Report of ESA Topical Team in Psychology

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HUMAN PERFORMANCE IN EXTENDED SPACE OPERATIONS

Contributors

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Abstract

The TT report covers topics related to the management of human performance in space environments, with an emphasis on applications to the problems of human crews on long-term missions. The topics are selected to emphasize the application of recently established methodologies and theoretical insights in performance research, and integrated through application of the operator functional state framework, outlined in the introductory chapter. Other chapters cover the separate but overlapping topics: environmental stress and fatigue, work demands, sleep and sleepiness, psychophysiological state, human-automation interaction, skill maintenance and teamwork. Each aims to summarize background issues, mainly based on Earth-based research, draw together relevant research findings from space environments, and suggest research needs and implications. A final chapter highlights broad themes and research directions that cut across chapter topics, and makes a number of specific recommendations for further research and development.

1 Introduction

1.1 Scope of the Topical Team

The goal for this Topical Team (TT) was to assess the current state of knowledge relating to the integrity of human performance in space missions, particularly involving long duration missions, such as the proposed Mars expedition. The review has a primary focus on problems associated with maintaining effective work and mission-skills in individual crewmembers. However, because many of the activities of space missions are necessarily crew based, it also addresses problems that are more effectively considered at the group level, including crew-level task activities and organizational issues. In addition, because of the inevitable effect of the social environment on performance, the work of the TT addressed relevant social psychological and interpersonal issues, though not problems specifically associated with psychological adjustment and mental health. (These will be dealt with as part of a separate TT: *Psychosocial and neurobehavioural aspects of human space flight*.)

1.2 Background

Psychological considerations have been included as an integral part of the space research programme from the earliest period of manned flight. The many important insights and applications concerning human psychological adjustment are comprehensively reviewed in the recent second edition of the reference textbook on space psychology by Kanas and Manzey (2008). Threats to human performance have always been to the fore in this endeavour, and a substantial body of knowledge has been built up over the past 30 years or so. However, the envisaged extension of human involvement in space exploration to very long missions with massively increased threat and sense of remoteness (such as the 30 months scenario for Mars expeditions) poses new problems on all levels. It seems unlikely that the knowledge gained from experience with Moon, ISS and the earlier LTPO simulation programme of isolation and confinement will be adequate to support space exploration of this kind; further, more focused research will clearly be necessary. As a precursor to this, the present report aims to provide a summary and evaluation of the current state of knowledge in the area of human performance: the aspects of psychology that relate to the effectiveness and competence with which operational tasks and activities are carried out during space missions.

Formal programmes of research on aspects of psychology in space-related activity, generally based on simulations of isolation and confinement or analogue environments such as Antarctica, have not always yielded the valuable results anticipated. In particular, work on human performance has had some notable successes, though has generally failed to reveal coherent principles that can be applied to extended missions. Part of the problem may be the absence of a consistent overarching methodological framework to guide the research programme. This may be particularly true for human performance, where the applied methodology of laboratory based cognitive tests may have only tangential relevance to the demands of actual missions.

There are a number of unavoidable obstacles to establishing a strong body of evidence. One is the serious constraint of having to design studies around the very small samples of participants typically available in simulator studies. Another is the impossibility of matching the physical and psychological threats of actual missions with even the most severe test conditions. However, the ESA simulation studies have been generally successful in capturing the essential elements of the habitat and psychosocial environment (isolation and confinement, long duration, small groups, limited communication with the outside world, and so on). They have also insisted on selecting participants who match the individual characteristics of successful candidates for astronaut training. One area where research has been less successful, however, is in the detail of the work environment used as the test bed for space-related stressors. The tasks used to test participants have not typically provided an effective simulation of the type and complexity of mental work that mission crews need to do. As the Kanas and Manzey (2008) review indicates, the widespread use of simple laboratory tasks to test the effects of space-like conditions has revealed few and generally small effects on performance. Research at the forefront of applied experimental psychology (for example, as published in journal such as *Human Factors* and *Journal of Experimental Psychology: Applied*) has made it clear that the application of experimental results to real world tasks is less successful when the task/simulation fails to capture the essential cognitive demands of the real work activities.

1.3 Operator Function State (OFS) as a Framework for Performance

The Operator Functional State (OFS) methodology is adopted in this report as a general framework for an integrative approach to research of human performance in space. It was the focus of a major 3-year NATO Human Factors and Medicine (HFM) task group, led by Glen Wilson and resulting in a major review of the field (NATO, 2002). It also gave rise to a successful NATO Advanced Research Workshop (ARW), directed by Bob Hockey, Tony Gaillard, and Oleksandr Burov (Hockey et al, 2003).

The OFS framework recognizes the need for a more integrative psychophysiological analysis of performance than has been the case in previous space research programmes. It is characterized by two major assumptions:

- that what we measure as human performance is the end-result of an adaptive response to the individual's attempt to manage specific imposed task demands under prevailing environmental conditions
- that human capabilities for mental work are always moderated by constraints imposed by the current state of the individual and the physical and mental costs of having to maintain task goals over a prolonged period of time (at the expense of other personal goals).

Interestingly, even under high levels of stress or extreme workload, highly motivated, well-trained operators (such as mission crewmembers) typically succeed in protecting their major task goals, for example by increasing the level of mental effort. Such behaviour is obviously adaptive, in minimizing threats to critical mission objectives, but also attracts costs. If this compensatory control process is sustained for long periods it leads to fatigue, and ultimately to a breakdown in skill. Because major goals are protected, it is not always possible to detect such threats by routine measurement, which is one reason why low fidelity task batteries often fail to detect underlying problems caused by environmental stressors. It has become clear that more subtle methods are usually needed, notably measuring the various costs of performance protection. These *latent decrements* (Hockey, 1997) include a reduced commitment to peripheral goals, leading to increased failures on subsidiary tasks, an increased tendency to make use of more risky strategies in decision making (short cuts), and increased physiological activation and subjective strain.

1.4 Goals and Strategy of the Review

The report is organized in relation to a number of specific topic areas. We have chosen not to consider the fundamental architecture of perception or cognition. Apart from low-level disturbances to visual-locomotor coordination under low gravity (see Kanas & Manzey, 2008), there is little evidence that any of the changes during extended space missions have any significance for operational integrity. Rather, we have concentrated on the effectiveness with which mental resources can be deployed in stressful environments to maintain high-level cognitive goals. The chapters are not meant to provide a comprehensive coverage of the field, but to identify what we believe to be the essential and distinctive research areas that future work needs to prioritize. In some cases, there is a degree of overlap in coverage, with chapters offering different perspectives on the same general set of questions. In others, they raise quite specific sets of questions that point to a need for more focused analysis.

1.4.1 Performance Issues addressed in the report

The main body of the report is organized in three sections:

- *Influences on operator functional state*
- *Specific performance Issues*
- *Conclusions and recommendations*

The central themes addressed in the chapters of the report are summarized below.

Stress states. Having to work under the impact of stressors is an inevitable part of space missions, though there is little evidence of major disruption in operational contexts. It is now clear, however, that the way in which stress states affect human performance depends both on their interpretation as potential threats and on active decisions about the importance of task goals. To assess these effectively, research needs to consider not only direct effects on performance but indirect costs of the adoption of task management strategies.

Work demands. The management of work demands is at the core of human performance problems in all industries. This means not only having too much to do but not having the right things to do, prioritization issues, or having to make efficient and timely transitions between workload levels. Although this is a highly developed research area, more needs to be known about how operators adjust to increased workload in terms of strategies for managing effort and task goals. The problem of mental fatigue is commonly associated with high workload, though it appears that high levels of controllability of task activities can prevent fatigue. Furthermore, the planning of long duration missions also raises the issue of under-stimulation. More work is needed on the boundary conditions for the workload-fatigue causality link, as well as the planning of work to minimize problems of transitions and maximize control.

Sleep. Sleep is a fundamental factor in effective work performance, which requires rest and recuperation from the demands of the day. We need to assess effects of disturbed sleep, sleep deprivation, changes in work/sleep schedules and patterns of adaptation to changed shift schedules. Fatigue from sleep deprivation is not the same as that from mental and physical work, and is resolved by sleep rather than rest or change of task. We need to improve our understanding of the relationships between different forms of fatigue; not only the impact of sleep disturbances, but also effects of both sustained mental and physical work.

Physiological state. Monitoring of physiological responses is necessary in order to assess the costs of maintaining performance (measured as phasic responses to imposed tasks) under stress and high workload, and its impact of strain on short-term reactivity. Furthermore, in the specific environment of space, physiological adaptation in itself is a highly demanding process, which can interfere with performance. Hence, there is a need to monitor long-term (tonic) effects on baseline processes such as metabolic activity, ANS function, EEG, neuromuscular tone, and other indicators of normal functioning.

Human-automation interaction. Research on the design of human-machine systems is fundamental to overall success of space missions, determining the nature of crew interactions with all technical and robotic systems. Greatly extended missions will assume increased crew autonomy and require continued sophistication and refinement of such systems. Much more still needs to be known about the design of collaborative control, decision support systems, etc, and the use of adaptive interfaces and augmented cognition to support crewmembers.

Skill maintenance. A major threat to operational effectiveness over long space missions is the problem of maintaining necessary levels of operational skills – made more difficult by high levels of automation and the infrequent need for many critical activities. More focused research is needed to determine the effectiveness of for training programmes for long-term skill deployment and the possibility of on-board support for skill maintenance.

Teamwork. Because of the core teamwork nature of crews it is important to examine performance not only of individuals but also of whole crews, where cognition is distributed rather than focused. Currently, little systematic work has been carried out in this area, particularly in relation to stressful and sustained operations. Team behaviour is not simply the average of the individuals involved, but has emergent properties of its own, depending for example on the degree of cooperation or interaction required. Research is needed on team cognition in relation to the design of crew-level tasks, and options for flexibility in the assignment of specialist function within crews.

1.4.2 Recommendations

The body of the report is used to make a small number of specific recommendations in Chapter 9. These address overarching themes that emerge from the detailed review of the literature, and are meant to provide an input to ESA for the planning of future psychology-related activity. In particular, they advise specific developments in technology, training and operational management of long-duration missions.

2 Environmental Stress and Fatigue

2.1 Introduction

A characteristic of all environments is that they make demands upon the stability of the individual's bodily processes. This is a normal and inevitable process, calling into play the homeostatic mechanisms that maintain critical body states within safe limits. These processes are also designed to provide the body with an emergency response to environmental stressors – extreme conditions that are recognised as threatening major goals, such as survival and protection of young – initiating a 'fight or flight' reaction via intense sympathetic activation (Selye, 1956). From a modern human perspective, such potential consequences are rare, yet the stress response still occurs. We perceive threats everywhere but, outside of war (and sport), we have no one to fight and nowhere to run. This represents a problem of adaptation for humans, since the extreme physiological response to stress is not appropriate to the low metabolic demands of the situation. The stress response can result in organic damage, particularly when extended over time (Sapolsky, 1994), and may also interfere with the need to carry out tasks effectively.

Table 2.1: Sources of threat to performance from the space environment (adapted from Kanas & Manzey, 2008)

Physical	**Habitability**	**Psychological**	**Interpersonal**
acceleration	space constraints	isolation	leadership issues
microgravity	vibration	confinement	gender/cultural issues
ionizing radiation	noise	sleep disturbances	interpersonal conflicts
meteoroid impacts	air quality	monotony	communication
light/dark cycles		high workload	

Space missions are characterized by a number of distinctive stressors, arising out of different features of the environment (*Table 2.1*). Some are real threats to health and survival (radiation, meteorite impact, compromised air quality), giving rise to a sense of danger; others less so (acceleration, low gravity, abnormal light-dark periodicity, other habitat features, and all other psychological and interpersonal stressors). Many of these second level stressors are similar to those experienced on Earth: highly demanding or unpredictable workloads, interpersonal problems, sleep disruption, and so on. Dealing with some of these requires a medical or engineering approach, but many lie within the remit of a psychological analysis, including concern about the danger of impact of physical stressors, which may trigger background increases in state anxiety and fatigue. Other factors, such as high workload (see Chapter 3) are directly responsible for fatigue, by forcing crewmembers to maintain task goals for long periods.

As yet there are no formal studies of psychological effects of stressors on humans in actual space missions, or how to safeguard the skills and wellbeing of crewmembers against stress effects. Much of the evidence comes from Earth-based laboratory studies or from exposure to simulations based on analogue environments. While these are often able to mimic the main physical features of the environment (e.g., isolation and confinement), they may have the limitation that they may not be perceived as genuinely threatening. For example, Sandal (2000) found that anxiety was much lower during simulations based on land-based hyperbaric chambers than for polar overwintering, where the real threats of physical danger and difficulty of evacuation were much greater. This is a major limitation of simulation studies; since participants always know that there is a way out, the study cannot be an effective way of conveying threat, and ethical considerations mean that such consequences cannot also be simulated. Nevertheless, the large amount of research that has been conducted in laboratories and field studies indicates that there are very likely to be threats to mission goals from failure to adapt to the space environment. Furthermore, since most of this evidence has been obtained under low threat conditions, it is highly probably that effects will be much greater under space conditions. The occurrence of inappropriate stress states are likely to be common in space environments, and may compromise psychological wellbeing and interfere with the adequacy of task performance. We have not always recognised this; Suedfeld (2005) has traced NASA's changing perception of humans in spaceflight from that of invulnerable superheros (the right stuff) to a concern with vulnerability to stress. It is now recognised that even highly competent human beings are vulnerable to major challenges to their adaptive capacity and may become anxious and error-prone. The right stuff may now be better considered as high levels of adaptability or resilience - the ability to cope successfully with stress encounters The space environment is a combination of very challenging physical stressors and a sense of enduring threat, which will severely test even high levels of resilience. For example: cardiovascular deconditioning may hinder reactivity and the normal mobilization of resources. Because of this, it is essential, especially in space, to treat stress as a psychophysiological construct.

These psychological state changes are the focus of this chapter. The effects of stress are two-fold: it has been known since the 1970s that the nature of the task is a strong determinant of how performance will be affected, while it is also clear that there is a general problem that affects the performance of all tasks. The key to understanding this appears to be to consider the goals that drive performance-related behavior. Under extreme stress, goals are likely to change – away from the current task and towards the need to carry out emergency responses. Even when stress is less intense, task goals may be supplanted by those that are more comfortable or preferred. The problem is that, in routine operational contexts, threatened task goals need to be protected from displacement, a strategy that typically gives rise to unwanted side effects.

2.2 Background

2.2.1 Patterns of stress states

A formal analysis of the effects of stress on performance (see Hockey (2006) for a summary) identified several distinct stress states, in terms of their patterns of effect across different indicators of performance. As an example, compare the effects of three of the most commonly studied laboratory stressors: loud noise, sleep deprivation and heat. Noise was found to increase the level of selectivity (narrow the focus of attention), impair performance on tasks that require decision accuracy, working memory or problem solving, but not speed. Sleep deprivation was associated with impairment on bothspeed and accuracy, a high level of selectivity, and more general effects on memory. Both noise and sleep deprivation had effects that were more pronounced under fatigue conditions (when tasks involve long periods of work without breaks). Working in hot conditions had widespread effects on most aspects of performance, especially where tasks involved more complex decision-making, but, unlike noise and sleep deprivation, did not appear to increase with time at work.

The most general pattern of decrement is associated with environmental conditions such as noise, danger, or uncomfortable social interaction, that give rise to subjective states of threat or anxiety. This may be regarded as the modal stress pattern, characterised by feelings of anxiety or threat, increased selectivity of attention, a preference for speed over accuracy, and reduced effectiveness in executive level functioning. Decrements are more common on tasks of long duration, especially where the continued use of working memory is central to maintaining the flow of the work. Selective attention is normally very effective, unless response is required to a number of different events or sub-tasks, in which case only the most important may be maintained. A familiar effect of such stressors is narrowed attention, in which high priority features of tasks are maintained and secondary aspects neglected. Such an effect has been observed for a wide range of stress states, including noise, high workload, threat of shock, danger, and most forms of induced anxiety. Other stressors are associated with different kinds of changes. For example, working memory appears relatively stable under hot working conditions, or with extended work periods. In all cases, however, it has become clear that we cannot separate underlying effects on cognitive processes from those relating to changes in performance goals or strategies. An increase in reliance on one kind of process may be the result of a strategic reduction in the use of another. Because of this, patterns of stressor effects cannot be discussed without reference to an understanding of what the performer is trying to do when carrying out a task, and of what conflicts exist between different goals.

2.2.2 Compensatory control

Modern treatments of psychological stress emphasize the cognitive transactions that mediate between stressful events and the adaptive response to them (Hancock & Warm, 1989; Hockey, Gaillard & Burov, 2003; Lazarus & Folkman, 1984). This appraisal process evaluates the implications of the stressor for both current activities and personal wellbeing. In terms of the effects on human performance this may mean focusing information processing resources more strongly on the need to maintain primary goals (performance protection). Alternatively, the individual may prefer to withdraw resources from the task in order to combat the stressor itself. This strategy will be more effective in reducing effects on bodily or emotional states, though it will inevitably lead to a decrement in performance. Performance protection appears to be the default strategy in ideal work conditions – where the individual is highly skilled, the task sufficiently important, and the stressor familiar and manageable. Serious disruption is rare for high priority activities, especially for highly motivated operators, and then only because of unforeseeable and major disruptions. This is because a compensatory process operates to maintain primary task goals under the increased threat of disruption, resulting in a reduced response to the control of emotional state and other competing goals. The increased effort underlying compensatory control is considered to reflect the involvement of the central executive functions responsible for the maintenance of high-level cognitive effectiveness, as observed in problem solving, reasoning, and all goal maintenance activity. As such, it is a limited resource that inevitably attracts costs when it is over-employed.

