters and 10 degrees of the illustrated final placement).

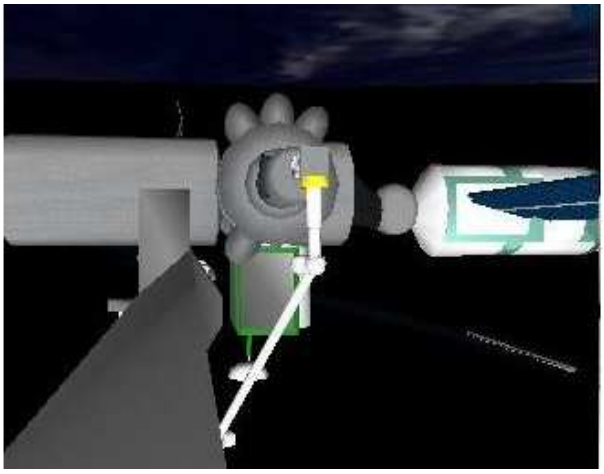
Camera views to use:

	Monitor #1	Monitor #2	Monitor #3
Initial cameras	Cam “4”	Cam “1”	Cam “5”
To pre-grapple position	Cam “0”	Cam “9”	
After grapple, over Destiny	Cam “4”	Cam “27”	Cam “8”
During move	Cam “31”	Cam “33”	
Near berth	“Cam 34”	Cam “32”	Cam “35”

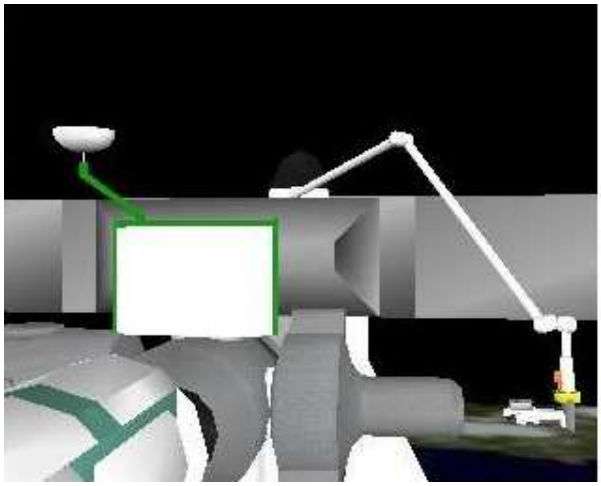
Final placement:



Monitor 1



Monitor 2



Monitor 3

Autosequence Scenario

Task description:

Move over to the habitation modules of the ISS and inspect them to ensure their health and safety. Monitor the arm's movement for any clearance violations, and stop the arm if necessary.

Command mode:

FOR

Option:

Option 3

Camera views to use:

	Monitor #1	Monitor #2	Monitor #3
Initial cameras (Stay the same throughout)	Cam "18"	Cam "11"	Cam "19"

Complete 12 Track-and-Capture Tasks before proceeding.

Grapple Scenario

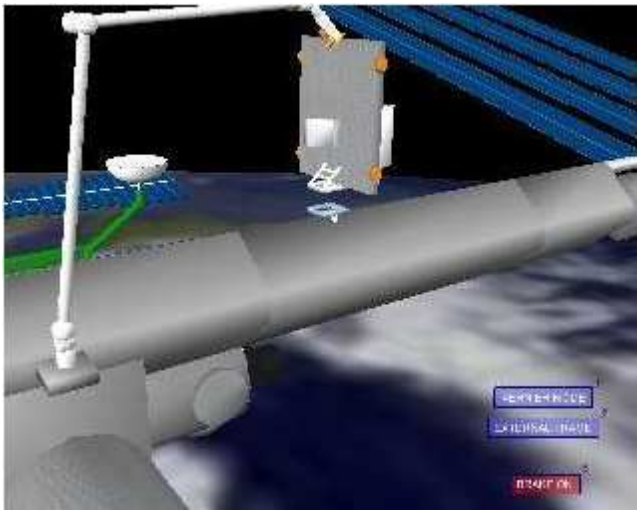
Task description:

Fly to the ExPRESS Logistics Carrier (ELC) at the starboard-side position, forward of the Shuttle. After grappling the payload, move it to a position just above the ELC platform on the upper part of P1 (within 2 meters and 10 degrees of the illustrated final placement).

