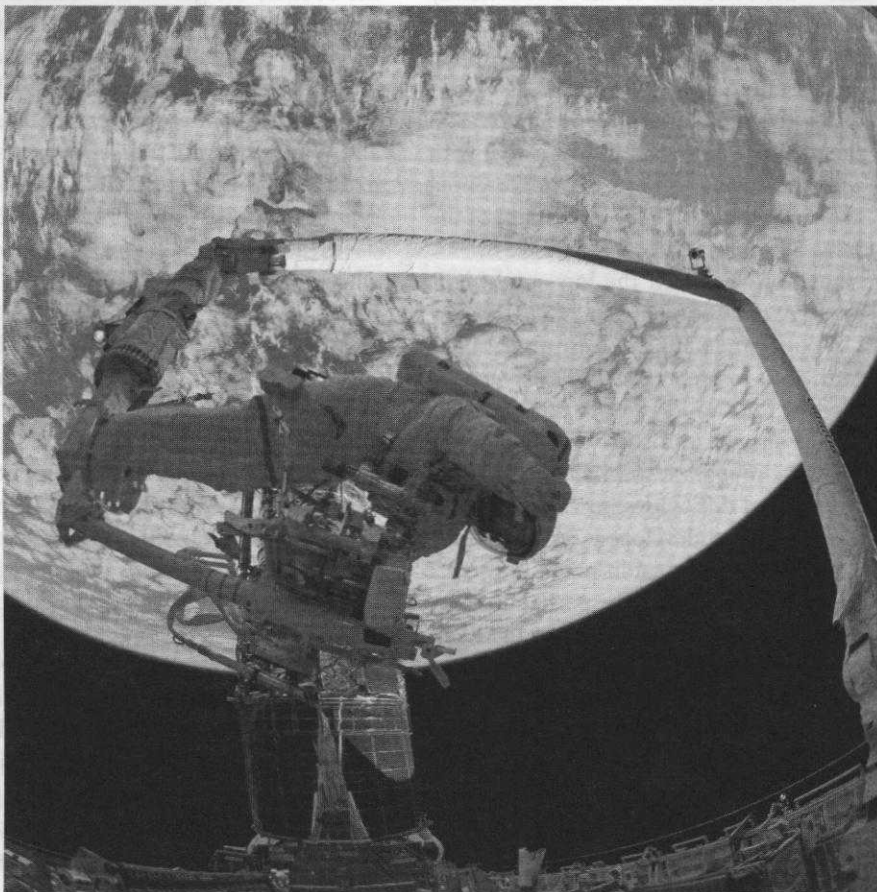# HUMAN PERFORMANCE IN SPACE

Shuttle astronaut controlling the remote manipulator system during a Hubble Space Telescope servicing mission. Photo courtesy of NASA.

Cognitive task analysis of the complex skills involved in robotic arm maneuvering will help to ensure safer and more effective spaceflight operations.

BY M. EPHIMIA MORPHEW, DANIELLE V. BALMER, & GEORGE J. KHOURY

So, you think you've had a bad day? Try this one on for size: You're floating 250 miles above Earth's surface in the Space Shuttle Orbiter, traveling at 17,500 miles per hour toward a free-flying satellite in orbit. The shuttle commander has just maneuvered the orbiter within reaching distance of the orbiting satellite. You have less than one minute to capture the satellite. The continually changing lighting conditions from the 90-minute orbital period are casting shadows on your camera views of the payload bay and robotic arm, making distance estimation in and around the payload bay and arm challenging. If you miss the capture, you've just wasted a lot of taxpayer money and decreased the U.S. National Aeronautics and Space Administration's margin of safety

(in the extremes, causing loss of the mission to the tune of millions of dollars or, worse, loss of life). At the very least, you've increased fuel consumption by having to remaneuver the orbiter into the satellite capture position. Oh, and everybody is watching – everybody.