On the other hand, we know that decrements are relatively common, especially in laboratory studies, or where skill and motivation are relatively low. Within this framework, the specific patterns of decrement outlined earlier may be considered a baseline or default pattern of decrement under different stressors – how performance might be expected to suffer *in the absence of compensatory control activity.* As an illustration of this consider a pair of studies carried out by Frankenhaeuser and Lundberg (1974) and Lundberg & Frankenhaeuser (1977), showing that noise impaired performance on an arithmetic task on one occasion but not on another. This can be understood only by considering motivational factors such as compensatory effort, and the physiological and subjective costs associated with having to work under noise. When performance was unimpaired, there was a marked increase in adrenaline and subjective effort. However, in the case where performance was disrupted by noise, no such changes were observed. The most satisfactory explanation of this is that noise (and other similar stress states) imposes an additional load on our capacity to maintain adequate orientation towards the task. If we can make an additional effort under such circumstances to maintain the task goal, performance may be protected against disruption, though only at the cost of increased strain. Alternatively, we may be unwilling (or unable) to make such an effort, in which case we will experience less strain, but inevitably suffer a decrement in task performance. Such trade-off options are the routine consequences of having to manage stress and other environmental demands while still carrying out our commitments to external task goals.

2.2.3 Indirect effects of stress

Although stress does not always result in any obvious reduction in performance, this should not be taken to mean that there is no threat to task goals. There is now considerable evidence of 'knock-on' effects of performance protection to secondary aspects of performance, what Hockey (1997) has referred to as 'latent degradation'. By reducing the safe working margins of the adaptive control process, these changes may threaten the overall integrity of performance – for example, resulting in the adoption of information processing strategies that only work if there are no unexpected problems to deal with. Four kinds of latent degradation can be identified (*Table 2.2*): two direct effects on performance – secondary task decrements and strategy changes, and two indirect costs of compensatory activity – a shift towards sympathetic activation and fatigue after-effects. This last type is discussed separately in section 2.2.4.

Decrements in secondary aspects of performance are commonly observed in studies of effects of high workload where primary task goals are preserved (Wickens & Hollands, 1999). They have been studied less systematically in assessing threats from environmental stressors, though they are, in fact, also common in this context (Hockey, Wastell & Sauer, 1998). One of the best-documented forms of secondary task decrement under stress is the neglect of peripheral elements in spatially complex tasks (Baddeley, 1972; Hockey, 1986). This attentional narrowing is likely to be related to the second type of decrement, strategy changes. These are normally adaptive, serving the need to maintain primary task goals. However, there may also be more subtle changes, involving a shift to less executive-demanding modes of control. An example of this is Sperandio's (1978) well-known study of air traffic controllers, who adopted a simplified method of dealing with aircraft when they exceeded a manageable number (switching from individual 'plane by plane' routing instructions to a fixed procedure for all contacts). By minimizing the demands for planning and aircraft management, operators reduced the need to involve the vulnerable working memory system. The strategy change is adaptive since accuracy matters more than speed in such work. But there are costs; while safety goals are maintained, secondary goals such as airport schedules and passenger comfort are necessarily compromised. However, in situations where time constraints are greater, this kind of change may lead to an observable stress-induced impairment. For example, the reduced involvement of working memory may lead to premature closure and unsafe decision-making (Keinan, 1987).

Table 2.2: Types of latent decrement found under stress and high workload

Decrement type	**Characteristics/examples**
Secondary task decrements	Selective impairment of low priority task components neglect of subsidiary activities; attentional narrowing
Strategy changes	Within-task shift to simpler strategies reduced use of working memory; use of responsive rather than proactive mode
Regulatory costs	Strain of effortful control increased anxiety, mental effort, fatigue; sympathetic activation
Fatigue after-effects	Post-task preference for low effort strategies post-work fatigue; risky decision making—use of short-cuts

One of the most reliable costs of the use of increased effort to protect performance is the observation of increased levels of strain-induced activation. This is particularly true of the physiological systems involved in emergency reactions to stressors (e.g., sympathetic and musculoskeletal responses, and neuroendocrine stress activity). These effects are typically accompanied by changes in subjective reports of emotional and mood states reflecting the affective response to threat and sustained coping effort. They may be thought of as the unwanted side effects of the compensatory control that helps to maintain primary performance under threat from environmental conditions. This performance-cost trade off is seen in several studies of noise effects as increased heart rate, blood pressure, adrenaline and subjective effort, though only in tasks where performance is maintained.

2.2.4 Stress and fatigue

A final form of latent degradation is one that appears only after high priority tasks have been completed, taking the form of decrements on new (and less critical) tasks (Broadbent, 1979; Holding, 1983; Hockey, 1997; Muraven & Slessareva, 2003). Such after-effects have been studied very little, and then normally within a workload/fatigue paradigm, rather than stress per se. However, they are equally appropriate as a response to the sustained effort required to maintain effective levels of working under stressful environmental conditions. It has proved surprisingly difficult to demonstrate carry-over effects of fatigue. Even intensive research programs carried out by the US Army failed to find any marked fatigue effects of periods of up to 60 hours continuous work. Broadbent (1979) and Holding (1983) have shown that there are methodological difficulties in the analysis of this apparently straightforward problem. As with the compensatory response to stressors, participants in such experiments appear able to work harder (make more effort) for brief periods to respond to the challenge of any new test, effectively compensating for any reduction in capacity. However, when tired (and stressed) participants are provided with alternative ways of carrying out the post-work test they are more likely to choose one requiring low effort, even though it carries a higher risk of error. Similar results of high workload and stressful jobs have been found for driving examiners, bus drivers, and junior doctors (Hockey, 1997; van der Linden, Frese & Sonnentag, 2003). This approach to fatigue reveals it to be a state in which there is a shift towards preferring activities that are more relevant to the person's needs or interests—and that require less effort or use of executive processing to carry out (Hockey, 2010). It has been known for many years that fatigue is rare when control of activity is high—when people choose the work they do. So far, there has been little direct research on this form of decrement with laboratory stressors, though similar effects have been found for noise and high workload.

The link between stress and fatigue is a very strong one. It is likely that actively managing stress in order to protect performance leads directly to fatigue, so that recovery is necessary before we can function effectively, even when the stressor is no longer present. Recent work suggests that fatigue is an adaptive response to the over-use of the executive control system that maintains the activation of tasks in working memory, triggering both withdrawal of effort and compensatory changes in information processing strategy (Hockey, 2010; in press; van der Linden, Frese & Sonnentag, 2003). At present, we have no direct evidence of the brain processes involved in this *stressor→ control/effort→ fatigue* chain, but such problems are currently being addressed in a number of laboratories. Clearly, a better understanding of the physiological basis of the control of stress during task performance will help us to manage work and other tasks more effectively, as well as informing our approach to the design and management of the working environment in space missions. However, it is also likely that stress from unwanted demands and the ensuing effects of fatigue may be reduced by a better understanding of individual preferences and interests.

2.3 Evidence from Space

While there are clear indications from laboratory studies about how stress states may affect human performance, very little direct evidence exists from actual space missions. Adverse effects of stress on performance during space missions are commonly referred to in articles and reports, though very few have, in fact been demonstrated in formal research studies. In any natural environment, a major difficulty in assessing the threat to performance from stressors is the near-impossibility of manipulating environmental conditions. This means that while we may suspect that impairments may be attributable to stressors, they may also be the result of fluctuating response to background conditions such as isolation and confinement, changes in work demands, skill deterioration or sleep disturbances, or physical constraints imposed by working in microgravity. However, there can be little doubt that stress problems occur, in space as on Earth – even more so because of the very real dangers and threats of the space environment.

There have been many reports of what appear to be genuine stress-related problems in actual missions (e.g., Rivolier, 1997; Shaylor, 2000), but these refer mainly to disturbances of well-being and mood. In practice it appears that major performance failings in operational tasks are very rare (Kanas & Manzey, 2008), although analyses of crew errors during Mir missions suggested a link between the occurrence of errors and changes in work-rest schedules, periods of high workload, and so on. One problem is that the frequency of such events may be underestimated because of under-reporting, though there may be cultural differences in this; for example, Russian crews are thought to be more likely to report operational difficulties. A small number of studies have included cognitive tasks as part of the mission payload to monitor changes in performance, mainly during short duration missions; however, even when ground-based simulations are included (Hockey & Sauer, 1996; Hockey & Wiethoff, 1996) the available database is small. In general, cognitive skills seem relatively unimpaired intact during space missions.

Extrapolating from Earth studies, it is likely that the most vulnerable cognitive activities are those that were strongly dependent on working memory and executive control, when crewmembers have to carry out two tasks at the same time, or a single activity that makes heavy demands on attention. A few studies carried out by Manzey and colleagues have reported some decrement (Manzey & Lorenz, 1998; Manzey, Lorenz & Polyakov, 1998) using intensive monitoring of a single cosmonaut on Mir missions, though others have not (e.g., Fowler, Bock & Comfort, 2000). Another feature is that, where small effects are observed, they are most evident during the first few weeks of long-duration space flight before adaptation occurs, suggesting that they are more likely to be stress-induced than a direct effect of microgravity or other aspects of the physical environment (Kanas & Manzey, 2008). In general, there is little evidence of impairment even with such demanding tasks. It is likely, however, that any such impairment would be hidden by the use of compensatory strategies, such as those summarized in Table 2, especially since crews are highly trained and motivated. It is also not at all clear what might be the cause of any observed effects, since psychological stress is always present with many other factors. Kanas and Manzey have argued that effects are due to a combination of the direct effects of microgravity and indirect effects of background stressors such as sleep disruption, anxiety or high workload.

2.4 Research Needs and Implications

Given that there is very little evidence of performance impairment in space, why should we be concerned about this kind of problem? As argued earlier, the observed pattern of results is exactly what we would expect of the performance of high priority goals by highly motivated crewmembers – a high level of protection, with little evidence of disruption. However, as *Table 2.2* indicates, there are likely to be costs. The problem is that research has generally not examined these indirect indicators of performance decrement. Questions about effects of stress and fatigue on performance – in space as in other contexts – need to be recast in terms of changes in the patterning of both overt performance of primary tasks and associated costs.

A research programme based on such a framework would be capable of revealing not only whether top-level goals were at risk but also what kinds of hidden problems might be expected. This requires a new approach to the analysis of performance in space. In order to observe costs of performance protection, analysis should include one or more of the following features:

- *Use of multi-level analysis*. Performance analyses should make use of both primary and subsidiary tasks, in order to examine trade-offs between performance and changing task management strategies.
- *Use of complex tasks*. Complex tasks demand more of the operator, and allow for a variety of strategies, including optional use of working memory and executive control when they become difficult to manage. Ideally, these should make use of simulations of actual work tasks, in order to enhance task engagement and professional commitment.
- *Assessment of strain*. Strain from managing a task under stress can be measured using indicators of both subjective state (anxiety, effort and fatigue) and psychophysiological state, ideally through continuous monitoring.
- *Enhanced control of work*. Such a programme should also evaluate the advantages of maximizing control options, as a way of reducing the problem of fatigue. Where crewmembers have discretion for how or when tasks may be carried out we would expect fatigue to be less of problem.
- *Stress exposure training*. In addition, there is a need to consider techniques for managing the response to stress, such as the use of stress exposure training (Driskell & Johnston, 1998). This involves cognitive interventions, including instruction in the likely impact of stressors, and practice in performing operational tasks under simulation conditions that are increasingly similar to those expected in space. Such methods could also be profitably extended to provide training in the use of biomedical feedback to manage psychophysiological state and its response to stress.

3 Work Demands

3.1 Introduction

Despite the significant developments in robot technology, it seems likely that the success of future human space exploration will continue to rely heavily on the performance of astronauts. Effective human performance across the wide range of tasks and situations facing astronauts during long space flights will depend critically on the relationship between an astronaut's functional state and the performance of multiple tasks. As space exploration mission durations increase with the current focus on Mars and beyond, the need to manage astronaut workload is becoming increasingly prominent.

In order to make predictions about future performance, potential problems and training needs for complex work situations, we need to consider the interaction between human operators and task demands. In doing so, we usually have a good idea of the tasks to be performed, the likely time pressures and requirements for quality of performance. In space, the specific tasks of astronauts will depend on the duration and stage of the flight, the scientific and operational requirements of the particular mission, and the astronaut's specific job(s). The majority of tasks are likely to be primarily cognitive in nature and will require the astronauts to process information and to make decisions as effectively as possible. However, a huge variety of skills (e.g. visual, psychomotor) and cognitive functions may be involved in the performance of simple tasks, multiple tasks, interaction with complex equipment and processes, routine tasks and less frequently performed tasks. In terms of phases of flight, some are easy to identify - lift off, landing, docking and other specific 'flight' operations, but others depend on the nature of the mission. Conducting scientific experiments, building and maintenance activities, life support, routine cleaning, communications, and dealing with a range of unpredictable events constitute part of the daily duties. Other tasks, such as inspection, maintenance, and repair in space become more important for long duration space travel, such as for missions to the Moon and Mars and lengthy periods spent aboard the ISS.

The work (and living) environment is very constrained but the tasks can be quite varied depending on the phase of flight and job role. Some of the time these tasks can be very demanding, some have to be performed precisely under heavy time pressure. Others are more routine, but may become monotonous over a long mission. Heavy physical demands are relatively infrequent, although on occasion there may be a requirement to replace heavy equipment or to conduct extra-vehicular activity (EVA), which is physically demanding. Astronauts in space for more than a few days also need to spend about two hours each day doing some sort of physical exercise in order to counteract muscle tissue loss which occurs as a result of microgravity. Such physical exercise may be beneficial in terms of well-being and in counteracting the less desirable outcomes of dealing with stressful or demanding situations. However, although there are particular issues peculiar to space environments which have different physical effects on astronauts this chapter will concentrate on the effects of mental demands on cognitive performance. It is argued that under normal circumstances in space, the standard tasks that astronauts have to perform should not be problematical, but if unforeseen difficulties occur, we need to be able to predict the consequences for safety and performance. The chapter will therefore consider the impact of work demands on the performance of astronauts and approaches to workload assessment and management.

An important distinction needs to be made between work demands and workload. The term *work demands* refers to the objective level of task difficulty of work activities being performed by astronauts at a particular point in time. Workload is a multidimensional construct and is not defined by level of work demands alone. Rather it acknowledges the importance of the interaction between an individual astronaut and the tasks he or she is dealing with.

3.2 Background

3.2.1 Performance impairment

In complex task situations, performance impairment is primarily associated with high or excessive levels of task demand producing overload or situations involving requirements to combine activities which are incompatible, either in terms of their information demands or perceptual or motor demands (Wickens & Hollands, 1999). In addition to these task-related characteristics, impairment during space flight is also associated with environmental conditions, such as noise, vibration, microgravity and sleep deprivation (Kanas & Manzey, 2008). Long duration space flights, for example 500 day or 1000 day trips to Mars, may well pose additional challenges, as they may involve 200-300 day flights each way with either a short-term stay on Mars (500 day trip) or 400-500 days on Mars until the next opportunity to return to Earth. It has been proposed that some crewmembers will continue to orbit Mars for this period, thus experiencing almost 1000 days in a microgravity environment. Such isolation, confinement and other environmental factors have led to the identification of psychological factors as the principle challenges to any such mission.

However, the outcomes of a huge amount of experimental work on single-task performance suggest that degradation is unlikely to be observed under normal conditions – under high or low levels of workload, or different stress environments. This is especially so with highly trained personnel. Impairments of task performance are only likely to be observed under complex multiple-task situations or in unpredictable conditions such as emergencies, although dual-task performance (tracking and a reaction time task) was unimpaired in the highly trained astronauts (n=6) tested in the 16-day NASA Neurolab mission (Fowler et al., 2000). In terms of research conducted in space and analogue environments there is little evidence of disruption on a range of single tasks, other than for some relatively short-lasting decrements in tracking and dual-task performance in the early stages of a flight (Kanas & Manzey, 2008; Manzey et al., 1998). Adaptation to the new environment over the first few days in space appears to erode these effects.

There appear to be gaps in existing knowledge when one starts to consider the interactive effects of different work and environmental demands. Astronauts have been found to sleep less in space so may therefore be sleep deprived to a certain extent. Monk et al. (1998) reported shuttle astronauts having an average sleep duration of just over six hours. NASA (1995) has cited findings that complex tasks are performed less effectively than simple tasks at high levels of fatigue, thus indicating an interaction between sleep deprivation/fatigue and task demands on performance. For example, Chmiel, Totterdell & Folkard (1995) found that following one night's sleep loss and several hours performing an adaptive control task, performance quality could be maintained but the work was carried out more slowly, particularly towards the end of a 1.5 hr work session. In a simulation study (Hockey et al, 1998), sleep-deprived operators engaged less in monitoring system parameters, which help in the anticipation of developing problems, and relied more on correcting the system by all-or-none manual interventions, triggered by alarms whenever parameters went slightly out of range.

