THESEUS

Cluster 2: Psychology and Human-Machine Systems - Report

CLUSTER 2
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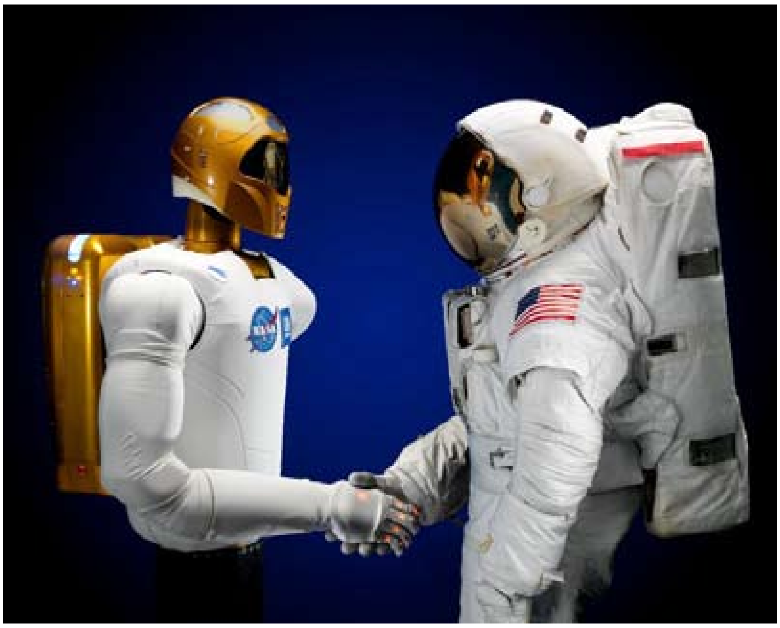
Towards Human Exploration of Space: a EUropean Strategy



Cluster 2: Psychology and Human-Machine Systems - Report

Group/Team Processes

Human-Machine Interface

Skill Maintenance

THESEUS: Towards Human Exploration of Space – a European Strategy

Past space missions in low Earth orbit have demonstrated that human beings can survive and work in space for long durations. However, there are pending technological, medical and psychological issues that must be solved before adventuring into longer-duration space missions (e.g. protection against ionizing radiation, psychological issues, behaviour and performance, prevention of bone loss, etc.). Furthermore, technological breakthroughs, e.g. in life support systems and recycling technologies, are required to reduce the cost of future expeditions to acceptable levels. Solving these issues will require scientific and technological breakthroughs in clinical and industrial applications, many of which will have relevance to health issues on Earth as well.

Despite existing ESA and NASA studies or roadmaps, Europe still lacks a roadmap for human exploration of space approved by the European scientific and industrial communities. The objective of THESEUS is to develop an integrated life sciences research roadmap enabling European human space exploration in synergy with the ESA strategy, taking advantage of the expertise available in Europe and identifying the potential of non-space applications and dual research and development

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THESEUS Expert Groups

The basis of this activity is the coordination of 14 disciplinary Expert Groups (EGs) composed of key European and international experts in their field. Particular attention has been given to ensure that complementary expertise is gathered in the EGs.

EGs are clustered according to their focus:

Cluster 1: Integrated Systems Physiology
Bone and muscle
Heart, lungs and kidneys
Immunology
Neurophysiology
Nutrition and metabolism

Cluster 2: Psychology and Human-machine Systems
Group/team processes
Human/machine interface
Skill maintenance

Cluster 3: Space Radiation
Radiation effects on humans
Radiation dosimetry

Cluster 4: Habitat Management
Microbiological quality control of the indoor environment in space
Life support: management and regeneration of air, water and food

Cluster 5: Health Care
Space medicine
Medication in space

Identification of Research Priorities and Development of the THESEUS Roadmap

Each Expert Group based their work on brainstorming sessions dedicated to identifying key issues in their specific field of knowledge. Key issues can be defined as disciplinary topics representing challenges for human space exploration, requiring further attention in the future. These key issues were addressed to the scientific community through an online consultation; comments and inputs received were used to refine them, to consider knowledge gaps and research needs associated to them, as well as to suggest potential investigations.

The outcomes and main findings of the 'Integrated Systems Physiology' EGs have been synthesised into this report and further integrated to create the THESEUS roadmap.