HUMANKIND IS UNDERTAKING THE MOST CHALLENGING and complex construction project in history with the assembly of the International Space Station (ISS). Before completion, more than 100 components will be pieced together more than 400 km (250 miles) above Earth. To accomplish this, crews will perform roughly 160 space walks, or extravehicular activities (EVAs) – more than all previous manned missions combined.

Fortunately, the international crews will have the help of two large robotic arms, called remote manipulator systems (RMSs). These devices can grapple station pieces and hold them in place, reach to the shuttle payload bay, hand to station arm, move supplies, and ferry crew members to hard-to-reach places.

As in most space operations, constant attention to safety must govern all aspects of ISS assembly. Accordingly, safe EVA and RMS activities are a priority for NASA and its 15 international partners. A first step in this process is to understand the cognitive demands associated with performing critical on-orbit tasks, such as operating the robotic arm or conducting EVAs.

Experience from the Phase 1 program, in which seven American astronauts took turns living and working aboard the Russian space station *Mir* between 1995 and 1998, highlighted the need for a better understanding of the psychological and human factors issues affecting performance in spaceflight operations.

To address this need, we employed cognitive task analysis (CTA) methods to analyze the demands associated with operating the RMS. This task was chosen because we believe it to be among the most demanding tasks involving ISS assembly and operations. In addition to the enormous responsibility of handling multimillion-dollar satellites and ISS components, or crew members on the end of the arm, RMS operators often perform under significant time pressure, stress, and workload. CTA offered an ideal way to begin uncovering the cognitive and performance demands required by RMS operations, along with the most likely challenges to be experienced by expert operators. Furthermore, we hoped to illustrate the factors that negatively affect RMS operators.

APPLYING COGNITIVE TASK METHODS

The research described here was conducted as a pilot study to identify the cognitive and performance challenges associated with operating both the shuttle and station RMS. Our goal was to apply these findings to the eventual development of a self-assessment performance tool capable of determining crew member readiness to perform RMS operations. Using existing task documentation and conducting several subject matter expert interviews, we constructed an inventory of representative critical RMS-related tasks. These tasks included (a) grappling a fixed or free-flying object, (b) unberthing a payload, (c) maneuvering EVA astronauts at the end of the arm, (d) berthing a payload (especially critical when the interface between payload and pallet structure cannot be seen), (e) handing off between two manipulators, and (f) recovering a tumbling satellite or payload.

In selecting these tasks, and in later analysis, both traditional interview and CTA techniques were used to identify the human performance demands associated with operating the RMS. Before presenting our results, we first briefly describe CTA.

CTA offered an ideal way to begin uncovering the cognitive and performance demands required by remote manipulator system operations.

Cognitive task analysis is a knowledge elicitation and representation method derived from the domains of instructional and cognitive psychology that is designed to identify the cognitive elements of expertise associated with operating in dynamic, complex, high-information environments. CTA has been successfully used in numerous operational domains, including firefighting, piloting, neonatal intensive care nursing, military command and control, air traffic control, emergency medicine, air weapons commanding, and numerous other domains that are characterized by complexity, high information load, automation, time pressure, uncertainty, risk, and continually changing information.

The ability of operators in these and similar domains to make rapid, precise assessments of a system and/or environment's status comes largely from their experience and acquired expertise with the task. However, the nature of this expertise is usually difficult for the expert to articulate. It involves skills that are so well learned and familiar that the expert often may not be aware of using them in the course of performing a task (Crandall & Getchell-Reiter, 1993). CTA focuses on making expert knowledge explicit and can provide information on expertise that is typically difficult to capture by other knowledge elicitation methods (Crandall & Getchell-Reiter, 1993; Waterman, 1986). To learn more about CTA methodology, see Militello and Hutton (1998) and Hoffman, Crandall, and Shadbolt (1998).