This chapter has so far concentrated on what might be termed overload, or the effects of high levels of work demands. Although little research has been conducted to examine the effects of extremely low levels of demand, or what could be termed underload, on performance, there is at least anecdotal evidence from astronauts that having too little to do constitutes a source of stress for them. There is a danger that astronauts experience periods of monotony or circumstances that lead them to disengage from tasks.

3.2.2 Workload and performance

Under 'normal' circumstances, primary-task task performance has been described as being protected or maintained at desirable levels, particularly in laboratory-based situations (e.g. Hockey, 1997; Kahneman, 1973). This has been found to be true of tasks based on classical industrial activities, such as vigilance (monitoring and inspection activities), tracking (manual control of all kinds) and sequential responding (underlying the kind of complex perceptual motor skills found in many office tasks). Where decrements are found, they are usually not serious, have minimal practical implications, and are actively managed. In general, the management of performance under stress and high demand may be said to exhibit a 'graceful degradation' (Navon & Gopher, 1979), rather than a catastrophic collapse.

Despite few reports of problems with workload in space, there are, however, undoubtedly threats to an astronaut's performance associated with high levels of work demands and environmental stress. It has been proposed that a key threat may arise as a consequence of managing such demands and conditions observed in the development of costs such as high effort and fatigue. Recent approaches to such problems (see Hockey, Gaillard & Burov, 2003) refer to 'operator functional state', (OFS: see chapter 1) to describe an adaptive transaction between individuals and the environment. This approach assumes that individuals have choices about how to handle environmental factors that threaten performance goals, and that different strategies result in distinctive patterns of performance and costs. This is congruent with the notion that workload cannot be defined by objective level of demand or task difficulty alone. Workload will depend on the interaction between demands, the strategies adopted by an operator to deal with them, and the desired trade-off between level of performance and costs.

Managing workload may incur costs even under normal operating conditions due to the transactional and multidimensional nature of workload (e.g., Gopher & Donchin, 1986; Hockey, 2005). If performance on a demanding task is below a desired target level, we cannot simply assume that the operator is 'overloaded' and cannot work harder to achieve these goals. An alternative possibility is that the person is not sufficiently motivated to maintain the high level of effort required to achieve satisfactory performance. This may be due to a lack of awareness of the importance of the operating goals, or the result of a strategic withdrawal from high effort engagement in order protect valuable resources for dealing with future predictable or unpredictable events. Suboptimal levels of individual physiological or emotional state caused by illness or environmental conditions may also result in impaired performance.

Hockey (1997, 2005) described the role of regulatory processes in complex work. This 'compensatory control' approach provides an explanation of the effects of increased task demands, workload, impaired operator state (which he described as latent degradation). Primary task decrements as mentioned above are not usually observed in critical situations. Secondary task decrements may be more commonly observed under these conditions as effort is withdrawn to protect and support primary task performance. The exact nature of such changes will however depend on the particular strategy and set of priorities adopted by the operator. Strategy changes – to less demanding or simpler strategy, involving less resource-intensive task performance – may therefore indicate critical transition phases. An important consideration is the choice of methods to detect threats to performance disruption: psychophysiological state, after effects, secondary task performance, subjective state.

It may be possible to assess latent degradation using post-task/end of work period tests (e.g. Holding, 1983). These tasks may be sensitive to fatigue, as it is argued to result from the sustained expenditure of mental effort during work. It has, however, proved difficult to find a sensitive test of such carry-over effects. Various studies have failed to find any marked effects on post-work tests such as tracking or multiple choice reaction time from periods of up to 60 hours continuous work (e.g. Holding, 1983). This may be because people are able to work harder (make more effort) for brief periods in response to the challenge of the new test. On the other hand, when given alternative ways of carrying out the post-work tests, more tired participants were more likely to choose one requiring low effort, even though it entailed more risk of error. Meijman, Mulder, van Dormelen & Cremer (1992), for example, found driving examiners invested less effort (both subjective and physiological) in performing cognitive tasks following working days with higher levels of demand. A study comparing the effects of working and non-working days in city bus drivers reported by Aasman, Wijers, Mulder & Mulder (1988) found less efficient and effective task performance to be associated with increasing workload. The same effect has also been observed in laboratory studies of simulated work (Schellekens, Sijtsma, Vegter & Meijman, 2000; Hockey & Earle, 2006). This latter study showed after effects of high workload/effort in terms of reduced persistence on an information search task, though only under conditions of low control during the normal work period (being made to follow a particular task schedule, as opposed to being able to choose one's own). Such findings emphasise the importance of understanding the role of strategic effects on human performance.

The compensatory control model identifies three kinds of workload management strategy, characterised by distinctive patterns of trade-off between performance protection and costs. These are referred to as (1) engaged, (2) disengaged and (3) strain. Engagement involves the application of direct (high effort) coping within the limits of planned effort expenditure. Increased effort allows performance to be protected under demands from unexpected difficulties, periods of time pressure or additional stress conditions, but the engaged mode is generally manageable, since it is allows periods of routine activity, and does not exceed the individual's capabilities. It may be considered a standard feature of any complex mental work, especially where employees are actively involved in their task and 'working well'. It corresponds to Frankenhaeuser's (1986) description of 'challenge' situations ('effort without distress'), and characterised by feelings of enthusiasm and elation – of having had a 'good day'. It also involves increases in catecholamines (adrenaline and noradrenaline), but not cortisol. Regulatory problems occur primarily when external demands are greater than expected, so that they exceed current levels of effort. There is evidence that subjective limits for maximum effort expenditure are relatively conservative, even for physical tasks (Holding, 1983), so that increases beyond the set 'maximum' are possible. Nevertheless, operating at a very high level for any length of time is likely to be uncomfortable, and impose considerable strain, giving rise to fatigue (Hockey et al, 1989; Hockey & Meijman, 1998). Two control options are available in such circumstances, referred to here as the disengaged and strain patterns.

The disengaged mode involves a reduced commitment to work goals. It may be achieved by reducing required levels of accuracy or speed, by adopting strategies which make less of a demand on limited resources such as working memory, or by neglecting secondary activities. In some cases, individuals may disengage completely from task goals, especially when an attempt at direct coping has little effect (Schultz & Schönpflug, 1982), but this would be extremely unlikely in an operational space context. This would correspond to Frankenhaeuser's (1986) 'distress without effort' mode of coping, with low levels of catecholamines, but high levels of cortisol, and anxious and depressed feelings.

The strain mode is characterised as a striving or struggle to overcome environmental demands in order to maintain task goals. It is assumed that striving effectively increases resources by drawing on the energy mobilisation capabilities of the system (Kahneman, 1973). Considered as a voluntary process, striving demonstrates a willingness to sustain an aversive strain state, corresponding to Frankenhaeuser's 'effort with distress'. At the end of a high strain work day employees feel tense and weary, and have increased levels of both catecholamines and cortisol. There are also likely to be spill-over effects in the period following work, affecting the ability to relax or sleep. Cropley & Millward (2004), for example, found that high-strain teachers took longer to disengage from work-related issues than low-strain teachers, finding it more difficult to stop ruminating or thinking about work or future work-related tasks.

3.2.3 Workload and performance assessment

It is important to develop and use appropriate measures to identify the particular outcomes that result from an individual's approach to workload management in a specific situation. The resulting information will provided feedback to those individuals but may also be used by adaptive systems to maintain appropriate levels of workload. *Table 3.1* summarizes the most useful measures, their suitability for use in a space environment, in terms of the degree to which they may affect ongoing activities, their potential for identifying workload problems, and their applicability.

3.3 Evidence from Space

For astronauts it is extremely difficult to generate a simple measure of an individual's level of performance (e.g. speed, accuracy or errors and slips of action). Due to the differing characteristics of tasks, primary task measures are also not easily transferable from one situation to another. More often the problem is that effects of workload may be underestimated, either because primary task measures may not be immediately sensitive to the effects of changes in task load or working procedures or as a result of performance protection – the compensatory effort that operators typically apply to cope with additional demands. Thus, only a crude indication may be obtained of the cumulative effect of sustained and high task demands. The effects of these factors may only be detected by primary task measures once performance suffers or errors are made.

There have been examples of performance decrements in space, perhaps most notably the collision involving the MIR Space Station in 1997. Ellis (2000) concluded that a key contributory factor was the prolonged period (approximately 4 months) since the cosmonaut last practiced the particular skill (a docking manoeuvre). However, such degradation is not inevitable and will depend on other activities and starting skill levels. The studies by Sauer, Hockey and Wastell (1999a, b) of complex skills performance in confined conditions suggest that performance can be maintained over long periods (4-8 months in this case).

While primary task measures may not show impairment, it may sometimes be possible to detect a shift to a simpler or less demanding strategy. By changing the way in which tasks are carried out, the individual may be able to minimize disruption to primary outputs by more effective or simpler management of resources. For example, more time can be allocated to important elements by reducing the time spent on fringe activities, or what are perceived to be less important tasks. Strategic changes may also involve a shift to less resource-intensive modes of task control, reducing dependency on demanding processes such as working memory. Air traffic controllers, for example, have been found to vary their strategies according to task demand, taking fewer variables into account with increasing traffic load (Sperandio, 1978). Similarly, Bainbridge (1974) found that process operators under time pressure used faster but less accurate methods of finding data values. Sauer et al. (1999b) observed such a transfer to a less effortful but more risky strategy during a 135-day ground-based simulation of a space mission.

Astronauts are likely to be required to satisfy many different goals at different times (controlling the craft, life support systems, experiments, communications etc.). This means that switching of the priorities of different goals will be quite common and thus knowledge of transitions between different tasks and how these are managed will be required. Very little research has been reported on this important variable.

Table 3.1. Summary of the applicability and capability of different broad categories of workload assessment technique

Measure Type	Intrusiveness	Sensitivity	Diagnosticity	Relevance
Primary task	not a problem	high when relevant data available	low	depends on task
Secondary task	possible problems	high	high	may require training and extra equipment
Strategy changes	not a problem	high when relevant data available	medium-high	suitable range of task measures required
After effects	not a problem	can be high	low – global index of fatigue	minimal requirements
Subjective				
Post-task	generally not a problem	high – may depend on length of task	low-medium	minimal requirements
Instantaneous	potentially intrusive	high	can be high – depends on task structure	equipment usually required
Physiological				
EEG	not usually a problem	high	depends on measure	needs extensive equipment and analysis
ECG	not a problem	high	low –medium	needs extensive equipment and analysis
Hormones	not a problem	high	medium	analysis and storage may be problematical

Kelly et al. (2005) demonstrated the possibilities for monitoring performance repeatedly during a 10-day space flight, although there were relatively few indications of performance impairments over this time. It would be desirable to monitor all aspects of performance in space, so that primary task performance changes can be identified, but just as importantly, so that trade-offs between tasks, and changes in effort and task strategies can be observed. As primary task performance is likely to remain high, the consequences of dealing with heavy work demands may be measurable only in the form of tradeoffs between performance and other domains of individual activity, and longitudinal sampling of performance as well as subjective and physiological measures may well be required.

Physiological processes have long been identified as potential markers of mental effort or workload (see chapter 5).

3.4 Research Needs and Implications

Three primary areas for research focus in relation to work demands have been identified:

- *Monitoring of performance and individual state*. It would be beneficial for astronauts to be able to access as much information as possible about their own level of performance. Evidence from extensive work on knowledge of results (KOR) shows that this is important for both the development and maintenance of skills. There is also some evidence that motivation resulting from KOR can overcome circadian effects on performance (e.g., Blake, 1971) and performance affected by sleep loss and time on task (Becker, Warm, Dember & Hancock, 1995). Providing astronauts with information about their own state, both physical and emotional, and their performance will also be an important source of support for them in terms of helping them to identify changes from desired state levels or trends that may indicate the development of an abnormal situation. Such information could be used to identify changes that could lead to impairments in health and performance.
- *Adaptive automation*. Adaptive automation is a type of automation in which changes may be made in the allocation of functions/tasks between a human operator and the system on a dynamic, rather than a static, fixed basis. Adaptive automation, sometimes referred to as dynamic task allocation, is considered to offer considerable promise for the design of effective work systems, particularly in safety-critical task environments. Such automation involves the flexible allocation of tasks or functions between the operator and the system in complex human-machine systems depending on the functional state of the operator and the performance of the system.
- *Engagement and disengagement with work activities*. There is obvious overlap here with the Chapter 5, but it is important to be able to measure the performance of astronauts in order to help identify underload, overload or workload management issues. A primary objective of adaptive automation is to adjust the form and type of automated support to the needs of the operator in real time in order to maintain optimum levels of work demands for the operator, and to ensure that he or she does not become overloaded or underloaded (e.g., Parasuraman, 2000). For obvious reasons, issues of disengagement from ongoing work activities require research attention. This has been a neglected topic.

4 Sleep and Sleepiness

4.1 Introduction

Space flight presents particular challenges for sleep and a number of studies have indicated that sleep is impaired due to suboptimal work/rest schedules, unsuitable temporal light patterns, noise, stress, microgravity and other factors. Sleep impairment will, in turn, impact performance and increase the risk of mistakes. This chapter will try to summarize the major practical problems that might be encountered, ways of preserving effective work performance, identify measurement techniques for understanding and monitoring sleep and its effects.

4.2. Background

4.2.1 Sleep loss

Sleep physiology or 'polysomnography' (PSG) gives a good picture of the detailed effects on sleep in space. Normally, sleep is continuous (*Figure 4.1*), with very few awakenings and with an orderly progression from Wakefulness, via Stage 1 sleep, to sleep stages 2, 3, 4 and REM sleep, repeated in 4 or 5 cycles. Stage 3 and 4 are usually confined to the first two sleep cycles. From a performance and health point of view, the important parameters are, duration, frequency of sleep interruptions (micro arousals), and amount of sleep stages 3+4 (labelled Slow Wave Sleep (SWS) because of its content of a large number of slow oscillations in the EEG.

The effects of sleep loss have been relatively extensively studied under ground conditions. An acute reduction down to 6 hours of sleep does not seem to have an effect on mental functioning on the first day (Van Dongen et al., 2003), but the effects accumulate across days. The effects increase in steepness with increasing shortness of sleep. The long-term lower limit of sleep duration seems to be about 7 hours (for healthy 25-40 year olds). The results from this and other studies also indicate that monotonous, attention-demanding tasks are most vulnerable to sleep loss, for example serial reaction time or number of lapses in such a test. However, at higher levels of sleep loss cognitive effects may be dramatic. Particularly memory is affected.

Deep sleep, or SWS, appears to be important for brain restitution (Vassalli and Dijk, 2009). Thus, the redistribution of deep sleep (SWS) from the start to the end of the sleep episode may also be of significance since this may jeopardize the restitution that SWS provides in

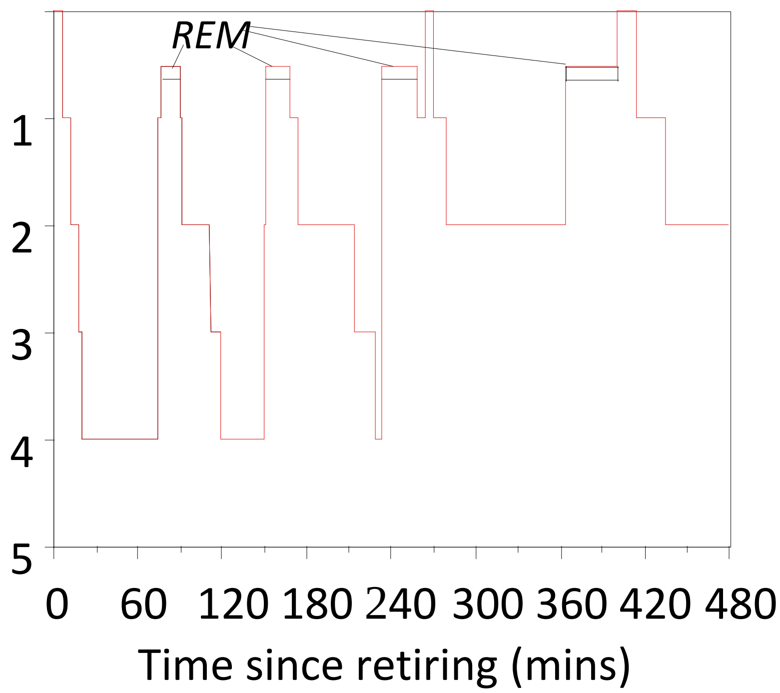

Figure 4.1. The development of sleep stages 1-4 and REM across the night

its 'protected' position during the early part of sleep. Postponement of SWS may increase the risk of loosing SWS because of premature awakening. In general, the first hours of sleep are crucial, whereas the last hours of an eight-hour sleep are of modest importance for mental functioning. Sleep fragmentation is a third component (together with sleep reduction and suppression of SWS) of sleep loss. The importance of the rate of fragmentation has been established in several studies (Bonnet & Arand, 2003) to be related to next day sleep latency tests and performance. It should be emphasized that despite SWS and lack of fragmentation are considered important aspects of sleep quality there is no consensus on detailed criteria.

4.2.2 The causes of disturbed sleep

The effect of work at the wrong circadian phase is well established in traditional shift work (Akerstedt, 2005). The biological clock will interfere with sleep taken during the 'window of circadian high' (WOCH) (Dijk & Czeisler, 1995), that is, normally daytime. The effect of the timing of work/rest (wake/sleep) is regulated by mainly three factors: circadian phase, time since awakening, and amount (and quality of prior sleep). The latter means that too much sleep will reduce the need for a long night sleep, which will cause difficulties of maintaining sleep.