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1 Group/Team Processes

1.1. Introduction

One of the defining characteristics of space missions is that humans operate primarily as a team, yet, they also have individual needs, preferences, skills and personalities. Crews sometimes operate explicitly as teams (with common task goals) and sometimes as separate individuals within a group (with personal goals). These roles, however, can overlap and effective inter-personal interactions between crew members are critical to overall mission success. The concern of the Expert Group on 'group/team processes' was directed at managing the potential problems associated with this intrinsic dilemma. Although this is a very general issue that has long been at the forefront of human space research, many problems remain unresolved. In addition, it is likely that the demands of extended voyages will make them of even greater relevance to mission success.

Figure 1: Astronauts from Expedition 20 and STS-127 crews having a group meal on the International Space Station (Credit: ESA/NASA)

Almost all aspects of team and group processes are considered important for future research activities, though a number of distinctive aspects can be highlighted. A central issue is the impact of team cohesion on individual wellbeing and performance. While negative emotions and reduced goal orientation are inevitable as a part of everyday interactions, such states can strongly interfere with mission goals. A much better understanding of such effects is required in order to develop procedures for optimising the maintenance of effective performance. A specific problem is the implication of reduced reliance on mission control, necessitated by the greatly increased lag in space-ground-space communications during a journey to Mars. Very little is known about how such delays can affect communication - not only with ground control but with family members - or its impact on the wellbeing of crewmembers. One likely consequence is that the astronauts will be obliged by default to take on an increased level of autonomy in decision making.

Another theme is the development of robust systems to support team cognition - the shared use of tasks and information by the whole crew, rather than individuals. A widespread complication is the knock-on effects of group interactions on individual psychological health, which in turn has implications for team level functioning. At present, there are a number of proposed tools for psychological monitoring and support, sometimes designed to be embedded within the human-machine interface However, the scientific database for such countermeasures remains relatively weak. There is a need to develop effective support tools for the psychological support of crew members, monitoring and responding to both interpersonal conflicts and individual stress reactions. As with the requirement of countermeasures for skill maintenance, there is a need for procedures aimed not only at in-flight support, but also for ground-based training. In all, a total of four broad key issues were identified as worthy of attention by the Expert group.

1.2. Group/Team Processes– Key Issues

1.2.1. Key Issue 1: Maintenance of team cohesion, wellbeing and performance

Relevance for long-duration missions

Figure 2: Japan Aerospace Exploration Agency (JAXA) astronaut Soichi Noguchi photographs the Earth from a window in the Cupola of the International Space Station. It is thought that loss of visual contact with the Earth during a voyage to Mars, may lead to significant behavioural issues (credit: ESA/NASA)

A major concern for extended missions is the stability of performance and well-being of astronauts, which is likely to be threatened by the extreme physical, social and psychological conditions, with reduced communication, monotony and boredom, as well as the loss of a direct visual contact with the Earth (Kanas & Manzey, 2008), which may undermine established systems of values and behavioural norms. These conditions can give rise to loneliness and loss of mission-oriented motivation (e.g., Van Baarsen et al., 2009). Crew members with a good interpersonal network tend to accomplish more than people with smaller networks, even if the latter think they are psychologically well adapted. Ground-based research (Karasek & Theorell, 1990) has demonstrated that high social support and good communication among team members may decrease the negative impact of individual strain, buffering the effects on team effectiveness.

Case studies, interviews and surveys suggest that crew cohesion could play a critical role in maintaining performance and well-being during spaceflight. This is especially important during long-duration expeditionary missions, where the crewmembers will function autonomously and depend on each other for support and safety. Interpersonal tension and group cohesion has been studied under normal terrestrial conditions, in space analogue environments (Sandal et al. 1995, Sandal 2000, Kanas et al., 2010), and during LEO space missions, but more work is warranted in preparation for missions to Mars and/or asteroids. Also, more research is needed to determine which contextual factors (such as social support), interpersonal skills and personal characteristics (such as coping style and self-efficacy) best support psychosocial adaptation during long-duration missions.

Earth benefits and applications

There are many applications; e.g., to group conflict research; personnel operating under isolated conditions; peace-keeping forces; weather stations, military units stationed in foreign countries, industrial teams, and personnel stationed for prolonged periods in remote areas. In addition, knowledge on the impact of cohesion on performance would benefit all work groups where the effective interaction of individuals in teams is required to produce products and services.