Camera views to use:

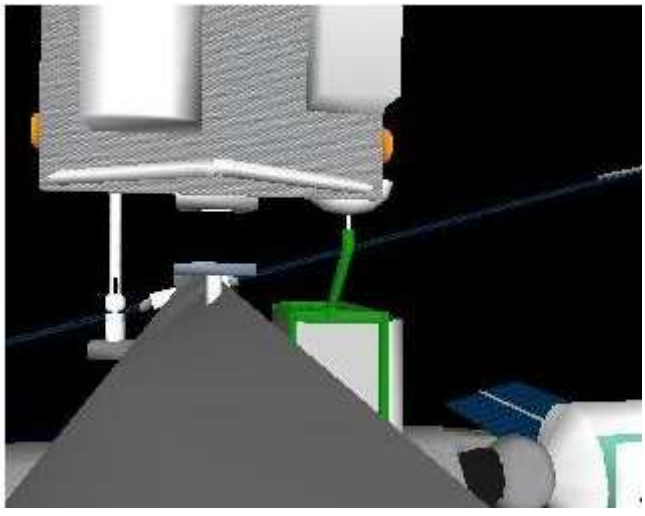
	Monitor #1	Monitor #2	Monitor #3
Initial cameras; fly-to to pre-grapple position	Cam "9"	Cam "4"	Cam "36"
During grapple		Cam "0"	
After grapple	Cam "37"	Cam "38"	
Near platform			Cam "16"

Final placement:



Monitor 1

Monitor 2



Monitor 3

Autosequence Scenario

Task description:

Move from installing the ELC on P1 to the next ELC to be installed. Monitor the arm's movement for any clearance violations, and stop the arm if necessary.

Command mode:

FOR

Option:

Option 4

Camera views to use:

	Monitor #1	Monitor #2	Monitor #3
Initial cameras	Cam "20"	Cam "21"	Cam "22"
When end effector approaches habitation modules		Cam "13"	
When end effector is clear of the habitation modules			Cam "14"

Grapple Scenario

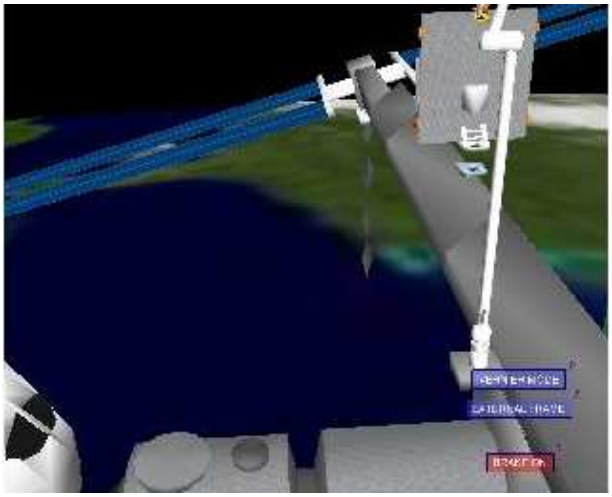
Task description:

Fly to the ExPRESS Logistics Carrier (ELC) at the starboard start position, aft of the Shuttle. Grapple the payload, and then move to a position just above the ELC platform on the upper part of S1 (within 2 meters and 10 degrees of the illustrated final placement).

Camera views to use:

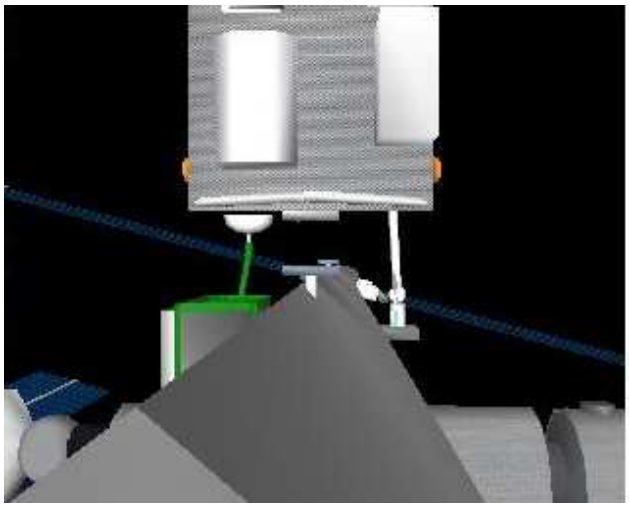
	Monitor #1	Monitor #2	Monitor #3
Initial cameras; fly-to to pre-grapple position	Cam “7”	Cam “6”	Cam “8”
During grapple		Cam “0”	
After grapple	Cam “39”	Cam “40”	
During move			Cam “41”

Final placement:



Monitor 1

Monitor 2



Monitor 3

Autosequence Scenario

Task description:

Inspect the base of the second ELC on S1 to ensure that it was installed correctly. Monitor the arm's movement for any clearance violations, and stop the arm if necessary.