Apart from circadian and homeostatic influences stress, noise, temperature, amount of physical and mental activity (lack of work or of physical activity), and other factors such as stress, worries, anxiety, etc, will affect sleep quality and sleep duration.

4.2.3 Circadian influences

The biological clock will also strongly affect alertness and performance, together with sleep loss and time awake (Dijk et al., 1992). Thus, the effects of the biological clock are superimposed on the effects of sleep loss, such that alertness and cognitive performance will be strongly decreased during the window of circadian low (WOCL, usually night-time) and increased during the window of circadian high (WOCH, usually daytime). This means that the level of performance during irregular work hours will be heavily dependent of the timing of these two factors.

The effects of suboptimal timing of sleep on real life performance and safety are considerable and the risk of road accidents is, for example, strongly related to suboptimal sleep/wake regulation (Akerstedt et al., 2008). The biological clock has two important further aspects: it will start to delay if it doesn't get its daily input of morning light and it will also start to delay if it becomes too much exposed to light in the biological evening (Czeisler & Dijk, 2001). Both these possibilities will strongly affect alertness/performance patterns (as well as sleep duration). The timing of light in relation to the phase of the clock is, therefore, of great importance for sustained functioning and may be used to counteract negative settings of the clock.

4.2.4 Countermeasures

The effects of sleep loss or wrong circadian timing may be counteracted in several ways. One such countermeasure is napping. Even a nap as short as 10 minutes, has remarkable effects on subjective, behavioral and physiological sleepiness (Lahl et al., 2008). And, sleep does not need to be taken in one homogenous bout, but may be subdivided into many sleep episodes during the 24 hours (Mollicone et al., 2008). Thus, one or more sleep episodes may be used to handle difficult timing of the sleep/wake pattern. Caffeine is a traditional and widespread antidote, preferably ingested in controlled amounts (tablets) rather than coffee or similar drugs.

Fatigue Risk Management Systems for space flight. This includes optimization of work/sleep scheduling in space in terms of sleep, alertness and performance. This includes use of mathematical models (see below) for optimization and individual advice on strategies. It also involves training in the use of strategies such as napping or use of caffeine and other drugs. There have been attempts to develop FRMS for space use (Rosekind, 2005) but no validation has been carried out for long space flights

Another issue is that the individual differences are considerable and some individuals seem to be exceptionally resistant to partial sleep loss (Van Dongen et al., 2003), while others easily succumb to sleep loss. Recently, a gene polymorphism in one of the clock genes (PER3) has been linked to vulnerability to sleep loss (Viola et al., 2007). Research on selection depending on the need for sleep or vulnerability to sleep loss seems an interesting way to enhance screening for space flight. The same polymorphism is also related to being more of a morning type (early riser), which may be another factor to screen for if research finds it important in connection with, for example, crew scheduling on long-term missions.

Noise attenuation and reduced workload are simple countermeasures that may not need much research. Drugs for sleep without hangover effects are still not available, but seem to be underway. Drugs for setting the circadian system have begun to be used in a systematic way, but the knowledge of timing and dosing is still not sufficiently established.

4.2.5 Monitoring sleep and sleepiness

The standard way of recording sleep is polysomnography—the combination of EEG, EOG and EMG derivations. Present day approaches include small, solid state recorders, which, however, still might be too intrusive for regular use in space. Recently, new one-electrode approaches with do-it-yourself application have become commercially available. These include the Myzeo (www.myzeo.com) with one electrode on a headband, streaming data wirelessly to a small base sataion.. Another one is MindKit (www.neurosky.com). It uses Fp1-A1 electrodes and transmits to a mobile phone for blink detection. Further development of products on nano-levels should be an attractive research topic. One can envision completely unobtrusive 24h recording of the EEG across long periods of time with continuous updates on the level of restitution of each crew member (e.g., using nano-electrodes).

Alternative techniques include actigraphy. Today, actigraphs are respected monitors of the duration of sleep, but not really of sleep quality. More research is needed in that area. One should also consider heart rate or heart rate variability (see Chapter 5). Both are well correlated with sleep (low heart rate and high variability) and may combine with the measurement of activity. Again, nano-techniques are being developed for unobtrusiveness.

With respect to PSG and actigraphy, there is considerable need for developing criteria for sleep quality. Today there is no consensus on what constitutes sleep quality. Thus, subjective ratings are still the main clinical indicator of sleep quality. However, studies of experimental manipulation of sleep continuity and content of sleep stages in relation to subsequent measurement of physiological sleepiness, neuropsychological performance, brain metabolic rate, as well as sleep quality related indicators such as secretion of growth hormone, prolactin, testosterone, all of which decrease with reduced sleep.

One may also consider measures of sleepiness as indicators of sufficient sleep / restitution. These include the EEG variables mentioned above, but used during wakefulness. Eye movements, including blink duration has been a promising measure for many years, even if commercially available devices do not appear to have reached high levels of validity. Here one sees the development of nano-class cameras that monitor blink duration and slow eye movements built into work stations where the crew member sits in front of a screen carrying out his normal tasks. One might also conceive of 'testing stations' with a wall mounted screen dedicate to ocular sleepiness testing

Subjective ratings of sleepiness are widely used and seem superior to any physiological measure with respect to predicting performance breakdown (performance monitoring is discussed in chapter Y).

4.2.6 Models for alertness and performance prediction

There are several mathematical models available for prediction of alertness and performance (Mallis et al., 2004). These models are quite successful at predicting sleepiness/alertness as a consequence of sleep loss. They are based on circadian and homeostatic (sleep loss, recovery during sleep) components. A few of these models have been validated against road accident risk (Akerstedt et al., 2008), but as a rule their prediction of performance below the level of break-down is not well established.

Individual differences have not been considered to any great extent, however, and it is likely that different individuals have different circadian phase and amplitude and different time constant for the dissipation of alertness over time, as well as for recovery of alertness during sleep. Time on task, type of task, work context are other issues that are not covered by present models. More research on these issues is necessary to make the models applicable to monitoring of individuals. This research includes learning from the individual's prior and present behavior to improve the individual fit.

One particular use of such modeling could be based on unobtrusive actigraphy as input to modeling software. This may be used to continuously monitor predicted alertness levels (given the recent sleep pattern), with a warning feedback when alertness is expected to fall below acceptable levels.

4.3 Evidence from Space

The reason for the interest in sleep in connection with space flight is that virtually all space missions show complaints of impaired alertness and performance, as well as of poor sleep throughout the mission (Mallis & DeRoshia, 2005). Sleep appears to be shortened by about two hours on most missions (Santy et al., 1988, Kanas & Manzey, 2003, Dijk et al., 2001). The sleep problems are also reflected in a sizeable increase in the use of hypnotics – more than 50% of the astronauts used them according to one survey (Santy et al., 1988).

The effects of space flights on sleep architecture appears include strong reductions of Stage REM (Stickgold & Hobson, 1999, Dijk et al., 2001) and a redistribution of Stages 3+4 to the second half of sleep (Dijk et al., 2001, Gundel et al., 1997, Gundel et al., 1993), as well as a decrease of SWS (Monk et al., 1998) and a strong reduction of sleep efficiency, down to 63% (Stickgold & Hobson, 1999). Also sleep fragmentation is increased. The latter is likely to contribute to impaired mental functioning. Dijk et al (2001) also showed a pronounced rebound of REM sleep after return to Earth. It is not clear if such observations can be linked to impaired mental functioning. However, the same authors also described consistent performance impairment and fatigue during space flight.

The main reason for sleep loss is probably the organization of work hours. Sleep time frequently has to be used for urgent operational work. In addition, part of the crew works at the wrong circadian phase and sleeps at an equally inappropriate other circadian phase. Schedules may be simply inverted for half the crew, thus working a 'night' shift throughout the journey (Neri et al., 2003). In other cases one may use 'slam shifts' (12 h jumps in the work schedule) or staggered shifts (gradual shifts) (Mallis & DeRoshia, 2005). Complaints of fatigue and impaired performance mainly occur in relation to such schedules (Santy et al., 1988).

Another aspect is that work scheduling is based on operational necessities and seem to result in an approximately 22.5 h day, which would be difficult to entrain to. As mentioned above, research is being initiated to ameliorate such effects, using light intensity, spectral content, exposure duration. Studies on the ground suggest that entrainment to the Martian 24.6 h cycle is possible but more difficult than expected (Czeisler, 1999).

There are also effects on circadian regulation in itself**.** Thus, phase delays are common (Dijk et al., 2001) and circadian amplitude may be reduced. The latter may be linked to reductions in mood and performance. The causes of circadian disruption are very likely the irregular work rest schedules or schedules with other periods than the 24 hours. This, in combination with lighting effects, may cause circadian disruption since light is the major determinant of the setting of the biological clock (Czeisler, 1995). Light levels may, for example, be very low (10-20 lux) in much of the vessel and 80.000 lux on flight deck common (Dijk et al., 2001).

Effects of microgravity on sleep have not been evaluated systematically, but studies on the ground show shorter sleep, sleep fragmentation, result in longer sleep latencies (Myasnikov, 1975). Noise is a frequent complaint linked to poor sleep in space (Willshire & Leatherwood, 1985). So is high workload, which often interferes with planned work hours (Stampi, 1997). The effect of long-term isolation and confinement has not yet been studied in space missions to Mars may present problems not really conceived of yet. Ground studies may not be relevant to these particular issues, especially in relation to very long duration missions, for example Mars missions. Still sleep is impaired by stress, worries and anxiety and there is a high likelihood of a link between space-related mood changes and impaired sleep. Motion sickness is another possible factor that affects some astronauts (Thornton et al., 1987).

The available research only contains knowledge on short-term missions or long-term stays at space stations. Presumably, missions to Mars will present different challenges. Possibly, the most important countermeasure is physiological work scheduling, that is, preventing sleep from interference with work duties. This should require rather simple adjustment of work/rest schedules, perhaps using mathematical models of sleep/wake regulation as an aid in evaluating high risk schedules. Such approaches are available for general use, but will need adaptation to space and in particular to long missions as well as adjustment to the individual astronaut and his history.

Training of space crew and mission planners is another way of reducing the risk of fatigue. Fatigue Risk Management training is available for air crew and NASA has developed similar training for air crew for future missions to Mars (Rosekind, 2005). Fatigue Risk Management Systems (FRMS) have also been proposed for space flight. This includes optimization of work/sleep scheduling in terms of sleep, alertness and performance, using mathematical models for optimization and individual advice on strategies. It also involves training in the use of strategies such as napping or use of caffeine and other drugs. There have been attempts to develop FRMS for space use (Rosekind, 2005) but no validation has been carried out for long space flights.

In studies on the ground, lighting to cause entrainment to the Martian 24.6h day has been studied. Pulsed strong light (9000Lux) towards the end of the day did cause entrainment (Gronfier et al., 2007). Scheer et al. (2007) showed that 450 lux was sufficient for entrainment to the Mars day when used during the second half of the day, but also that the same level during the first half caused entrainment to the 23.5 h day that often is the result of space crew scheduling procedures. Light slightly above normal room level, it should be emphasized, also has strong direct effects on mood, subjective sleepiness, psychomotor vigilance and EEG and EOG indicators of sleepiness (Cajochen et al., 2000), which may be important for mood on long space flights. Still, we lack important information on how to use light during long-term space travel.

4.4 Research Needs and Implications

The research needs in this area concern:

- *The effects of space flight on sleep*. In particular we need information on long term effects of microgravity, circadian desynchronization, lack of physical activity, as well as the effects on alertness performance on the particular sleep disturbances.
- *Fatigue Risk Management Systems for space flight*. This includes optimization of work/sleep scheduling in space in terms of sleep, alertness and performance, but also application of mathematical models (see below) and strategies such as napping or use of caffeine and other drugs. One may also conceive of training programs exposing astronauts to sleep deprivation in order to make it easier to judge one's on capacity to respond to sleep loss and recognize the danger signs.
- *Astronaut sleep/wake advisory system*. This requires modification of existing mathematical models for prediction of sleep, alertness, and performance to provide with a system that can make recommendations for when to work and when to sleep. The work includes work on the precision of performance prediction, on modifications to account for individual differences (in circadian phase, need for sleep), as well as on effects of work load, time on task and the particular context of long term space travel.
- *New ways of monitoring sleep duration and sleep quality*. This includes technological development of unubtrusive devices for continuous use (nano-approaches to EEG and activity monitoring, but also sleep related hormones such as human growth hormone, prolactin, TSH, testosterone; perhaps via skin-worn nanopatches with detectors for certain molecules, as well as nano-powerplants scavenging from the skin. The embryos of such devices are already present. Sleep/wake recommendations are obviously important also for Earth conditions
- *Objective indicators of sleep quality*. There is no consensus in this area and thus no clear critera exist, but we need valid measures of the quality, continuity and stage composition of sleep of astronauts. This recommendation is important also for Earth conditions.
- *Modification of existing methods of self-reporting of sleep quality and sleepiness*. Can they be used as proxies for objective measures?
- *individual adaptability to sleep under space conditions*. We need to develop methods for expressing intra-individual changes in sleep and sleepiness, as well as individual risk criteria, for which critical levels are established, for example by using sleep deprivation experiments.

5 Psychophysiological State

5.1 Introduction

Extended space missions are very demanding, even for the well-selected crews on these flights, and this are expected to have major effects on physiological state changes. One of the reasons for such large effects is the strongly varying workload and time pressure as well as the changing character of the work during different phases of the flight, including the long-time stay on, for instance, Mars. The activities will vary from short phases that are highly critical, with high responsibility, to long periods in which monitoring and maintaining alertness are the main requirements. Although the crew is well selected, prepared and trained on all aspects of the work in space, this does not mean that their physiological reactivity can be assumed to remain within normal boundaries. Crewmembers will be faced by situations where workload is too high, increasing the risk of making errors. In addition, the problem of maintaining alertness will be exacerbated by inevitable periods of boredom.

We know that diversity in individual physiological response patterns in critical situations (time pressure, extreme workload, stress) is high. However, detailed knowledge in this area is relatively low, and more attention to the topic is required. Moreover, it has to be recognized that various kinds of measure are necessary to assess changes in physiological state during working in space. For instance, it might be expected that cardiovascular measures would provide more insight during prolonged stress, while EEG measures may give more information about alertness changes during working periods.

Earlier chapters have focused on stress related to the extreme conditions of astronauts and the type of workload that they have to face, as well as the problem of impaired sleep. The present chapter addresses the psychophysiological aspects of working in space for a long time. First, the current state of knowledge will be outlined with respect of state changes during mental workload and stress, in particular in relation to (semi-)realistic working conditions on Earth. Then, physiological state changes in space related studies will be discussed, followed by some research issues for extended space missions.]

5.2 Background

Operator Functional State (OFS) concerns the physiological state changes and related response processes that reflect the adaptive task performance of the operator. Operators have to be in a required state for optimal functioning, during their work on Earth or in space. From the other side, working for a longer time under stress or time pressure will induce physiological state changes, while on a smaller time scale reactions to specific events in the work (e.g., warning messages, alerts) will result in specific physiological reactions. Patterns of such reactions will describe the individual responsivity of an operator.

Physiological measures can be used to either detect such state changes or to classify the operator's responsivity during the work. Boucsein and Backs (2000) give an overview of the responsivity of several measures at the mental, physical and emotional level and indicate as well the different studies and conditions under which effects were found for a wide range of measures. In the same volume, Gaillard and Kramer (2000) present a framework for the theoretical and methodological aspects of this field of research.

Several types of measures are available as indicators of psychophysiological state changes. Their usefulness depends on where we are interested in: short or long term effects, state changes versus reactivity to specific stimuli, mental and physical aspects of work, stability of effects, and in the present context the sensitivity to gravity circumstances. Both theoretical and practical aspects thereby have to be taken in consideration. The present summary will pay attention to these aspects. *Table 5.1* summarizes the uses and limitations of the various psychophysiological measures discussed in the chapter.

5.2.1 Brain processes

Optimal functioning of brain processes during the work is of eminent relevance for operators working either in space or on Earth. At the present several complex imaging technique, such as fMRI, are available for studying such processes. Knowing, however, that such methods are, at present, too complex for use in space, the review is restricted to EEG methods for the detection of state changes and operator responsivity.

EEG measures are attractive because of their direct relation to cortical brain functioning, although measurement and interpretation are not always simple and in particular not in complex task situations. EEG evoked potentials (ERPs) give a direct reflection of task related responses in specific brain areas. In laboratory tasks impressive progress has been made during the first decades of their use. Background EEG measures (activity in different frequency bands, such as alpha or beta) are relevant with respect to the activation state of the brain (Kramer, 1991). EEG background measures are used in many studies on mental fatigue, sleepiness and recovery from stress. In particular an increase in the power in the alpha rhythm (8-12 Hz) is seen as an index of stress reduction and relaxation. EEG theta activity at frontal sites (power in the frequency band between 4-7 Hz), and beta activity (frequencies higher than 13 Hz), in general, give information about activation of brain processes during the work (Sterman & Mann, 1995; Hankins & Wilson, 1998; Gundel et al., 2000).