Brief review of latest developments

In terms of loneliness, preliminary results in the Mars105 simulation mission suggest that long-lasting isolation may increase feelings of loneliness and abandonment. This may have a detrimental effect on cognitive performance (Van Baarsen et al., 2009), however loneliness may also have a positive effect, supporting adaptation to isolation and confinement. Earth-based studies relating the purpose and meaningfulness of life to wellbeing, sociability, and group-oriented effectiveness (e.g., Lazarus & Delongis, 1983; Harlow, Newcomb & Bentler, 1986; Zika & Chamberlain, 1992) may also be significant for adaptation to confinement and isolation in space (Van Baarsen, 2011). Although major breakdowns are unlikely, problems such as loss of motivation, failures to cope effectively, and reduced team cohesion and self-confidence may reduce effective involvement in both mission and team goals. For example, Kass & Kass (2001) have demonstrated the importance of management of emotions and building of supportive and constructive relations between crewmembers during confinement. Poor team cohesion, as indicated by breakdowns in coordination, exchange of resources and information, and role conflicts have been mentioned as contributing to both the Challenger and Columbia shuttle accidents (Launius, 2004).

There are currently no studies relating cohesion to performance during space flight, though Kanas et al. (2007) found that the cohesion of ISS crew increased with a more supportive commander. Most evidence regarding the relation between cohesion and performance comes from non-space domains, in particular from military and civil aviation research findings. In aviation, various reports have estimated that crew errors contribute to 65-70% of serious accidents (Walters & Sumwalt, 2000). Accident and 'mishap' reports note a lack of communication and coordination, and poor decision making as significant causes of performance failure. Meta-analysis across studies from different domains (Muller & Copper, 1994; Thompson, 2002; Beal et al., 2003) show that cohesion enhances performance, especially in real (vs. ad hoc) and small teams.

A variety of dependent variables have been used to assess the effects of changes in team cohesion: performance outcomes (both individual and team), behavioural health, job satisfaction, readiness to perform and absence of discipline problems. Beal et al. (2003) demonstrated that the impact of poor cohesion on performance was larger when the work required more collaboration. In a meta-analysis of 67 ground-based studies, Gully et al. (2002) noted that team performance is affected by individuals' generalised beliefs about team capabilities. Extreme negative attitudes and interpersonal conflicts will degrade team cohesion. In contrast, moderate amounts of disagreement on how to perform a task may enhance performance because team members may correct each other's perceptions, offer alternatives or argue about how to solve a problem (Mannix & Neale, 2005). Although there is little direct evidence that poor cohesion in teams leads to major performance errors and failure to meet the demands of the mission, it is likely that failure to maintain an adequate level of cohesion may results in sub-optimal performance.

Knowledge gaps and research needs

More research is needed to determine which contextual factors (such as social support, loneliness or boredom), interpersonal skills, and personal characteristics (such as coping style and self-efficacy) best support psychosocial adaptation during long-duration missions (see also; Solodilova-Whiteley, 2007; Suedfeld, 2010; Whiteley & Bogatyreva, 2008; Van Barsen et al., 2009). Little is known about the optimal strategies to maintain resilience and team performance during space missions. Central aspects include confidence, motivation, focus, and stress management. External motivation and self-determined motivation has been studied in sport and work environments and show different results over time on performance and mental health.

The effects of stress on team decision making are also receiving more attention given the critical tasks undertaken by military and industrial teams in hazardous environments. Although astronauts often engage in expeditionary training activities to promote team cohesion, there is little evidence regarding the type and method that are most effective to promote team performance for long-duration missions (Schmidt et al., 2008). While persons and teams who have been trained and are highly motivated are expected to be more resilient to stress (physical, emotional, and managerial) and performance degradation, there is still limited evidence on the personal characteristics that can predict who is more likely to adapt effectively to the psychosocial demands of long-term missions (Kanas & Manzey, 2008). Studies that examined astronauts during MIR operations suggest 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. On the other hand, there is also research on personnel operating in isolated and confined settings that indicate that psychological reactions in a time-limited situation change in a similar manner, independent of the actual duration.