A mission specialist perches on the end effector of the RMS trying to grapple the inoperative Intelsat VI satellite (1992). Photo courtesy of NASA

For this pilot study, we sought to identify the demands associated with information processing, decision making, problem solving, cognitive workload, judgment, situation assessment, short- and long-term memory, and attentional focusing involving RMS operations. The preliminary CTA also allowed us to begin eliciting the perceptual discriminations, critical cues/visual indicators, and levels of operator expertise associated with the task. The particularly demanding aspects of the task were also revealed. In general, the preliminary CTA data collection served to

- provide a preliminary analysis of the cognitive and performance demands associated with performing the RMS task;
- identify the cognitive abilities most required by the RMS task and therefore provide input to the development of a performance battery that is most sensitive to, and appropriate for, assessing the crew member's mental and cognitive operational task readiness; and
- identify factors that can mediate performance on the RMS task.

CTA methods were employed during interviews with recognized subject matter experts, who included five RMS trainers and a veteran shuttle astronaut with significant on-orbit RMS experience. Each RMS trainer had several years of experience in training crew members on RMS operations.
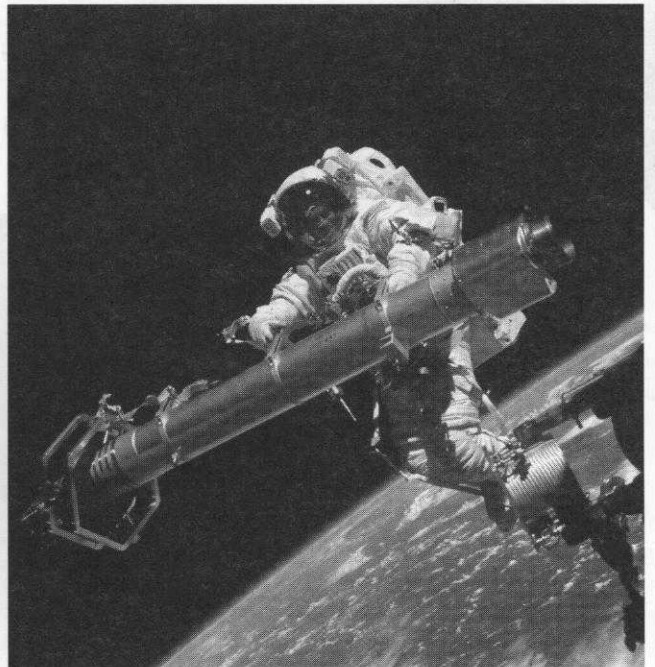
To understand the demands associated with the tasks of operating the RMS, we performed both categories of task

A mission specialist handles the newly delivered main boom of the Russian crane (Strela) to be connected to its operator post (May 2000). Photo courtesy of NASA.

EXAMPLE OF A TASK DIAGRAM

Task: Capture of Free-Flying Payload

1. Set up software.
2. Maneuver arm to precapture position.
3. Commander maneuvers Shuttle to intercept payload.
4. Decide if payload is at precapture position.
5. Set up camera to view interface between arm and payload.
6. Look at TV monitor to view grapple fixture and window view.
7. **Move end effector to grapple position and issue command to grapple.***
8. Monitor payload as it is snared and pulled into the grapple fixture.

Highest task complexity, therefore focus of knowledge audit portion of CTA.

analysis (traditional and cognitive). Details of the structures for each of these can be found in the preliminary project report (Khoury, Morphew, & Balmer, 1999). The CTA was oriented toward identifying the cognitive and mental demands associated with the task, and the task analysis consisted of an inventory of the written procedures and guidelines associated with critical RMS tasks.

Our applied CTA required both an *interview* and a *data analysis* portion. The interview portion involved guiding the subject matter expert through the creation of a task diagram. A task diagram (see left) provides a broad overview of the subtasks associated with the critical task under examination and identifies which parts of the job or task require complex cognitive skills. To complete the task diagram, the expert is asked to list the high-level steps required to perform the task (e.g., "Think about what you do when you're capturing a free-flying payload . . . can you break this task down into between five and eight high-level steps?").