Command mode:

Joint Angle

Joint Angles:

Shoulder Yaw	78.0
Shoulder Pitch	45.9
Elbow Pitch	-83.2
Wrist Pitch	-141.2
Wrist Yaw	173.5
Wrist Roll	-2.4

Camera views to use:

	Monitor #1	**Monitor #2**	**Monitor #3**
Initial cameras	Cam "23"	Cam "16"	Cam "17"
When end effector becomes hidden behind large square object (ELC)			Cam "45"

12.5. Karolinska Sleepiness Scale

Please indicate your sleepiness during the 5 minutes before this rating by checking the box next to the appropriate number. Use also the intermediate steps!

☐ 1 –very alert

☐ 2 –

☐ 3 – alert – normal level

☐ 4 –

☐ 5 – neither alert nor sleepy

☐ 6 –

☐ 7 – sleepy – but no effort to keep awake

☐ 8 –

☐ 9 – very sleepy, great effort to keep awake, fighting sleep

12.6. Additional test descriptions

Category	Test	Test Length	Metric	Data Type	Description	Data Collection	
						During Robotics	Outside Robotics
Cognitive	NLT: Number Letter Test	6 min	Inv response time	continuous	Inverse of average response time	Hourly, 1 per block	None
			Percentage Incorrect	discrete	% of incorrect responses	Hourly, 1 per block	None
	DSST: Digit Symbol Substitution Test	2 min	Correct Responses	discrete	Number of correct responses	Hourly, 1 per block	Every 2 hours
			Attempts	discrete	Number of attempts	Hourly, 1 per block	Every 2 hours
	PVT: 10 min Psychomotor Vigilance Test	10 min	Inv response time	continuous	Inverse mean response time	Hourly, 1 per block	Every 2 hours
			Lapse Percentage	discrete	% response times > 500 ms	Hourly, 1 per block	Every 2 hours
			Fastest 10% RT	continuous	Mean fastest 10% response times	Hourly, 1 per block	Every 2 hours
			Slowest 10% RT	continuous	Mean slowest 10% response times	Hourly, 1 per block	Every 2 hours
	EEG		Sleep Staging	continuous	Stage 1-4 for NonREM, or REM	Continuously, 30 sec epoch	Continuously, 30 sec epoch *
			Eye movement detection	continuous	% slow eye movements	Continuously, 20 sec epoch	Continuously, 20 sec epoch *
	EEG		Microsleep Episodes	continuous	Length, # of microsleep episodes	Continuously, 20 sec epoch	Continuously, 20 sec epoch *

Category	Test	Test Length	Metric	Data Type	Description	Data Collection	
						During Robotics	Outside Robotics
Sleepiness/ Drowsiness	KSS: Karolinska Sleepiness Scale	1 min	KSS Sleepiness score	ordinal	Subject rated level of sleepiness with the scale as reference	Hourly, 1 per block	Hourly
	KDT: Karolinska Drowsiness Test	3 min	KDT score: EEG Power Density	continuous	Power density changes in EEG activity under each condition of test relative to subject's baseline	Hourly, 1 per block	Every 2 hours
	VAS: Visual Analogue Scale	1 min	VAS Appetite Score	ordinal	Subject ratings on VAS	none	Every 2 hours
			VAS mood score	ordinal	Subject ratings on VAS	none	Every 2 hours
			VAS hunger score	ordinal	Subject ratings on VAS	none	Every 2 hours
			VAS alert score	ordinal	Subject ratings on VAS	Hourly, 1 per block	Every 2 hours
	Opt Alert		OA Drowsiness Score	ordinal	John's Drowsiness score: Software derived score on scale of 1-10 (low-high)	Continuously, 1 min epoch	None
Circadian Phase	Blood		Melatonin/ Cortisol	discrete	Melatonin/ Cortisol levels	None	Hourly during dim lighting periods in WP 1, 5, 9, and 13.
	Urine		6-sulfatoxymelatonin	discrete	aMT6s, the urinary metabolite of melatonin	Every 2 hours	Every 2 hours
	Saliva		Melatonin	discrete	Melatonin measure as back up for any problem with plasma collection	None	Hourly during dim lighting periods in WP 1, 5, 9, and 13.

* EEG electrodes are not on continuously outside of robotics. There are scheduled breaks.