Space organisations have learned a great deal during the past decades from a variety of spaceflight operations. However, new technologies and changes in organisation continually impose new challenges on training programmes. In ISS operations, working procedures had to be adapted to multi-cultural teams who were working in different time zones, at distant locations, and for different organisations. Differences in working habits, values and attitudes, which were not aligned and often incompatible, reduced the efficiency of these teams. Logistics and organisational constraints have resulted in the development of skills in separate training sessions instead of joint sessions. A drawback of this approach is that the team cannot develop team cohesion, although emergency training is done in a few sessions where the six crewmembers are required to train together. When teams are not able to train together as a group, it is even more important that they receive the same behavioural training; using similar case studies, situations and role-plays create a common culture and language for all personnel involved in the programme. The reinforcement of behavioural skills during technical training can increase the possibility that team skills are properly used during all critical technical activities (Kanas & Manzey, 2008).

Proposed investigations and recommendations

These knowledge gaps may be addressed by examining interpersonal tension and crew cohesion throughout LEO or lunar missions and isolating the major factors (e.g., time effects, stressors, personality conflicts) that have a negative impact on them. Such studies may form the basis for the development of countermeasures to prevent the negative impact of team dysfunction and conflicts on performance, individual health, and even safety. Opportunities to conduct research in this area have recently improved, with the wider implementation of simulator-based training for emergency decision-making team and cockpit crews. However, little is known about the transfer of team skills learned during pre-flight training to new, stressful environments.

Figure 3: ESA astronaut Frank de Winne and NASA astronaut Nicole Stott work controls together at the Canadaarm2 workstation to unberth the HTV

More research is needed on the following aspects:

- What are the (mission-related) factors that determine the ability of crewmembers to bond and work together during extended periods?
- How can crew dysfunctions be prevented or mitigated during the course of the mission, especially long-duration missions beyond the Earth-Moon environment?

Empirical knowledge in these areas should result in the development of the following countermeasures:

- Training programmes for multicultural crews that are applicable across agencies and national cultures (for example, NASA Behavioral Health and Performance Training)
- Programmes for joint training between flight and mission control crews for optimal communication and prevention of inter-crew tension during missions
- Monitoring programmes for crews to facilitate self-regulatory behaviour and to identify and deal with team dysfunctions during flight. These programmes should combine stress and team training to maintain cohesion, team cognition, motivation, and effective coping with stress

Trans-disciplinary aspects

No clear links with other disciplines were identified by the Expert Group.

1.2.2. Key Issue 2: Impact of reduced communication between crew and Earth

Relevance for long-duration missions

In planning for a space mission to Mars or an asteroid, crewmembers will be far away from home, and there will be up to a 40 min or longer delay in the two-way communication with Earth, having major implications for both social and operational aspects of crew behaviour. Because of the delay, normal real-time methods of communication are not possible, and mission control will be able to exert less control over the planning and behaviour of the crew. Therefore, crewmembers must adapt to the increase in autonomy. They will need to be responsible for planning their work and leisure time activities, dealing with on-board medical and psychiatric emergencies, and coping with interpersonal problems with little support, not only from personnel in mission control, but also from their families and friends. This will have far-reaching consequences for the way crewmembers will work and live together. For example, they may displace in-group tension to people on the outside, such as their families or mission control personnel, and 'groupthink' may occur which could lead to a loss of individual responsibility for decision-making. Strategies need to be developed for the effective management of communication, despite time delays. For example, one speaker might have to propose a set of alternative responses to his questions that the other can select from in making their response.

The enforced increase in autonomy with delayed communication also has major implications for crew performance; the crew being required to take increasing levels of responsibility for decisions, including interactions with technology that have a default setting for automatic control. Crew 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 extra-role performance—the willingness to attend to and care about other crew members. The effectiveness of these team processes is facilitated when crewmembers share similar mental models. These encapsulate the knowledge structures teams possess about team member functions and the task environment (Cannon-Bowers, Salas, & Converse, 1993). Teams draw on their shared mental models to coordinate and adapt their actions to changing demands of the work and other team members, enabling 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 crew level coordinated actions through access to a shared understanding of the task and how it needs to be managed. This 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.