Once these steps are identified on paper, the expert is asked to indicate which steps require the most complex/difficult thinking skills, judgments, problem-solving, and decision-making capabilities. These complex steps are then brought forward through the next step of the interview process, called the *knowledge audit*, which focuses on assisting the subject matter expert in articulating the specific cognitive demands of the challenging subtask. Examples of such questions include the following:

"What types of situation assessments do you have to make when determining whether the payload is in the correct position?"

"What are the critical cues or strategies that you use to make these assessments?"

"What are potential errors that an operator would be likely to make during this step of the task?"

"In what ways would this be difficult for a novice or poorly trained operator?"

The final step in the CTA is to analyze, structure, and represent the data gained in the interviews and observations. The data are catalogued and classified into important categories of information, and key decision-making requirements and cognitive demands are described along with major themes. The outcome is an understanding of the key elements of RMS operator expertise and the cognitive strategies and skills employed by operators.

Although CTA methods have typically been used to understand cognition/decision making, in this study, we expanded the application of CTA to include data collection on the physical, biomechanical, technology-interface, and psychomotor challenges associated with the task.

Preliminary efforts to identify the explicit human performance and cognitive demands associated with operating the robotic arm revealed important data regarding both the task and the expertise required by the operator. We found that the RMS task relies heavily on two primary categories of human performance: psychomotor functioning and cognitive functioning (Khoury et al., 1999). Other major performance factors that were found to be challenging in the RMS task included psychomotor control, situation awareness, mental rotation and spatialization, distance and depth estimation, shifting and focusing of attention, and assimilating and interpreting cues and information.

Data analysis results were summarized and classified into the following four categories: (a) determining critical performance demands; (b) extracting their associated cognitive requirements; (c) determining the most typical challenges for the operators; and (d) identifying the cognitive factors leading to these challenges. These are listed in Tables 1(below) and 2 (see page 10) and discussed in the following sections.

IDENTIFYING CRITICAL PERFORMANCE DEMANDS

The first column in Table 1 lists the most critical and challenging human performance demands required to successfully operate the RMS. The second column lists the cognitive requirements necessary for meeting the performance demands.

We expanded the application of CTA to include data collection on the physical, biomechanical, technology-interface, and psychomotor challenges associated with the task.

The most critical aspect of the RMS task was (not surprisingly) the psychomotor component of the task. The task is highly cognitive in nature and requires the processing of dynamic environmental information and translation of that information from multiple sources into motor control inputs. In particular, crew members must notice, assimilate, and interpret a broad array of environmental cues and information (such as multiple camera views, observer comments, and digital distance data), make any necessary transformations of the information, and translate those cues and information into goal-oriented actions.

TABLE 1: CRITICAL PERFORMANCE DEMANDS OF RMS OPERATIONS AND ASSOCIATED COGNITIVE REQUIREMENTS

Critical Performance Demands	Cognitive Requirements
Psychomotor control	Psychomotor, information processing
Situation awareness	Perception, information processing, long-term memory, attention allocation, projection (of future status)
Mental rotation (spatialization)	Working memory, information processing
Distance estimation/depth perception	Visiospatial
Shifting/focusing of attention	Attention allocation
Assimilate/interpret cues/info	Information processing, long-term memory

TABLE 2: SPECIAL CHALLENGES ON THE RMS TASK AND ASSOCIATED COGNITIVE FACTORS

Most Typical Challenges	Cognitive Factors
Hand controller inputs	Psychomotor
Translating environmental cues into hand controller inputs	Perception, memory (long-term and working), and psychomotor
Lack of situation awareness	Perception, information processing, attention
Mode difficulties	Memory, attentional focus
Omissions	Memory, attentional focus
Commissions	Memory, attentional focus
Incomplete processing of information	Perception and information processing

EXTRACTING CHALLENGING ASPECTS OF RMS OPERATIONS

The first column in Table 2 lists the most typical challenges for RMS operators. The second column lists the cognitive factors that lead to these challenges. Performance-mediating factors regarding both the cognitive demands and typical challenges associated with operating the arm include fatigue, stress, time pressure, anxiety, and mental and physical workload.