Next to the background EEG effects, event related EEG components (ERPs) are used in studies of mental workload and (visual and auditory) attention. P3 amplitude and latency are seen as indications of increased task load, especially with respect of memory load aspects; CNV amplitudes are related to motor preparation effects (Kramer et al., 1987; Sirevaag et al., 1993). It seems that the pattern of results on EEG background measures is more consistent than that of the ERP components. In this respect it has to be realized that ERP effects are strongly dependent on the specific tasks that are used. In the field of aerospace almost no relevant studies with EEG measures are available, which can be partly related to earlier practical problems and measuring difficulties.

Gevins and colleagues (Gevins & Smith, 2008; Gevins et al., 1998) partly bridge the gap between laboratory based studies and adaptive automation in semi-realistic worlds. In the latter field several research groups are trying to find adequate physiological parameters for optimization of task allocation between the human operator and automation. In two studies combinations of EEG background measures were successfully applied to what the authors referred to as an 'engagement index' (Pope et al., 1995, Prinzel et al., 2000). Scerbo et al. (2000) confirmed the work of Pope and concluded in this context that negative feedback leads to better performance. The conclusion can be drawn that using EEG-based adaptive support is promising, but additional research is needed on consistency, reliability and task dependency of effects.

5.2.2 Cardiovascular state

Next to brain activity, cardiovascular state regulation is highly relevant for maintaining an optimal OFS during either work on Earth or in space. Short-term blood pressure control (baroreflex functioning) is strongly related to mental activity during work. Its basic function in this context is to supply the brain with sufficient blood flow. Although the increases in blood pressure and heart rate are much smaller than during physical activities such as walking or sport, in essence the same processes occur. Two types of mechanism can be distinguished that are concurrently active and have contrasting effects: (1) a defence reaction, occurring with each increase in workload, and (2) activation of baroreflex blood pressure control, which prevents an on-going increase in blood pressure. The defence reaction consists of an increase in blood pressure and heart rate (HR), in combination with a decrease of heart rate variability (HRV) and diminished effectiveness of the baroreflex (Mulder et al., 2009). HRV is defined as the variation of successive changes in inter-beat interval durations. So, HR becomes more regular during higher workload. The baroreflex mechanism protects the system from overload by counter regulation of blood pressure (homeostasis, negative feedback).

In general, HR is increased during both mental and physical activity, while HRV decreases during more demanding tasks, as an indication of additional invested effort (Mulder & Mulder, 1981; see also the review of Boucsein & Backs, 2000). This is found in a number of studies, including workload in flight, especially during take-off and landing (Hankins & Wilson, 1998; Veltman & Gaillard, 1998), and workload studies of ATC specialists and during car driving. Such (defensive) response pattern (Mulder et al., 2009) can be explained in terms of autonomic regulation with a pattern of additional sympathetic activation in combination with vagal suppression (Van Roon et al., 2004; Berntson et al., 2008). Systolic and diastolic blood pressure are increased in general during more effortful task performance, as found, for instance, in air traffic control and in a simulated ambulance dispatchers' task (Mulder et al., 2009). They may be accompanied by increased respiration rate and lower breathing amplitude during higher task load conditions (Pattyn et al., 2010; Backs & Seljos, 1994; Lindholm & Sisson, 1985, Wientjes, 1992; Wientjes et al., 1996; Grossman& Taylor, 2007).

Although this pattern of results looks fairly consistent, this is not all that happens. During longer task performance (15 min or longer) HR may show a habituation response, and decrease with time on task, while HRV increases. This can be seen as an indication that short-term blood pressure regulation (the baroreflex) tries to prevent a further increase of blood pressure by initiating higher baroreflex sensitivity (Mulder et al., 2009). This finding of the time-on-task dependency of HR and HRV variables restricts the usability of HRV as a general index of mental effort in applications in real world or in simulated working environments. However, now that we are able to understand the mechanisms responsible for this pattern, ways can be found to further develop methods to separate the regulatory, time-dependent effects from the short-term changes related to specific task load aspects (De Rivecourt et al., 2008).

5.2.3 Other peripheral changes

Next to cardiovascular processes, there are several other peripheral processes that are related to mental activity or to emotional responses. Electrodermal responses (EDR) are merely seen as indices of emotional activation, although also relations with workload are found (Boucsein & Backs, 2000). Several eye tracking related measures, such as eye blink rate, eye closure duration and pupil diameter, have been used for indications of changing mental workload in aviation and other complex task performance (Sirevaag & Stern, 2000; Hankins & Wilson, 1998; Sirevaag et al., 1993). Also, EMG power has been used in either task-specific or non-task specific muscles, showing in general an increase in EMG power during higher task load conditions. Van Someren and colleagues studied the relation between task performance and changes in skin temperature, sleepiness and sleep stages (Raymann & van Someren, 2007), and found a typical decline of response speed with increasing time-on-task; proximal skin warming accelerated this decline.

Another measure that has not been used frequently, but may have prospects as an index of emotional stress in applied contexts, is voice stress monitoring. Johannes et al. (2000) show that voice pitch can be related to stress responses and reactions to emotional stimuli in a consistent way at an individual level. They concluded that this measure was a good indicator of participants' self-control but did not give strong information about their strain state (Johannes et al., 2007).

In some situations it has great advantages to have combinations of measures from different fields in order to enlarge the insight in state changes that might have been occurred during task performance. This insight, however, will to our opinion only be increased if the theoretical backgrounds and the underlying mechanisms of the resulting response patterns are understood sufficiently. In this context, the relation between physiological costs and task performance quality, sometimes indicated as the cognitive energetical framework, as discussed earlier in this report is a particularly relevant framework (e.g., Hockey, 1997). Indeed, since there is no direct measurement of human performance, the only way to achieve practical relevance in an operational context is to combine different measures, in order to encompass the operator functional state (OFS).

This has been successfully applied in psychophysiological performance studies so far. Melis and van Boxtel (2001) used weighted multidimensional scaling to conceptualize the different factors underlying variations of nine different autonomic response measures and respiration rate, and the relationship to task performance. Johannes et al. (2008), in a similar approach, included HRV, pulse transition time (time between the pulse measured at the heart and the finger), skin conductance level and skin temperature. This set of autonomic measures was used to construct a 'psychophysiological arousal vector' (PAV); individual participants could be classified in groups according to their response patterns as having different autonomic response types. Obtained values reflect individual characteristics of the autonomic responsiveness to mental load and could therefore be interpreted as differences in 'strain'. This type of integrative methodology is still scarce in psychophysiological performance research, but holds considerable promise for future operational applications.

5.3 Evidence from Space

Kanas and Manzey (2008) reviewed human performance literature with respect of working in space; also some connections were discussed with respect of specific brain processes and (general) effects of stress. They concluded that during the first days in space specific brain processes related to spatial orientation, spatial perception and representation and mental rotation might be affected due to microgravity effects. Also, slowing and a loss of precision of voluntary movements were observed. Such effects are transient, and will be recovered within a few days through normal human adaptation. When using specific EEG measures related to these affected processes, different ERP effects might be expected in these first days. The extreme conditions of working in space, in particular during the first few days, might increase general stress effects in astronauts, including impairments of attentional and cognitive processes. Kanas and Manzey argue, however, that in general only moderate effects at this level might be expected, because astronauts are very well trained to do their work in these circumstances.

During this early period, the overall threat to performance may become large because of an interaction between microgravity and stress, though Pattyn et al. (2009) suggested that potential performance decrements in space are more likely to be due to combinations of multiple stressors than to brain processes being affected by microgravity changes. Although the research database, with respect of physiological effects of mental work in space, is still small, available results suggest that the psychophysiological approach to the assessment of human performance may yield additional insights about mechanisms of resource allocation. However, psychophysiological studies in space face an additional challenge, given that microgravity in itself causes disturbances of the physiological parameters used to provide information about OFS, particularly for cardiovascular function. Indeed, the adaptation of the autonomic regulation of the cardiovascular system is a research field in itself, for it is related to one of the most stringent operational problems with regard to spaceflight, namely orthostatic intolerance upon return to normal gravity.

Previous results are also somewhat contradictory: It has been reported that in-flight sympathetic activity may be reduced (Fritsch-Yelle et al., 1996) or increased (Ertl et al., 2002), while post-flight sympathetic activity may be increased (Fritsch-Yelle et al., 1994) or normal (Levine et al., 2002), following upright tilt. It is largely accepted that in microgravity the alteration of the pre-load conditions of the heart, which results from the disappearance of the hydrostatic pressure gradient, leads to increased stroke volume (Prisk et al., 1993) and decreased HR (Fritsch-Yelle et al., 1996), involving several cardiovascular and cardiopulmonary adaptation mechanisms. This change in preload condition and its consequences would be sensed by atrial- and pulmonary stretch receptors, as well as arterial baro- and chemo- receptors, thus altering these responses, all potentially having an influence on HR, HRV and respiratory sinus arrhythmia (RSA) (Migeotte et al., 2003).

Table 5.1: Psychophysiological measures and their usefulness in space flight

Measures	***Main aspects***	***Usefulness***	**Restrictions/remarks**
Cardio-respiratory *(Known to be modified by microgravity in space)*			
Heart rate (HR)	Activation level	If good reference available: HR increase is a robust sign of mental activity	Strongly dependent on physical activity and blood pressure regulation
Heart rate variability (HRV)	Autonomic regulation indicator	Rest – Task difference: good indicator of mental effort, esp. in short task segments	Sensitive to large task differences; time-dependent , baroreflex control; needs local time reference
RSA (as part of HRV)	Vagal activation/ mental relaxation	Respiration related changes in HRV where resp. pattern is stable: good indicator of vagal activity (relaxation)	Dependent on respiration rate and depth
Blood pressure and related measures	Stress and sympathetic activation indicator	Baroreflex related to mental effort; Increased blood pressure influences all CV measures	Difficult to measure during normal work; can be used in specific sessions
Respiration rate and depth	Activation/ task & state related	Resp. rate and depth increase with activation and tension	Dependent on physical movements and signal quality
EEG-measures *(Measured with caps/helmet-mounted in test situations; results affected by eye movements)*			
Alpha-rhythm (8 – 12 Hz)	Relaxation	Stress reduction/relaxation, alertness, sleepiness	Finding good reference(s) is not easy Eyes open/closed: differences
EEG-Theta (4 – 7 Hz)	Activation	Increased during high cognitive demands, memory load	Finding good reference(s) is not easy
EEG – Beta (13 – 20 Hz)k	Activation	Increased levels during high memory load	Finding good reference(s) is not easy
ERP: P3-amplitude and latency	Task load	Indicator(s) of task load and memory activity	Strongly task dependent
ERP - CNV		Motor preparation effects	Strongly task dependent
Other measures			
Skin conductance	Emotional responses	Emotional activation, workload, time pressure	Sensitive to unrecognized daily changes,
EMG	Task load	task load related changes	Sensitive to movements
Eye related pupil diameter, eye blink, eye closure	Task load	Changing mental workload, state changes and sleepiness	Difficult to measure and to interpret during normal work; dependent on environmental lighting
Skin temperature	Emotional stress	Vigilance; related to sleepiness and sleep stages	
Voice pitch	Emotional stress	Sensitive to stress /emotional reactions, self-control	No strong relation with strain state

Considering the lack of consensus on the physiological adaptation, the available data are still too sparse to draw conclusions on psychophysiological changes. Furthermore, despite the fact that Di Rienzo et al. (2008) showed that short term blood pressure control and autonomic functioning needs an adaptation period of a few days before returning to pre-flight levels, there is still no clear description of the time constant of these adaptational processes.

Despite the lack of psychophysiological data from spaceflight, a few studies so far point out interesting leads for further research. Pattyn et al. (2009) compared the cardio-respiratory response patterns during mental task performance during the spaceflight and in other stressful operational conditions. They reported a link between decreased autonomic reactivity and impaired cognitive control, thus suggesting that decreased reactivity to challenge might underlie performance impairments under stress. Wientjes et al. (1996) studied cardiovascular and respiratory responses under prolonged isolation using a complex decision task. An important finding was that cumulative stress effects emerged in two of the four subjects, who displayed increased levels of interpersonal conflict, related to specific responsibilities of these two crewmembers for the success of the mission. This indicates the need for the use of customized single sample methodologies to counter the problem of small sample sizes that characterize spaceflight research, rather than trying to maintain the usual approach of population based inferential statistics.

5.4 Research Needs and Implications

As described before, psychophysiological measures will warrant a more complete evaluation of performance. However, the available data shows that, even for Earth application, further research is still needed before an operational applicable tool can be defined. This means, on the one hand, that knowledge obtained from existing literature in the field can be used for estimating possible effects in space, while, on the other hand, more specific knowledge has to be obtained in those relevant areas where insufficient information is available. These include the following:

- *Individual reactivity and stability of response patterns, both in normal working conditions and in space environments*. Almost all findings in literature are based on averages of groups of participants, rather than individuals. However, it is well known that both the levels and responsivity of physiological variable levels vary remarkably between operators under changes in workload and stress. The long selection and training period of astronauts offers great possibilities to study in detail these individual response patterns during work on Earth and to compare them in a later phase with patterns in space, for instance during the flight towards or during the stay on Mars. Moreover, the response patterns of the group of astronauts may be compared to a *control* group of operators on Earth. The challenge is to find working conditions of such a group in real world that meet those of the astronauts
- *Testing fitness for work*. These same pre-flight baseline data can be used to test daily deviations in physiological state of the astronauts before the working day begins. This allows the detection of possible risks of starting to work while being in a non-optimal physiological state. Up to date relatively little knowledge on this topic is available in literature.

- *Providing adaptive support*. Knowing the individual pre-flight response patterns, as well as possibly those under normal working conditions in space, it might be expected that periods of overload (and underload) can be predicted from sets of relevant physiological measures. This information might be used to provide adequate support (adaptive automation or adaptive support) to the astronauts (on the right moment, in the right way) to improve task performance or to maintain performance at a high level.
- *Analysis of individual response patterns to performance under stress*. The main issue identified by the present chapter is to follow work-related physiological state changes of astronauts during their extended flights and to identify critical situations on the basis of these data. Therefore, individual characteristics have to be measured, starting during the pre-flight training periods and continuing during the flight. Comparison of individual pre-flight data with those during the mission gives insight in possible critical changes (overload, underload) for a particular astronaut. Comparison at group level gives more information about critical working conditions during the mission and about psychophysiological differences in task effects between working either in space or on Earth. The investigation of the set of measurements and the combination methodology allowing for an economic and sufficiently thorough approach to the psychophysiological measure of performance in real-time can be identified as a key issue in this regard.

6 Human-Automation Interaction

6.1 Introduction

Clearly, a high level of automation is essential for all technical aspects of space missions, particularly where precision of controlled movement and complex computation are involved. However, the role of humans as highly skilled experts is also critical for the success of overall mission objectives (McCann & Spirkovska, 2005). With respect to human performance issues, the main interest is in the design of automation for effective human-machine interaction, not only for individual operation of equipment and task management, but also to enable crewmembers to collaboration reliably with each other, and with technical systems, in the sharing of tasks. Research on human interaction with complex systems over the past 30 years has provided clear guidelines for the design of automation that supports the human operator (Parasuraman & Wickens, 2008). An understanding of how automation can best be employed by humans is highly developed in many other high technology areas, notably industrial process control and aviation. In these domains human factors research has played a major role in shaping the way in which automation operates. However, while applications to space missions have clearly been successful, there does not seem to have been the same strong tradition of evaluating automation solutions through human factors research programmes.

6.2 Background

6.2.1 Automation requirements for future space missions

The greatly extended missions envisaged for human space exploration will require continued sophistication and refinement of automatic systems. Current technology is characterized by the use of supervisory control systems, in which the role of humans is primarily one of monitoring and checking that the automation is working effectively. The inevitable proliferation of supervisory level control and robotics means that astronauts will have less direct control over actions, with a consequent loss of feedback and support for skill maintenance (Sheridan, 2002). Such systems also pose major problems in terms of increased demands for monitoring, and uncertainty in decision-making and in planning occasional required interventions. Ironically, problems caused by the lag in ground-space communications with missions to Mars and beyond mean that highly supervisory systems may not be suitable. The limited potential for ground command intervention means that crewmembers will need to have a semi-autonomous role in responding to evolving operational problems and emergencies. For example, Hoffman and von Richter (2003) have suggested that a high level of local autonomy will be essential for management of specific sub-systems involving robotic surface exploration, such as rovers, mobile laboratories and drilling. For all such operations, a high level of transparency and effective feedback are essential.

The requirements for automation extend to all technical aspects of future missions: on-board information and control, maintenance and fault management, robotics, surface exploration, medical problems, etc. This requires a high level of design to ensure compatibility and positive transfer of training between different modes and applications, and across the wide range of information sources needed: e.g., electronic documentation, piloting systems, monitoring systems, video and audio databases, health care databases. There has been a long-running debate about the use of automation in landing (Sim, Cummings & Smith, 2008; Tobin, 1999), but, in the absence of Earth-based control, it is clear that interfaces will be needed at least as a back up for real-time landing operations.