The requirement to take on a higher level of autonomy is likely to disturb both stabilised individual models and the shared model (team cognition), since crewmembers will have to incorporate these changes and differences between individuals in how they will do this is likely. Such differences may be due to personality, cultural norms or space agency organisational factors (Boyd et al., 2009). However, this may ultimately lead to a higher level of team cognition that is more effective and resilient under stress and task disturbances. While a certain level of autonomy will be built into the design of the human-computer interface, it will also be forced onto the crew by default because of the reduced and delayed communication with mission control. 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.

Earth benefits and applications

Figure 4: NASA Extreme Environment Mission Operations (NEEMO) simulates deep space exploration on the ocean floor (credit: NASA)

Studying the effects of reduced and delayed communication is relevant to many terrestrial contexts where changes in autonomy are relevant, particularly in environments where people will have limited communications with the outside (e.g., military units, crisis/rescue situations, Antarctic overwintering). Understanding the impact on team cognition will benefit teams that have to work in high-risk environments, including safety critical industries, military, police, fire fighters and rescue workers.

Brief review of latest developments

Few studies have been carried out in space simulation or analogue environments on the effects of increased autonomy and delayed communication. Crewmembers participating in simulation studies were found to respond very positively to the introduction of higher autonomy (Sandal, 2010). However, further research needs to be done in the space environment, possibly using the ISS as a platform, to test the effects of communication delays on crew and ground behaviour and performance.

One study done on Earth demonstrated that crewmembers can learn to adapt to this situation and still accomplish mission goals (Kanas et al., 2010). This involved three space simulation settings: NEEMO missions using the Aquarius submersible, the Haughton-Mars Project in a crater in northern Canada, and the pilot phase of the Mars 500 Programme, where a crew of six individual were isolated in a Mars simulator in Moscow for 105 days. High autonomy periods were those where crewmembers planned much of their work schedule, while low autonomy periods required them to work under the direction of mission control. In the NEEMO and Mars 500 pilot study, a delayed communication of up to 40 min was included in the high autonomy conditions. Based on questionnaire responses, results suggested that high work autonomy was well received by the crews, mission goals were accomplished, and there were no adverse effects. While providing a valuable test of the impact of increased autonomy on wellbeing, Kanas et al. (2010) did not, however, make any measurement of crew cognition or performance across the different conditions.

Maintaining and promoting team cognition has been shown to play a major role in preventing performance degradation in teams (Salas, Cooke & Rosen, 2008), from simple cross training (to becoming familiar with each other's roles) to Crew Resource Management (CRM) training (Kanki, Helmreich & Anca, 2010), which routinely includes shared cognition and team coordination of actions. So far, there is no direct research on training in relation to the need to manage changes in autonomy, and no relevant data for space environments.

Knowledge gaps and research needs

It is clear that there is 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 increase in required autonomy.

The crew-ground relationship has been studied under normal terrestrial conditions, space analogue environments and LEO, but more knowledge is necessary to prepare for longer missions. Little is known about how crew and ground personnel build a shared situational awareness of the mission and how it affects both crew and ground control performance. A particular issue concerns developing ways for mission control to participate in mission critical events under conditions of reduced communication. Although increased crew autonomy will be necessary, the involvement of mission control (in providing expertise and feedback) is still desirable for crews to function effectively in extreme situations (e.g., dealing with dangerous and unexpected situations; crises involving equipment, or the medical and psychological well-being of a compromised crewmember). Much more also needs to be known about the best ways of maintaining the relationship between crewmembers and their families and friends; how the crew micro-culture develops and affects team work, both positively and negatively; and the factors that determine the displacement of crew tension to outside personnel on the ground (Kanas et al., 2007).

On a limited scale, issues of crew cognition have been examined in military settings, and occasionally in spaceflight simulation, but there has been no direct research during space missions, either during flight activities or in distributed teams involving mission control or surface-orbital interactions (e.g., during a MARS mission). Even less is known about the way that changes in autonomy affect either mental models or team cognition, or how such changes interact with non-work factors such as loss of motivation and within-team conflict. Sandal et al. (2010) found that introducing greater autonomy during a space simulation study was perceived as highly positive by crew members, since frustration associated with outside factors (including Mission Control) was reduced. However, at the same time, individual differences between crewmembers became more salient as a source of tension. The value of team training has also been demonstrated by many studies, again mainly in aviation and military contexts (Salas, Cooke & Rosen, 2008), from simple cross training (to become familiar with each other's roles) to Crew Resource management (CRM) training (Helmreich & Merritt 1998), which routinely includes shared cognition and team coordination of actions. So far, there is no direct research on training in relation to the need to manage changes in autonomy.