In addition to identifying the cognitive demands associated with operating the RMS, CTA methods aimed to identify countermeasures designed to support and enhance performance on the RMS task. The most challenging aspect of operating the RMS involves hand controller inputs (i.e., psychomotor). Environmental cues must be translated into hand controller inputs. This translation relies heavily on the operator's situation awareness of the cues and information in the environment and the interpretation of these cues.

Time pressure can lead to challenges, such as incomplete processing of information. Challenges can also lead to omissions (forgetting to do something; e.g., arming a switch), commissions (doing something but doing it incorrectly; e.g., arming the wrong switch), and mode difficulties (thinking the system is in one mode of operation when it is really in another). Omission, commission, and mode difficulties can be exacerbated by lapses of memory or by operating in conditions that involve switching from multiple frames of reference.

FINDING PERFORMANCE-MEDIATING FACTORS

Several factors that were identified as having the ability to mediate performance on the RMS task include fatigue, time pressure, stress, and anxiety. Operators experience time pressure for a number of reasons, including orbital mechanics, limited sunlight intervals, risk to the orbiter and crew members' lives, and financial risk (e.g., through loss of payload capture, as mentioned earlier).

The data analysis also indicated that the sense of time pressure felt by the operators while conducting the critical parts of the task (e.g., grappling a free-flying payload) could lead to *attentional narrowing*. In attentional narrowing, a phenomenon documented in the scientific literature on stress and performance, humans under acute stress tend to experience a narrowing or focusing of their attention on

> Future efforts could involve applying the data derived from this study to the development of a test battery for assessing crew member readiness-to-perform RMS operations.

only the central part(s) of the task while ignoring more peripheral aspects (Berkum, 1964; Weltman, Smith, & Ergstrom, 1971). Under emergency conditions, this could both assist the crew member in focusing on the most critical aspect of the task and/or detract from his or her ability to maintain awareness of numerous critical factors in the environment. However, all crew members have been highly trained to anticipate numerous vehicle system failures, some of which would require the immediate response of jettisoning the arm, closing the payload bay doors, and/or preparing for deorbit. Crew training also serves to make crew members resistant to attentional narrowing.

APPLYING HUMAN FACTORS PRINCIPLES TO FUTURE OPERATIONS

The domain of aviation human factors has stressed the importance of the human element in ensuring the safety and performance of aviation personnel operating in complex, dynamic systems. With the on-orbit assembly of the ISS, the complexity and duration of spaceflight operations will pose a great challenge to the space human factors professionals tasked with supporting human operations. Flight safety and mission success depend on crew performance and spacecraft system performance, and accordingly, operation of the ISS will necessitate greater resource allocation devoted to the understanding, development, and application of effective performance, human factors, and psychologically oriented countermeasures (Morphew, 1999).

The goal of our study was to develop a preliminary understanding of the human performance demands associated with conducting particularly complex on-orbit tasks. Future efforts could involve applying the data derived from this study to the development of a test battery for assessing crew member readiness-to-perform RMS operations.

The potential development of such a readiness-to-perform tool is important, as it could be beneficial to crew members, trainers, flight surgeons and ground control personnel. Used in orbit, the tool could benefit flight surgeons and ground control personnel in anticipating performance decrements and challenges associated with task difficulty and conditions, as well as being a first step toward deriving countermeasures designed to support crew members during RMS operations. Findings could be applied to the training area in an effort to make training more efficient and effective. Data from this study could also be used to identify design considerations for future hardware, on-orbit tools, and human-technology interfaces.

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