6.2.2 Advantages and disadvantages of automation

Parasuraman and Riley (1997) have defined automation as '… a device or system that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator.' But how should this be achieved? The human factors literature on automation has identified severe shortcomings in the way systems have sometimes been implemented, taking little account for the needs and capabilities of the humans involved. In particular, over-automation has been shown to result in skill degradation and reduced involvement with the processes being controlled. The problem is not with automation per se, but with the need for automation to be designed in such a way that it provides appropriate feedback and dialogue opportunities for the human operators who need to use it (Norman, 1990). Woods and colleagues (e.g., Sarter, Woods & Billings, 1997) have argued that much automation suffers from 'clumsiness'; while not helping much with difficult jobs it actually makes simpler tasks more difficult. Apollo lunar surface astronauts interviewed by Mary Connors (Connors, Eppler & Morrow, 1994) confirmed this perspective: 'Automate all you want, but don’t make the crew’s job or the mission more complex.' Connors et al. (1994) added that NASA is '(still) not doing a good job in this area; the automation systems being tested increase the crew’s workload, not reduce it. Nobody is talking to the test subjects and crew before they come up with fancy widgets, or tailoring items to the exploration mission.' A core issue here is that human ability to interpret and respond to unspecified events may be compromised by over-reliance on automation. For example, with respect to teleoperated exploration, it has been observed that what robotic vehicles such as the Mars Exploration Rover (MER) can achieve during an entire day on Mars takes human geologists only a few minutes (NASA, 2004). For fine-tuning of landing sites, on-the-spot humans are likely to be better than the best-automated map databases and auto-land systems.

6.2.3 Approaches to allocation of function

How do designers decide what to automate and what to leave for humans? The main approaches are summarized in *Table 6.1*. During the 1950s, the primary goal of automation was to reduce human involvement to a minimum. This philosophy continues today, as the 'left-over principle': automate everything that can be done by the computer, and leave humans with those aspects that are too difficult (or expensive) to automate. Bainbridge (1983) pointed out the 'ironies of automation'; when things went wrong, operators could not respond effectively because they had been designed 'out of the loop'. A more informed (compensatory) approach adopted generalized recommendations for function allocation based on assumed relative human and machine capabilities (Fitts, 1951). While this has certainly been of considerable value, not least as a default comparison for alternative designs, it has proved too limited for complex modern systems, with the rapid evolution of machine capabilities and the demonstrated need for sharing of task control between human and computer agents.

Table 6.1. Approaches to the design of function allocation in automation

Left-over principle	Automate everything that can be done by machine; leave humans functions that are too difficult (or expensive) to automate
Compensatory	Automate functions machine is better at; leave humans functions they are better at (*Fitts list* approach)
Complementary	Automate only those functions that humans cannot manage reliably or are not attractive to them (*human centered design*)
Adaptive	Intelligent allocation policy, taking account of human limitations; design functions to be allocated dynamically

A reaction to the constraints of the Fitts list is found in recent recommendations for solutions based on ‘human-centered design’ (HCD), where the wishes, needs and responsibilities of operators are given priority (Billings, 1996). This (complementary) approach has many advantages and goes a long way towards answering the problems of clumsiness. However, it has not taken account of the natural limitations associated with impaired operator functional state (OFS). For example, human operators are vulnerable to surges of demand and loss of capacity under stress and fatigue (Hancock & Desmond, 2001; Hockey, 1997; Wickens & Hollands, 1999), and may not be able to maintain reliability of system performance. This represents a genuine design dilemma for automation. On the one hand, there is a demonstrated need for human involvement, even in machine-managed tasks; on the other, it is necessary to take account of operator limitations, even in human-centered tasks. An increasingly adopted solution is the use of dynamic or adaptive allocation (AA), in which functions may be switched between human and machine, depending on changing circumstances. This is discussed further in the next section.

6.2.4 Level of automation

It is clear that automation need not be an all-or-none feature of a function; rather, level of automation (LOA) can vary from minimal support of the machine for humans to carry out the work to full machine control, with no human involvement. Sheridan and Verplank (1978) identified 10 levels, from 1= no automation to 10 = full automation. These are differentiated primarily in terms of control of decision-making and action; for example, levels 2 and 3 offer moderate support to human decision-making, while levels 6-9 involve the operator successively less in computer-executed decisions. More useful in terms of function allocation, however, may be the extended framework proposed by Parasuraman, Sheridan and Wickens (2000), which considers LOA for four broad task functions, representing successive stages of the human perception-action processing cycle: acquisition, analysis, decision, implementation. The use of automation will usually need to vary between these different task elements, though there is little evidence of such issues being addressed formally by existing systems. Effective design needs to be based on a formal analysis of both task functions/goals and LOAs, and an assessment of human-machine performance under the full range of possible conditions in which the system is expected to operate. Miller and Parasuraman (2008) suggest that this should include not only overt performance (speed, accuracy), but factors such as workload and situation awareness that set limits on overall system competence.

A flexible function allocation design would allow LOAs to change for each of the different phases of tasks, with changes in priorities, criticality, operator states, etc. The use of adaptive automation appears to offer the most promise for this. Humans can be given control of most of the tasks requiring discretion and judgment, as well as other activities of interest and relevance to their needs. Intelligent decision support can be provided (using an LOA of, say 2 or 3), with the option of LOA being increased when they are under strain or unmanageable levels of workload, or when increases in load can be predicted.

6.3 Evidence from Space

The relevant questions for the use of automation to support human performance in space missions are centred on the assessment and comparison on different designs for the human-computer interface. Surprisingly, there appears to have been almost no direct research on this within either actual space environments or relevant simulations. This is perceived as an urgent need; supervisory control has become the default option for the development of new technical systems (Sim et al; 2008), even though their severe limitations for effective human involvement are well documented. McCann and Spirkovska (2005) make a further point, often overlooked in design of automation; a very high level of automation is not efficient for a crewed spacecraft since it fails to make use of available onboard resources—the highly skilled crewmembers—who, with appropriate training, can function as subject-matter experts.

The main indications of what might be appropriate for space missions come from the use of automation in highly technical systems such as aviation, air traffic control (ATC) and process control rooms, as well as laboratory simulations. For example, ATC controllers perform very reliably under normal conditions but are known to 'lose the picture' with very high levels of traffic (Sperandio, 1978). Adaptive automation can be used to increase LOA during high traffic periods, resulting in better overall system performance (Hilburn, Jorna, Byrne & Parasuraman, 1997).

Another way of introducing adaptive automation is through the identification of strain states in the operator, for example resulting from generalised stress or extended involvement with high-level demands. This may be inferred either from performance changes below the level of primary task error (secondary task performance or effort indices) or from changes in relevant psychophysiological systems. Kaber and Endsley (2004) showed that providing increased decision support when overload was detected improved both performance and situation awareness, while Wilson & Russell (2003) showed that triggering increased automation under physiological sates associated with high workload resulted in better multitask performance. Recent work by Hockey and associates (Ting et al., 2010) combined these approaches in the form of a fuzzy logic controller linking brain and cardiovascular indices of mental effort with indicators of performance variability. The adaptive controller switched to a higher LOA whenever previously identified strain states were encountered, reverting to the lower LOA when the state changed back to normal. Although more work is required to develop individual operator models, a normative version of this adaptive control model resulted in fewer system errors and reduced levels of fatigue in most of the participants. While such approaches to human-automation interaction are still at an early stage of development, they promise the possibility of flexible designs for automation that is able to take account of the inevitable variation in the human capacity for effort and reliable performance management.

6.4 Research Needs and Implications

Clearly, our understanding of the automation requirements for effective human involvement in extended space missions, such as that planned for Mars, is very limited. While autonomous systems will be needed for much of the routine management of system goals, much still needs to be known about the most effective kinds of automation for supporting on-board decision-making. But this may not be straightforward, particularly during the post-flight exploration phase. For example, it is estimated that crew time will be at a premium, with perhaps only 1-2 hrs per day available for system monitoring, maintenance, documentation and planning (Hoffman & Kaplan, 1997). This means that a very high level of autonomous control is required, and that the interfaces must be highly usable and reliable. Four broad areas of research effort are indicated:

- *Flexible interfaces.* A strong suggestion from the literature in other technical areas is that function allocation should be designed to operate in a flexible way, depending on human needs, requirements and constraints (Miller & Parasuraman, 2007). Accordingly, a major area of research effort is likely to be the use of adaptive interfaces and augmented cognition to support crew members when limitations are identified in their capacity for managing task information, or when high risk operator functional states are identified (e.g., in autonomic or brain indicators of fatigue). Coupled with this is the need for research on determining optimum LOAs for different task functions. A similar trend is the identified need for systems to be *adjustable* by the operator (Dorais et al., 1990). In this case, changes in the level of automation are initiated directly by crewmembers whenever a need is identified—for example, in the fine-tuning of instructions for Mars rovers (which otherwise function as autonomous vehicles) based on feedback received from sampling sites.

- *Collaborative cognition*. Another area hardly touched on within space research is concerned with human-machine interaction at the crew level. This requires the design of systems that embody and promote collaborative cognition – sharing of information and control – not only between crewmembers, but also between humans and non-human agents (computers and robots). Cuevas, Fiore, Caldwell & Strater (2007) argue that, even during supervisory control, the design of the interface should encourage the human operator to consider automation components as crewmembers, instructing their computer colleague to carry out sequences of actions or provide information for human use.
- *Skill maintenance and training*. A major problem for the involvement of humans in the management of complex mission tasks is the need to be able to maintain necessary levels of operational skills during prolonged journeys. A specific concern is the need to carry out unscheduled medical interventions, where top-up training needs to be complemented by effective computerized support tools. This is a third area where a programme of systematic research is needed, since skill maintenance is made more difficult by the highly automated on-board environment. Crew intervention is usually required only when faults occur with automatic control or when infrequent scheduled manual sequences need to be activated. However, research on the design of effective training for skill retention has generally been piecemeal and fragmented.
- *Interaction with robots.* The inevitable proliferation of robotic sub-systems during extended space exploration poses new challenges for human performance. In many cases, robots will act as surrogate crewmembers or have roles that overlap with those of humans. In such cases, there is a need to develop better understanding of human-robot communication: the ways that human and robotic agents interact; the advantages and disadvantages of investing robots with human-like qualities (facial expression, voice, gesture, etc); and issues relating to trust and transfer of control between human crew and robotic agents.

7 Skill Maintenance

7.1 Introduction

Extended exploratory space missions, e.g. missions to Mars, will provide many new challenges which mark a qualitative difference to orbital spaceflights or expeditions in extreme environments on Earth (Kanas & Manzey, 2008). One of these challenges involves long transfer phases between Earth and the other planet. During these phases the crew needs to maintain knowledge and skills that typically are acquired and trained pre-flight on Earth but will only be needed at the destination of the flight. For example, a mission to Mars will include transfer phases which can last 6-8 months, primarily dependent on the selected trajectory and propellant consumption. During this period, the crew needs to maintain all skills needed for critical operations after entering the Martian orbit and landing on the Martian surface. These might include, e.g., complex psychomotor skills needed for undocking and maneuvering the landing vehicle for a safe landing on the Martian surface; skills for operating rovers and specific robots and tools, or cognitive and psychomotor skills needed for conducting pre-planned experiments and scientific investigations on the Martian surface. As a consequence, the capability of crewmembers to maintain critical operational skills over prolonged periods of non-use or non-practice will become an important factor of mission success.

Human performance issues related to difficulties of skill retention have already been reported from long-duration orbital missions. One particular example involves a collision between a Progress capsule and the former Mir station. This collision occurred in 1997 when a cosmonaut failed to perform a docking maneuver correctly under conditions of restricted visual feedback. According to Ellis (2000) one of the factors which supposedly contributed to this event involved an issue of maintaining the appropriate skills over a prolonged period of non-use: 'In fact, because of the 4-month lapse since his last formal training, Tsibliyev *(the cosmonaut)* may not have received sufficient or timely practice for the specific docking conditions he faced.' (p. 8). Although in this example issues of skill retention just represent one of many contributing factors involved in this accident, it nevertheless highlights the possible risks related to a lack of long-term skill retention during spaceflight. Interestingly the relevance of skill retention for astronauts had already been acknowledged during the NASA Apollo program. Practical issues at that time regarded the retention of skills for operating the lunar lander during pre-flight quarantine and the transfer flight to the Moon. This led to one of the first literature reviews of skill retention research provided by Gardlin and Sitterly (1972), cited in Patrick (1992).

7.2 Background

7.2.1 Determinants of skill retention: state of current knowledge

Although issues of skill retention have attracted research interest for many years, relatively less systematic research has been carried out than in other areas of skill (e.g. training or acquisition). Most of this research has addressed retention of skills needed for discrete or continuous tasks with strong demands on visuo-motor coordination. In contrast, much less attention has devoted to mainly cognitive tasks, such as complex decision-making or problem solving (e.g., Sauer, Hockey & Wastell, 2000), and virtually no research is available on long-term retention of skills related to communication and teamwork.

Early examples of skill retention research are represented by studies of Neumann and Ammons (1957) and Fleishman and Parker (1962). Neumann and Ammons (1957) studied the retention of a serial perceptual-motor skill, operationally defined by operating to sets of eight switches in a certain sequence. Evidence for skill decay already was found after a retention interval of 20 mins and continued to decline with the retention interval getting longer. After one year of non-practice, task performance was found to be back to the level at the beginning of the original training. However, a different pattern of results was reported by Fleishmann and Parker (1962). They trained participants over six weeks with a two-dimensional compensatory tracking task, and tested their performance after retention intervals ranging from 1 to 24 months. In contrast to the findings of Neumann and Ammons (1957) very few indications of skill loss were found. These results already point to the impact of the nature of skill on skill retention. More specifically, they suggest that skills needed to perform continuous perceptual-motor tasks like tracking can be much better maintained without practice than skills needed to perform discrete tasks that involve remembering of a certain sequence of actions. This difference also matches the everyday observation that, once acquired, even complex skills such as cycling, skiing, or snowboarding can be maintained very well over long periods of non-use, whereas psychomotor or cognitive skills involved in discrete tasks (e.g., setting up a technical system according to a defined procedure) are much more vulnerable to forgetting over time. Narrative reviews of this early research are provided by Naylor and Briggs (1961), Annett (1979) and Farr (1987).

Summarizing the main findings of this research, Patrick (1992) identified three different factors which seem to represent the most basic determinants of how well complex skills can be retained after training. Not surprisingly, these include (1) the level of performance at the end of training, (2) the length of the retention interval, and (3) the possibility of rehearsal training during the retention interval. The first of these factors reflect two different aspects which need to be distinguished. One aspect involves the basic fact that certain amounts of skill decay are better tolerated if the decay starts on a relatively high compared to a low level of performance. This suggests '…that training variables which improve the level of performance at the end of the training will also improve retention' (Patrick, 1992, p. 102). The second aspect regards the impact of overlearning, which seems to represent an effective countermeasure for skill decay (Driskell, Willis & Copper, 1992). Overlearning does not necessarily lead to higher performance levels during training but a higher level of memory consolidation of a skill that makes it more resistant to decay over time (Schendel & Hagman, 1982).

Some more specific variables affecting skill retention have been identified in a first formal meta-analysis of studies dealing with skill decay or retention (Arthur et al., 1998). This analysis was based on a very large sample size (n=178) and still represents the most recent summary of research findings in this area. Less surprising, the most important factor determining the level of skill retention again turned out to be the length of the retention interval. Averaged across all kinds of skills and tasks, performance decreased at more than one standard deviation over a period of one year of non-practice. However, this basic effect was moderated by several additional factors, including the degree of overlearning, the similarity between the situational contexts of training and retrieval, and the nature of tasks. The first two factors were found to entail particular strong effects. This suggests that skill retention is directly dependent on how well the skill has been consolidated, and how well the training environment matches the work environment where the skill has to be applied. With respect to the nature of tasks the results provides evidence that performance in 'natural' tasks (i.e., real working tasks) is better maintained than performance in artificial tasks (laboratory tasks), and that cognitive skills are forgotten more quickly than perceptual-motor skills involved in continuous control tasks. The finding that performance in natural tasks can be better maintained than performance in artificial tasks might easily be explained by differences in motivation and, thus, challenges the validity of laboratory research for assessing risks of skill decay in real working environments. However, the difference between cognitive and perceptual-motor skills is of some theoretical importance. It partially it supports the earlier findings reported above and suggests that the efficiency of skill retention might also be related to the format in which these skills are represented in memory; i.e., to what extent they depend on procedural vs. declarative knowledge.

7.2.2. Example: retention of resuscitation skills

The retention of *c*ardiopulmonary resuscitation (CPR) skill may serve as an interesting model in the present context. Basic characteristics of this skill include that it represents a complex skill which is based on procedural as well as declarative knowledge components, can hardly be routinized during limited amount of training, typically needs to be applied after more or less long periods of non-practice, usually gets acquired under more or less relaxed conditions, but needs to be applied under conditions of high emotional stress and workload.

Most of these characteristics also constitute important aspects of operational skills of astronauts which are acquired during ground-based training on Earth but need to be applied only after an extended time of non-practice in space. The determinants of acquistion and retention of CPR skills have been explored in many studies (e.g,. Hamilton, 2005; Kaczorowski, Levitt, Hammon, Outerbridge, Grad, Rothman & Graves, 1998; McKenna & Glendon, 1985; Tweed, Wilson & Isfeld, 1980; Wik, Myklebust, Auestadt & Steen, 2002). The results show that maintenance of these skills over prolonged periods without any rehearsal training is hardly possible. However, the amount of decay can be quite different for different components of the skill. For example, McKenna and Glendon (1985) examined the decay of three different components of CPR skills over retention intervals of 3-36 months. The components considered included (1) the technique for inflating lungs and pressing chest, (2) the performance and timing of heart compression, and (3) the diagnosis of the patient's state. Their results suggest that cognitive skill components (i.e. providing a correct diagnosis of the patient' state) are much more vulnerable to skill decay than motor components, and that most of the skills already decay during the first three (diagnosis) to six month (motor components) after training. Kaczorowski et al. (1998) trained family physicians in neonatal resuscitation skills and knowledge. Follow-up tests conducted 6-8 months after training revealed that the physicians were better able to maintain their knowledge than their practical performance skills.