Proposed investigations and recommendations

To address these issues, two broad sets of questions need to be examined under conditions of space or simulated space conditions:

- Research is required on the effects of restricted and/or delayed communication on relationships between individual crewmembers, and also with (a) monitoring personnel in mission control, and (b) families crewmembers. This should also examine possible new ways of optimising communication and strategies of compensating for the restrictive and delayed communication with family and friends. This research should deal with a variety of two-way communication delays, from a few seconds to the 40 minutes or more that will characterise expeditionary missions to Mars and asteroids in deep space. Further work is required in space-relevant environments on the best ways to build and maintain team cognition, and the impact of changes in autonomy. This needs to examine the impact of changes in autonomy and communication changes on crew performance, and also on both individual mental models and team cognition. It should consider transitions in autonomy in both directions (increases and decreases), as well as comparing changes in autonomy as a (forced) requirement or as an (optional) opportunity. Finally, there is a need to develop training programmes that can help both crewmembers and mission control personnel in dealing with delayed communication problems.

Trans-disciplinary aspects

There are links with several of the issues related to human-machine interface and skill maintenance.
When considering Human-Machine Interface, the primary links are with the design of the interface and adaptation of the user interface during the mission. Considering skill maintenance issues, there is a general relevance of research on training and skill management at the group level, but the clearest links are with the provision of on-board training facilities.

1.2.3. Key Issue 3: Managing intra-crew differences and conflicts

Relevance for long-duration missions

A major source of potential problems for long-duration missions is the development of tensions and conflicts between crewmembers. Low levels of interpersonal compatibility between crew members is regarded to be an important determinant of psychosocial problems and interpersonal conflicts, suggesting that crew selection should concern itself not only with the qualities of individual crewmembers, but also with the dynamics of inter-crew relationships. However, identifying the ideal crew composition is a complex issue that has been so far studied on a limited scale only. Given the large diversity of individual differences (personality, experience, cultural and organisational background), every crew is unique and will behave differently, and it will be an all but impossible task to test all possible contributing factors and their interactions. In addition, particularly for long-duration missions, crews are likely to be selected partly on pragmatic grounds: for example, 3 male-female couples for a six-person crew. Therefore, it seems more efficient and practical to focus on training techniques and other countermeasures that will help crew members to deal with their differences in attitudes, personality and cultural background.

Earth benefits and applications

A better understanding of the factors increasing interpersonal tension and decreasing the cohesion of space crews working under isolated conditions can be used to ameliorate problems on Earth in a variety of work and social groups. In addition, space research related to cultural differences has great impact on international relations on Earth, where groups of individuals from different cultural backgrounds, nations, and organisational environments must interact together around common goals and activities.

Brief review of latest developments

As of yet, no studies have been done that relate cohesion directly to performance during space flight, although Kanas et al. (2007) found that the cohesion of an ISS crew was greater when the commander was supportive. Case studies, interviews, and surveys provide evidence that suggests that team cohesion plays a critical role in maintaining performance and well-being during spaceflight. For example, poor team cohesion, as indicated by breakdowns in coordination, exchange of resources and information, and role conflicts, have been mentioned as contributing to both the Challenger and Columbia shuttle accidents (Launius, 2004).

There is also little direct evidence for the role of crew composition in the effectiveness of teams. To study the impact of diversity on team cohesion and long-term performance, a distinction needs be made between surface-level (i.e., age, gender, and ethnicity) and deep-level diversity (e.g., attitudes, beliefs, cultural background). Harrison et al. (1998) found that the effects on team cohesion of surface-level diversity increased, whereas the effects of deep-level diversity increased when crew members got to know each other better. Similarity between members in attitudes appears to facilitate communication and reduce the effects of role conflict. The impact of deep-level diversity may be reduced by providing training and incentives to manage interpersonal conflicts. When teams have ample time to train together and receive instructions on how to deal with differences in attitudes, the effects of interpersonal conflicts can be reduced.