Factors which have been found to support CPR skill retention include overlearning (Tweed et al., 1980; Wik et al., 2002), practical simulator ('manikin') training with online feedback provided by an automated feedback mechanism or external instructor (Hamilton, 2005; Wik et al., 2002), or training with simulations of a variety of cardiac arrest scenarios (Hamilton, 2005). However, most interesting in the current context, even given a very good basic training, long-term retention of complex skills like CPR does not seem possible without frequent rehearsal trainings. Such trainings must be provided on a regular basis and address all essential components of the skill. Thus far, less is known about the optimal timing and design of refresher trainings. Whereas Berden et al. (1993) recommend trainings every 3-6 months, Kaczorowski et al. (1998) did not find any visible beneficial effects of manikin-based or video-based trainings provided at this time-interval. The finding that a considerably skill decay already takes place during the first three months at least suggest that more frequent rehearsal trainings would be necessary to fully prevent a decay of skills.

7.3 Evidence from Space

Maintaining complex performance skills during spaceflight does not only involve basic issues of skill retention but also issues of maintaining skills under the impact of extreme environmental conditions characterized by confinement and isolation, as well as a significant change of gravitational force. However, most of the research conducted during spaceflight only has addressed effects of specific stressors (e.g., microgravity, workload) on basic cognitive and psychomotor functions, and almost no studies are available that have monitored skill retention over the course of a long-term spaceflight (Kanas & Manzey, 2008).

Thus far, only very few sets of data are available from spaceflight or simulations studies which seem to be relevant in this context. For example, Salnitski and colleagues (Salnitski, Myasnikov, Bobrov & Shevchenko, 1999; Salnitski, Dudkin & Johannes, 2001) investigated the level of performance of cosmonauts in a simulated manual docking maneuver during their stay in space and a ground-based simulation study, respectively. This manoeuver requires complex perceptual-motor skills for controlling an approaching spacecraft that can move with six degrees of freedom. Without providing any refreshment training they found a considerable loss of skill after a period of three months, which, in case of spaceflight was mainly attributed to a lack of on- training under changed gravity conditions.

Another set of data involves results from a long-term performance monitoring study conducted during a 14-months space mission (Manzey, Lorenz & Polyakov, 1998; Manzey, 2000). This study examined performance in different laboratory tasks, including a compensatory tracking task and a dual-task consisting of tracking and concurrent memory-search. Effects on single-task and dual-task tracking performance over the course of the mission are shown in *Figure 7.1*. Significant decrements of performance compared to the level that was reached after skill acquisition training (days -87, -34) only occurred at times when the astronaut had to adapt to changes of gravitational force, i.e. after entry in orbit and immediately after return to Earth. However, it only needed few trials to adapt the acquired skills to the new conditions. Once relearned, performance in these tasks remained impressively stable without any visible performance changes even after several weeks of non-practice during the flight.

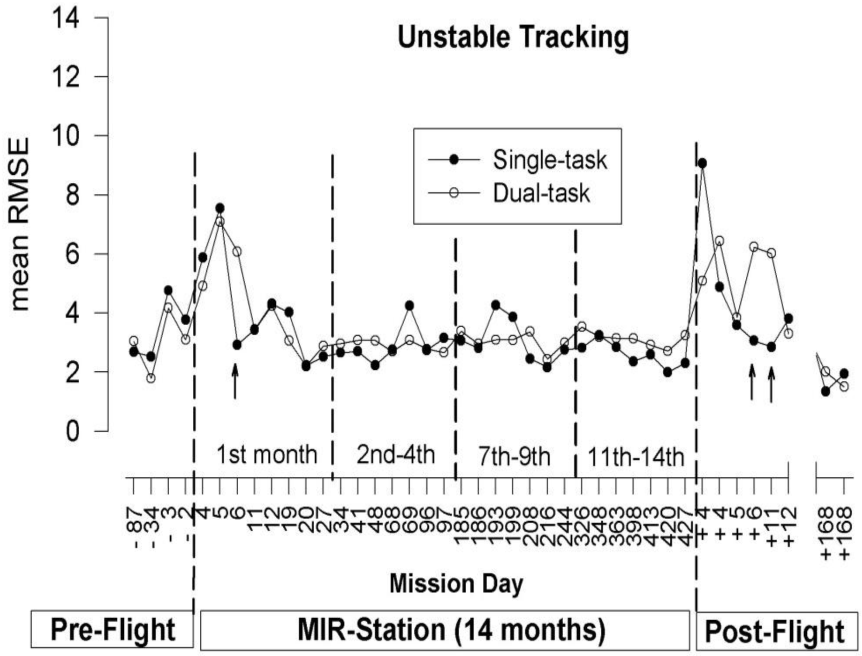

Figure 7.1. Maintenance of single-task and dual-task tracking performance over 14 months in space (adapted from Manzey, Lorenz & Polykov, 1998)

In contrast to the results found by Salnitski et al. (1999, 2001) these results suggest that overlearned basic performance skills can be maintained very well even under the extreme conditions of spaceflight. Similar results also have been reported from two studies which investigated the stability of complex performance skills in analogue environments: a 135-day ground-based simulation of a long-term spaceflight (Sauer, Hockey & Wastell, 1999a) and an 8-month wintering-over in Antarctica (Sauer, Hockey & Wastell, 1999b). Based on a 'micro-world' approach these studies investigated how well humans could maintain complex decision-making skills under conditions of confinement and isolation. The results did not show any evidence for a significant decay of performance skills over time, although some subtle performance changes were found, which seemed to be related to a stress-induced adaptation of performance strategies. However, the retention intervals in these latter studies never exceeded 30 days and, thus, their conclusiveness with respect to *long-term* skill retention under conditions of isolation and confinement is limited.

7.4 Research Needs and Implications

The research conducted thus far suggests that maintenance of basic perceptual-motor skills involved in tasks requiring continuous control does not represent a major problem as far as these skills become over-learned during the process of skill acquisition. In contrast, skills needed for performance of discrete (procedural) tasks seem to be much more vulnerable to decay over periods of non-use. However, because procedural skills usually are based on declarative (explicit) knowledge, a possible forgetting of skill can be very well compensated by means of written descriptions of procedures or checklists. Therefore, a possible decay of procedural skills also does not seem to represent a serious problem for long-term spaceflights.

More difficult in this respect is the retention of highly complex perceptual-motor skills (such as manual docking) which probably can hardly be overlearned, and skills which consist of sub-skills based on procedural and declarative knowledge. As has been exemplified by the research on maintenance of 'resuscitation skills', the latter skills often show a fast decay which often have been found to be more pronounced in cognitive than motor components. However, the pattern of results, thus far, is not very consistent, and clearly more research is needed to understand better the differences between different sorts of tasks with respect to long-term retention issues.

In addition, more knowledge is needed about the optimal frequencies and design of rehearsal trainings which might be applied to support long-term retention of different tasks. Furthermore, only less attention has devoted, thus far, on the link between processes of skill acquisition and retention for this kind of skills. Although it seems to be obvious that the efficiency of skill retention probably depends on how well the skill has got acquired, very few research has determined what training strategies (despite overlearning) are most effective in this respect for what sorts of tasks.

However, the probably most important lack of research thus far regards the possible impact of the extreme environmental conditions during long-term spaceflight in maintenance of complex skills. This relates to the more general question on how skill maintenance is affected by changes of environmental conditions. For example, most of the skills of astronauts are acquired during ground-based training under comparatively relaxed conditions. However, they usually need to be applied later under more or less stressful conditions, either induced by the generally harsh living conditions in space or a kind of high risk condition (such as undocking and docking of a Mars lander). This again resembled the situation known from resuscitation skills, but less is known about the effects of stress on skill maintenance. Although there is some evidence that conditions of isolation and confinement does not interfere with skill retention, the small number of studies available and the specific skills considered do not allow for any decisive conclusions in this respect. Even more important with respect to future interplanetary missions is the possible impact of gravitational changes on maintenance of motor skills. For example, during a flight to Mars, skills that have been acquired pre-flight under 1 g conditions will have to be maintained during the transfer flight to Mars under microgravity conditions (if options of artificial gravity are not available), in order to get applied on the surface of Mars in a 0.38 g environment. This will not only involve issues of skill retention over a long time but also issues of repeated re-learning of skills under different gravitational forces during the mission. Results from performance monitoring studies in space suggest that re-learning is possible and that it only needs a few trials to adapt skills to new conditions of gravity but this research thus far has limited to investigations of basic tracking skills. It remains to be seen to what extent these results might be transferred to long-term maintenance of complex skills under these conditions. In addition, research is needed about how trainings must be designed to make skills resilient against variations of external conditions and stress. Last, but not least, virtually no research is available about long-term retention of interpersonal and teamwork skills. Given the raised significance of these skills for success of long-term spaceflights studies addressing this issue is of high importance.

In summary, it is recommended to establish a research program focusing on issues of skill maintenance. The following research questions and topics should be addressed:

- *Skill maintenance*. Investigate to what extent qualitatively different sorts of skills are prone to skill decay over time; consider sufficiently long time periods (1 year +); investigate to what extent long-term skill retention is affected by conditions of confinement and isolation typical for long duration space missions.
- *Training*. How much overlearning of complex performance skills is needed in order to ensure long-term skill retention? What intervals of re-fresher trainings and what kind of training methods are necessary and most useful to maintain complex performance skills over long retention intervals under the specific conditions of space flight? What sorts of training methods are most effective to make skills resilient against variations of external conditions and stress? What sorts of training methods are most suitable for on-board rehearsal training of critical operational skills? What sorts of training methods are most effective to support a fast re-learning of perceptual-motor skills under different levels of gravity? To what extend are interpersonal skills and knowledge maintained over long periods of time? What training methods are effective to support retention of interpersonal and teamwork skills?

8 Teamwork

8.1 Introduction

Human performance during space flight may be degraded by shortcomings in communication, coordination and cooperation within the crew or between crew and ground control. Misunderstanding and interpersonal conflicts may reduce effective processing and team cohesion, which degrades effective performance. The longer the duration of a spaceflight, the greater is the risk that incidents will be triggered by interpersonal conflicts and negative emotional states. This not only will degrade performance, but also jeopardize team cohesion and the health of crew members. Even minor psychological problems can gradually result in performance failures, because of the strong interactions between work and non-work activities, given the restricted and isolated environment. With adequate intervention and countermeasures these negative effects may be prevented or at least mitigated, and both performance and health may be maintained.

According to the NASA Human Research Evidence Book (Schmidt et al., 2008) hardly any studies have examined team effectiveness during spaceflight. However, evidence collected in interviews with astronauts and research in analogue environments demonstrates that poor individual and team performance may be caused by ineffective team processes. The present chapter considers the factors that determine team effectiveness and the subsequent effects on performance. The key factors are team cognition, social skills, team cohesion, team training, and psychosocial adaptation.

8.2 Background

Mission success, in particular during long-duration space flights, is determined not only by the cognitive abilities of the individual team members, but also by the quality and effectiveness of team processes (Schmidt et al., 2008). In this a distinction may be made between two types of processes during work and during non-work activities: (1) work-related communication, coordination and cooperation, largely dependent on team cognition—the shared mental model team members have on the way work has to be planned and executed; (2) interactions between crew members during non-work activities, such as rest, sleep, leisure, care and support, dependent largely on interpersonal skills and team cohesion. Although in principle interactions between crew members outside work should be separated from those at work, this will not always be the case. Poor interrelationships outside work and low team cohesion are likely to influence team cognition negatively and therefore reduce team effectiveness.

8.2.1 Team cognition

Team performance depends not only on the knowledge, skills and processing capacity of the individual team members, but also on team-level factors (team cognition, quality of the communication, coordination of activities, cooperation) and on extra-role performance—the willingness to attend to and to care about other crew members (Stahl, 2006). The effectiveness of these team processes is facilitated when crewmembers share similar mental models. These shared mental models (SMM) encapsulate the knowledge structures teams possess about team member functions and the task environment (Cannon-Bowers, Salas, & Converse, 1993). Based on their SMMs team members adapt their actions to changing work demands and to coordinate them with those of other team members. This enables the crew to adopt an implicit mode of coordination and to reduce costs of task management (Entin & Serfaty, 1999). Team cognition provides the glue that binds together the individual mental models, allowing them to engage effectively and safely in coordinated team actions through access to a shared understanding of the task and how it needs to be managed. Team cognition is a critical limiting factor when crew performance is challenged by threats from system failure, time pressure, high workload, or by interpersonal conflicts and tension.

Maintaining and promoting team cognition has been shown to play a major role in preventing performance degradation in teams (Salas, Cooke & Rosen, 2008), though there is no relevant data for space environments. On a limited scale, these issues have been examined in military settings, and occasionally in space flight simulation. During spaceflight astronauts have to adapt continuously to a dangerous, isolated, and confined environment. Because of these limiting factors astronauts have very little control over their environment over a long period. These effects will be enhanced by the little control astronauts have over their work: they cannot always decide who is doing which tasks at what time.

Team cognition is assumed to play a critical role in maintaining team effectiveness, in particular when task performance is vulnerable for poor communication, coordination, and cooperation. Although research on this matter is not available, it is very likely that interpersonal conflicts and even moderate mutual irritations, both during work and non-work, will negatively affect the interactions between crew members, resulting in reduced team cognition, and therefore team effectiveness. Thus, the maintenance of team cognition is dependent not only on the design of the work environment, but also on the maintenance of team cohesion.

8.2.2 Social support and team cohesion

Ground-based studies have shown that a high workload in combination with a low task control increases the risk for performance failure, and psychological and health problems (e.g., Karasek & Theorell, 1990). However, these studies also show that these negative effects on performance and health can be mitigated by psychosocial factors, in particular social support and team cohesion. Social support and good communication among team members may decrease the negative impact of individual strain, buffering the effects on team effectiveness. Social support appears to play also an important role in the adaptation process during spaceflight. However, support by mission control and professional help, or family and friends, may become difficult or even impossible due to the long delays in communication with Earth. A crewmember has to rely fully on the support of fellow crew members (in particular the leader) and on self-help (computer) programs.

Members of cohesive teams sit closer together, focus more attention on each other, show signs of mutual affection, and display coordinated patterns of behaviour. They also are more likely to give due credit to their mates, whereas team members with weak relationships tend to take credit for successes and blame their team mates for failure. Most evidence regarding the impact of cohesion on performance comes from non-space domains, in particular from the military and civil aviation, showing that cohesive teams are more productive. In aviation, 'crew errors' have been estimated that contribute for 65-70 percent to serious accidents (Sumwalt & Watson, 2001). Accident and 'mishap' reports note lack of communication and coordination and poor decision making as significant causes of performance failure. Meta-analyses across studies from different domains (Mullen & Copper, 1994; Oliver et al., 2000; Beal et al., 2003; Schmidt et al., 2008) show that cohesion enhances performance, in particular in existing and small teams as compared to ad-hoc and large teams. The impact of poor cohesion on performance is larger when the work requires more collaboration (Beal et al., 2003). In a meta-analysis of 67 ground-based studies, Gully et al. (2002) noted that team performance is affected by the teams' generalized beliefs about the capabilities of their team. Negative attitudes and interpersonal conflicts will degrade team cohesion. Interpersonal conflicts should be distinguished from task conflicts. Interpersonal conflicts are about relationship issues, whereas task conflicts are about how to handle tasks. Interpersonal conflicts appear to be more destructive for team effectiveness because more often (negative) emotions are involved. In contrast, moderate amounts of conflicts on how to perform a task may even enhance performance because team members may correct each other's perceptions, offer alternatives, or argue about how to solve a problem (see review of Mannix and Neale, 2005).

Since future crews will be multi-national, and thus multi-cultural, the diversity in teams needs more attention. Cultural differences appear to have a negative influence on psychological adaptation. Therefore they will have an increasing impact on team effectiveness during long-term missions. Ground-based studies suggest that these effects may be mitigated by psychosocial factors, which act as a buffer: clarity of the roles of team members, social support and good communication within the team.

8.3 Evidence from Space

A major concern for extended missions is the stability of performance and well-being, which is likely to be threatened by the extreme physical and psychological conditions (loneliness due to loss of communication, monotony, and boredom). Although major breakdowns are unlikely, problems such as loss of motivation, failures to cope effectively, and reduced team cohesion and self-confidence may negatively influence involvement in both mission and team goals. More information and tools are needed to prevent performance degradation and reduced well-being.

Although it is clear (for example, from Antarctic studies) that persons and teams who are better adapted, are also more effective, there is still little evidence on the person characteristics, which predict who is more likely to adapt effectively to the psychosocial demands of long-term missions (see also Kanas & Manzey, 2008). For example, persons who find themselves well-adjusted to the work environment have fewer physical and psychological complaints, are more productive, and learn more. Studies examining astronauts during MIR operations show that there appears to be a limit to how long a person can adapt to a stressor. Although astronauts are capable of adapting for 6 months in orbit, MIR participants developed symptoms of fatigue, irritability and minor disorders of attention and memory.

8.3.1 Increased autonomy during long-distance flights

During long-distance missions, crew members will be isolated from ground control for a long time, because communication with Earth is delayed with 40 min or more. This implies that the crew needs to get a higher level of autonomy, which will affect the relationships between crew members, and the relation to ground control and to their families and friends. To meet these demands crew members will need to get more responsibility for planning their work and non-work activities, dealing with on-board medical and psychiatric emergencies, and coping with interpersonal problems with only little support from families, friends, and personnel in mission control.

The requirement of a higher level of autonomy is likely to disturb both stabilized interpersonal relations and team cognition. There will be large differences between crewmembers in how they will incorporate these changes (due to differences in personality, cultural norms, or space agency (Boyd et al., 2009). However, when these problems can be solved, a higher level of autonomy may even enhance team cognition and team cohesion, making the crew more effective and resilient for high task demands and stress reactions. A relevant issue is whether it would be better to provide a higher level of autonomy (i.e., an opportunity rather than an obligation) from the start of the mission, so that crewmembers do not feel that it is forced upon them by default, only when support is no longer available.

Very little is known about the way changes in autonomy affect team cognition, or how such changes interact with non-work factors such as loss of motivation and interpersonal conflicts, although Kanas et al. (2010) and Sandal et al. (2011) have begun to examine such factors affecting autonomy in space simulation environments. For example, Sandal and her colleagues found that introducing greater autonomy during a space simulation study was perceived as highly positive by crew members as frustrations due to outside factors (including Mission Control) were reduced. However, at the same time, individual differences between crew members became more salient, when tension increased.

One of the unknown aspects of long-duration missions is how the behavioural norms and values adhered to by crew members may change after a long period of isolation and confinement. According to Kanas and Manzey (2008), a partial or complete loss of commitment to the usual (Earth-bound) system of values and behavioural norms may result which can involve unforeseeable risks for the performance of mission tasks, the individual behaviour, and the interpersonal interactions, which might make any external control and guidance of the crew impossible. Crew members may displace in-group tension onto people on the outside, such as their families or mission control personnel (Kanas et al., 2007). During long duration expeditionary missions, crewmembers will have to function autonomously and depend on each other for support and safety. To guarantee that crew members remain able to perform mission tasks and interact appropriately with each other, tensions need to be detected as early as possible. Only when potential disrupting factors are identified, countermeasures can be employed to solve interpersonal problems.

8.3.2 Team cohesion and interpersonal conflicts

Although no studies have examined the impact of cohesion on performance during space flight, case studies, interviews, and surveys provide evidence, suggesting that team cohesion plays a critical role in maintaining performance and well-being during spaceflight. Failure to maintain a reasonable level of cohesion may results in errors and interpersonal conflicts (Grice & Katz, 2005). Instead of deciding what a reasonable level is, it may be more effective to develop means to build and maintain cohesion in teams, in particular during long-duration flights. Poor team cohesion, as indicated by breakdowns in coordination, exchange of resources and information, and role conflicts, has been mentioned as contributing to both the Challenger and Columbia shuttle accidents (Launius, 2004). A high cohesiveness may also be disadvantageous. It may lead to 'groupthink', which may reduce the willingness of crew members to voice disagreement or concerns that do not conform to the majority in the crew (Sandal, Bye & Van de Vijver, 2011).

8.3.3 Interpersonal skills and team composition

Although most authors agree that it is desirable to select astronauts who are best suited to work in a team, very little research has been done on this issue. So far only one study (Sandal, 1999) has reported that astronauts with good interpersonal skills performed better during teamwork. Similar results have been found in seven ground-based or analogue studies (see for a review, see Schmidt et al., 2008). Drawbacks of this type of study are the limited number of astronauts and the lack of general agreed methods to determine the quality of performance and interpersonal skills during space flight. Besides on interpersonal skills, crew members may also be selected on their interpersonal compatibleness. Although the empirical evidence is still scarce, this factor is regarded to be an important determinant of psychosocial problems and interpersonal conflicts, and therefore a real risk for the successful completion of the mission.

Several studies have shown that team diversity affects team cohesion and therefore team performance. Similarity between members in attitudes appears to facilitate communication and therefore reduce the effects of role conflict. In particular, deep-level diversity (e.g., attitudes, beliefs, cultural background) relevant for long duration spaceflights because the effects increase, when crew members get to know each other better, whereas the effects of surface-level diversity (i.e., age, gender, and ethnicity) become smaller (Harrison et al., 1998). The impact of diversity may be reduced by training team members together, by providing incentives to manage interpersonal conflicts, and by giving instructions on how to deal with differences in attitudes.

8.3.4 Culture and communication

In several recent space simulation studies (Kanas et al., 2010; Sandal, 2004; Tomi, 2001; Tomi et al., 2007), cultural differences were found to play a role in many of the personal conflicts that took place either within the crews or between the crew and ground control. A recent study by Tomi et al. (2007), involving astronauts and ground personnel working for one of the space organizations involved in the ISS program, found various problems associated with differences in work style and poor communication; misperceptions, misunderstandings and language problems were among the most often mentioned challenges. Besides language and cultural factors, the crew members mentioned the following aspects: attitude towards the mission, technologies, research practices, gender relations, and communication style. According to the crew members, an interpersonal training program including both the crew and ground control could have been prevented or reduced these problems.

Communication plays a critical role in the quality of team processes, during work as well during non-work activities. During work it is not only important for exchanging information, coordination and cooperation, but also for maintaining team cognition within the crew. During non-work periods, communication is important for maintaining team cohesion and good mutual relations and for solving conflicts between crew members. Poor communication may lead to misunderstanding, and therefore to errors which jeopardizes the success of the mission. In addition, it may lead to irritations, and therefore to interpersonal conflicts. Several surveys (e.g., Kanki et al., 2009) have reported that miscommunications may lead to problems in multi-cultural crews even between crews (e.g., UK and US) that speak the same language but have a different cultural background.

8.4 Research Needs and Implications

Most evidence on the impact of psychosocial factors on team effectiveness has been obtained in ground-based studies in related domains (e.g., army, police). More research is needed to show whether these findings can be generalized to spaceflight. Given the extraordinary psychosocial environment, in particular during long duration spaceflights, this generalization is not to be underestimated. Moreover, it will be more difficult for the emotional psychosocial processes than for the more rationalistic cognitive processes (for example, decision making).

The relation between cognitive processes (during work) and psychosocial processes (during non-work activities) has been examined only on a limited scale, because they are subject of different disciplines. For example, team cognition originates from human factors and team cohesion from social psychology. More integral research is needed to examine the interrelationships and mutual effects of the two types of processes.

Little is known about the optimal strategies to maintain resilience and team performance during long-duration space missions. Central aspects include confidence, motivation, and stress management. More research is needed to determine which psychosocial factors (such as team cohesion and social support), interpersonal skills, and person characteristics (such as coping style and self efficacy) best support psychosocial adaptation during long-duration missions (see also Whiteley & Bogatyreva, 2008). On the basis of this research measures can be developed to keep the team focussed on the mission goals and motivated to meet the work demands.

Specific research needs are summarized below.

- *Team cognition*. Within space research the problem of team cognition has been hardly touched. Research is needed to examine which factors influence the development and maintenance of team cognition. It appears likely that person characteristics (e.g., coping style, trust, attitudes, etc.) and team characteristics (e.g., team cohesion, interpersonal conflicts) will play a critical role. A related question is how changes in autonomy affect team cognition.
- *Delayed communication*. So far we have little direct understanding of the impact of reduced and delayed communication on crew-ground relationships or crew functioning, nor of the more specific effect of the resulting increase in required autonomy. Although one study on Earth demonstrated that crewmembers can learn to adapt to this situation, further research needs to be done in the space environment (Kanas et al., 2010).
- *Team cohesion and interpersonal conflicts*. Interpersonal tension and team cohesion have been studied in space analogue environments (see Kanas et al., 2010) and during LEO space missions, but more work needs to be done in preparation for longer missions. Although astronauts often engage in expeditionary training activities to promote team cohesion, there is no scientific evidence regarding the methods that are most effective to promote team performance for long-duration missions (Schmidt et al., 2008). More research is needed on the factors that determine the ability of crewmembers to bond and work together during extended periods, and on the measures that can be taken to protect performance from the effects of interpersonal conflicts and reduced group cohesion.
- *Team training*. As indicated in Chapter 7, training of crew members represents one of the most important countermeasures for preventing performance breakdown during prolonged space missions. Training may be regarded as the last line of defence for the human operator as it represents the opportunity to turn concepts into behaviours, and lessons learned into best practices (Kanki et al., 2009). This holds in particular for long-duration missions in which the crew is isolated and communication delayed for extended periods. Because of the limited opportunities for ground-based support and the impossibility of short-term rescue, crewmembers cannot rely much on external help, but are required to solve any conflicts and problems on their own (Kanas & Manzey, 2008). More specifically, crews on such missions must be able to deal with any internal or external crisis by themselves with only little help from ground. Each individual crew member must be able to protect her/his own performance state over long periods of time, ranging from a minimum of six to seven months during missions to the Moon up to three years during a mission to Mars. These challenges will clearly raise the importance of psychological pre-flight training compared to current approaches for ISS missions.
- *Stress training*. How well crew members are able to maintain an optimal performance state over long-duration space missions depend on their coping and social skills. These skills also play an important role in the prevention of the degradation of motivation,

well-being and health. Therefore, one way to secure the maintenance of performance and health is to train the crew to cope with stress and fatigue, and to handle interpersonal conflicts. Stress training and team training include all general skills needed for effective stress management, teamwork, and co-living within a small confined crew. The two types of training should be given within the same training program because they are closely related. There is an interaction between the stress tolerance of a particular crew member and the resilience of the team, and vice versa. Whether a crewmember experiences stress, depends not only on individual stress tolerance, but also on the resilience of the entire crew. When a team has a hardy leader the team members will be more resistant to threats during a mission (Bartone, 2006). Moreover when crewmembers know that they are supported by their colleagues, emotions evoked by threat are less intensive, which reduces the risk of performance degradation or unwanted behaviours (e.g., Karasek & Theorell, 1990).

9 Conclusions and Recommendations

9.1 Summary of Emergent Themes

The main body of the report has considered a range of topics that bear on the management of crew performance in space operations: stress, workload, sleep, psychophysiological state, automation, skill maintenance and team-level issues. All chapters make a number of general recommendations for new research that is needed to clarify the nature of threats to performance. However, a number of emergent themes may be identified, which cut across individual chapters. These illustrate the urgent need for new directions in ESAs research and development programme. While these themes provide a brief rationale for the specific recommendations (*R1-6*) in section 9.2, the mapping between themes and recommendations is not one-to-one; the relevance of themes for specific recommendations is indicated.

9.1.1 Countermeasures as proactive design (R1-6)

We have not assigned a separate chapter to the topic of countermeasures, since it is an intrinsic feature of all chapters. The end goal of any research on the core problem of assessing human performance in practical contexts is to determine how best to manage the potential threats identified. The most effective countermeasure is always attention to design: automation and the human-computer interface; habitat; crew selection and interaction; stress management; and a range of embedded monitoring, support and training procedures. Good design will prevent all but the most unexpected problems from becoming unmanageable. Thus, the recommendations below are intended to influence design at all levels—countermeasures that are proactive rather than reactive. When unexpected problems do occur during missions, an awareness of the general principles of human performance under stress and threat may help in providing *ad hoc* solutions, but planning for problems is a superior strategy.

9.1.2 The human operator as an adaptive controller (R1, 2, 3)

The OFS perspective shows us that human operators (or crewmembers) are not passive elements in the response to task demands. Instead, they are actively managing their actions in order to maintain a balance between the execution of task goals and the satisfying of personal values for competence, wellbeing, and cognitive comfort. Performance on important tasks is normally highly competent, but may be threatened by the need to sustain high levels of effort for long periods. Even though performance appears to be error-free, the strain of managing such states under stress or emergency situations gives rise to an increased risk of breakdown, and a switch away from memory-demanding strategies to the use of short-cuts and heuristics. It is now clear that such high-risk states attract increased costs of task management for autonomic and brain systems involved in cognitive control and effort, and may be inferred from appropriate analyses of psychophysiological state indicators. Systematic monitoring of psychophysiological state will enable high-risk states to be identified in crewmembers before a breakdown occurs in performance. However, the validity of such data is known to depend on being able to relate observed changes to individual response characteristics and patterns.

9.1.3 Inadequacy of standard performance testing (R1, 3)

Performance testing in space-related environments has relied on standard laboratory tests to examine changes in cognitive and perceptual functions, and, as is evident in the preceding chapters, have generally failed to demonstrate any serious problems. Three drawbacks of such tests is that: (1) they are often too easy to carry out, making only low level demands that do not stretch cognitive resources to the limit; (2) they are typically inadequately learned, so that performance improves with further practice during the testing phase; and (3) they are perceived by astronaut groups as games—trivial and unimportant—which do not engage their work motivation. The overall problem is that such tasks do not provide a realistic test of the operational work that needs to be carried out during space missions. Some success has been achieved by some of the TT group with a low fidelity (micro-world) simulator (CAMS), but a better match to actual operations is needed to provide relevant ecologically valid data on performance problems.

9.1.4 The need to improve skill maintenance (R4, 6)

Perhaps the greatest behavioural threat to successful space missions is the degradation of task skills, particularly during long duration missions, where critical procedures (e.g., landing, docking, emergency sequences) are required only rarely. Training for performance of complex tasks needs to be flexible, to allow for effective transfer to unusual operating conditions (unexpected events, novel problems, emergencies). Despite more than 100 years of research on learning and skill, it is still not clear how best to carry out ground training in order to make operational skills more resilient to degradation with long periods of disuse, and flexible enough to transfer to changing circumstances. There is a clear need for crewmembers on missions to have access to regular support from on board training systems. Again, only limited knowledge is currently available on how to make this effective, without intruding unnecessarily on leisure time or inducing boredom.

9.1.5 Issues relating to crew effectiveness (R5, 6)

The effectiveness of crews over long-duration space missions will depend on the ability to solve a number of problems related to their need to function as a team, rather than just as individuals. These include the maintenance of crew cohesion, and a common motivational direction and commitment to mission goals, and an ability to manage stress and fatigue, emerging from both outside the group (work or environmental stress) or from within (interpersonal conflicts). Such skills will also help to minimize the impact on individual well-being and health. A further issue is the growth area of team cognition, a concern with effective collaborative information management in task sharing, in which team performance is greater than the sum of individual contributions. Team cognition is recognized increasingly (e.g., by US military) as a superior way to design the work of teams, but it requires a shift of emphasis, with the team, rather than the individual, as the unit of analysis, in both training and the design of on-board equipment.

9.2 Specific Recommendations

The major recommendations of the TT report are summarized below. These are all issues that we believe are fundamental to the success of long-duration missions involving humans. While the majority of the recommendations assume the need for sustained programmes of research and development, in most cases fundamental ground-based work has already been carried out, providing proof of concept. We strongly recommend that ESA/ESTEC consider the feasibility of these proposals in relation to long term planning of human space exploration, and, where possible, incorporate them into new research programmes or technical development work. Where appropriate, they should also be built into future calls for research projects where psychological and performance issues play a central role.

R1 Modular integral monitoring

The strongest recommendation is for an integral monitoring system, to allow optimal management of human resources. We envisage a modular system with at least four components: crew performance monitoring, psychophysiological (and sleep) state, subjective state, and a group interaction monitor, including both team cognition and interpersonal information. These could be used separately or together, to provide convergent markers of operational risk.

R2 Database of individual state patterns

The interpretation of on-line psychophysiological data requires individually referenced databases. It is proposed that such data could be collected routinely from candidate astronauts, as they experience different kinds of tasks and stressor conditions at different stages in their training. These could be refined and validated during further training and used to provide stable reference criteria for real-time operational assessment of individual crewmembers.

R3 Medium fidelity simulation platform

We propose the development of a medium fidelity task simulation platform, based on actual simulation training. It should characterize the core cognitive and perceptual activities of the technical work of crews, but able to be implemented on a laptop. The platform would be available for use in research projects to provide an ecologically valid and sensitive indicator of performance. It could also be designed to provide a wide range of performance data for use in integral monitoring.

R4 Skills maintenance training

There is a need to consider adjustments to the astronaut-training programme to ensure effective training for long-term skill maintenance. We propose (1) a programme of research into how best to train skills for long-term stability, accessibility and flexibility of use; (2) incorporation of these findings into the training programme, with iterative evaluation; (3) development of on-board skill support tools.

R5 Design of collaborative work systems

We propose the development of technological aids and computer-based interfaces capable of supporting new methods of team working and learning. Such systems should be able to sustain knowledge sharing, problem solving, situation awareness, information management and role flexibility among crewmembers, while allowing them to retain individual ownership of specialized skills and responsibilities.

R6 Integrated crew level training

Beyond the individual training recommendations of R3, we propose the development of an integrated crew-level training programme that draws together team skills, interpersonal skills and group-based strategies for dealing with operational tasks, stress and interpersonal conflicts. The different types of group training should include the full range of skills needed for stability and resilience of team functioning: team cognition, stress management, social cohesion, and co-living within a confined habitat.

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