Figure 5: ESA astronauts Paolo Nespoli (left) and Roberto Vittori shake hands inside the ATV-2 (Credits: ESA/NASA)

Crew members inhabit several roles, not only as members of an international crew on a space mission, but as members of a nation, an organisation, and a profession; they also differ in their experience with spaceflight. In several recent space simulation studies (Kanas et al., 2010; Sandal, 2004; Tomi, 2001), cultural differences were found to play a role in many of the personal conflicts that took place either within the crews or between the crews and ground control. 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 programme including both the crew and ground control could have been prevented or reduced these problems. In a series of studies on-orbit with much larger samples, Kanas and colleagues (Boyd et al., 2009; Kanas et al., 2007) compared Russian and US astronauts, and mission-support personnel, in terms of mood and group interactions over time. Compared to the US personnel, the Russians experienced less pressure on the job; more tension/anxiety during ISS missions; and more direction, support, and self-discovery during MIR-missions. A recent study by Tomi et al. (in press) involving a total 75 astronauts and 106 ground personnel. The participants worked for one of the space organisations involved in the ISS programme. Poor communication due to misperceptions, misunderstandings, language problems, and differences in work style were among the most often mentioned challenges of the 25 multi-national space crews investigated.

The above problems mentioned reflect differences in policy between the space organisations with regard to selection, work organisation and rewards. For example, NASA astronauts receive a fixed salary and bonuses, whereas the salary of the Russian astronauts depends on the work accomplished. Also, the Russian space programme utilises fewer written procedures and relies more on expert opinion. One of the unknown aspects of long-duration missions is how behavioural norms and values adhered to by crew members may change after a long period of isolation and confinement. Crew members may displace in-group tension onto people on the outside, such as their families or mission control personnel (Kanas et al., 2007), while 'groupthink' leads to a loss of individual responsibility for decision making.

Knowledge gaps and research needs

Although differences between crew members are a major consideration to ensure high levels of interpersonal compatibility, only limited research has been done on the impact of crew diversity on team work in space or analogue settings. Some evidence exists to suggest that personality characteristics are relevant for effective teamwork in small groups, but this has hardly been tested in analogue or space environments. Relevant factors include personality characteristics, crew size, gender balance and cultural background (Kanki, 2009). During space missions, it is important that crewmembers work together cohesively with a minimum of interpersonal tension. Factors disrupting crew cohesion need to be identified, and countermeasures employed to decrease tension and allow crew members to perform mission tasks and interact appropriately with each other. On the other hand, it is possible that cohesiveness can be too high (Sandal, Bye & Van de Vijver, 2010), since it may reduce the willingness of crew members to voice minority disagreements or concerns—the phenomenon known as "groupthink". This is especially important during long-duration missions, where crewmembers depend on each other even more for support and safety. More research is needed to determine which contextual factors (such as social support), interpersonal skills, and personal characteristics (such as coping style and self-efficacy) best support psychosocial adaptation during long-duration missions (see also Whiteley & Bogatyreva, 2008; Solodilova-Whiteley, 2007).

Since it is likely that future crews will be multi-national (and multi-cultural), team diversity needs more attention. Since most findings have been obtained in ground-based studies, more work is needed to show whether they are also valid in analogue environments and during spaceflight. It also should be examined which countermeasures can reduce the effects. The focus of the research should be on managing the effects of deep-level diversity, since they tend to increase during long-term missions.

Proposed investigations and recommendations

- In general, more research needs to be done on the factors that determine the way in which changes in crew micro-culture develop, which may result in a displacement of crew tension to Earth-based personnel (for example in the form of groupthink). There is a need to know how such changes can be prevented or managed, should they occur during a mission;
- Existing knowledge on the impact of different crew composition factors on performance and well-being needs to be clarified by a meta-analysis of all studies performed in different isolated and confined environments. This method overcomes the problem of reduced statistical power associated with the typically small sample sizes of space studies. Combining the results from a group of studies allows for more reliable conclusions. For example, the crew characteristics (e.g., personality, gender, number and culture) collected during the studies at the Concordia polar station could be related to performance, well-being, and conflicts;
- More attention should be paid to the prevention of accidents in space by having (more) debriefings and group discussions on aspects topics such as miscommunication and organisational problems. To ensure that crew members, mission control and other personnel involved are not afraid to communicate their concerns, an open learning culture should be promoted able to foster safety and involvement. This requires that issues are discussed in workshops as part of team training programmes of astronauts and mission control personnel;
- Extended training programmes should be developed to train the crew on how to handle these differences, not only during the training pre-flight, but also during the flight. Refreshment courses may be given to remind the crew of the importance of these issues. This could also be part of

debriefings and group discussions that are scheduled regularly. This will improve the self-regulatory power of the crew, which is especially in particular important when the support of mission control is limited due to communication delays.

Trans-disciplinary aspects

No clear links with other disciplines were identified by the Expert Group.

1.2.4. Key Issue 4: Integral monitoring of crew and individual behaviour

Relevance for long-duration missions

Crewmembers have to adapt to a constrained and hostile environment characterised by both physical (e.g., microgravity, cramped conditions) and psychological stressors. These factors are likely to affect group dynamics and the effectiveness of cognitive and motor skills, both at the individual level and at the team level. Particularly in time-stressed, high-workload task environments, team performance is critically dependent on team members acting in reliable and predictable ways. In the case of interactions with automation, performance is also dependent on efficient coupling between crewmembers and technology. Although specific effects have been examined in a number of studies, little is known about their interactions, and how effects may change over time with increased exposure. Appropriate methods to detect and assess the occurrence of risky behaviours have to be developed. This requires an integral system, built into the on-board systems, designed to monitor and assess changes at all levels (overt actions, cognitive, physiological) in individuals and also on a group level.

Earth benefits and applications

Development of monitoring methods will have major value for all situations where personnel are operating in isolated, high risk settings, with a high inter-dependence between team-members (e.g., military units, oil platforms, remote weather stations, polar outposts), as well as for organisations and workplaces that depend on well-functioning teams for productivity.

Brief review of latest developments

Using an ethological perspective, Tafforin and Gerebtzoff (2010) showed that changes in movement, posture and social relationships could be captured using video analyses of everyday events, and analysed automatically to reveal individual differences in adaptation to microgravity. Such methods are being developed in current experimental protocols simulating future interplanetary missions, with an emphasis on Lunar stay and Mars, as part of EuroMoonMars campaigns at the Mars Desert Research Station (MDRS) in Utah-USA (REF) and for the Mars-500 study. In this very-long term simulation, video recordings of daily life activity and collective tasks are performed in coordination with psychological questionnaires and a wireless group structure monitoring system (WLGS-tool). In addition, new virtual-reality 3D training tools help astronauts to learn techniques and pre-flight strategies they can apply in space, and have been used to monitor different aspects of neurobehavioural and social performance in long-term spaceflight simulations (De la Torre et al., 2010).

Knowledge gaps and research needs

Although the effects of physical and psychological stressors have been studied in a wide range of isolation and confinement simulations of short- and medium-duration (e.g., ISEMSI, EXEMSI, HUBES, SFINCSS, MARS105, Concordia) there have been few systematic studies of their impact and interactions over extended time periods, or in space. One exception has been the work of Kanas and his colleagues, who have examined crewmember interactions and the crew-ground relationship during a series of Mir and ISS missions and attempted to relate a number of issues to the stressful conditions in space (Boyd et al., 2009; Kanas et al., 2007). A number of different monitoring methods have been used during simulation studies, but their relative effectiveness has not been validated. Although the effectiveness of several indicators has been examined in space-related studies, no attempt has been done to combine and compare these data in a meta-analysis. The limited exchange between researchers originating from different disciplines has inhibited a global analysis of inter-disciplinary data (medical, physiological, psychological, psychiatric, sociological, ethological, and ethological data (Tafforin & Gerebtzoff, 2010). An integral monitoring system is needed to be able to signal or detect critical changes in health or behaviour during space flights that endanger the completion of the mission. The goal of the system is to provide information that may be used to secure the completion of the flight and to mitigate the effects of inappropriate or unwanted behaviour. The data collected should provide indicators that can be used to regulate behaviour, either by giving feedback to the individual, to the crew, or to mission control. Procedures should be developed to decide who is getting what information. This information may also be used as a basis for making decisions about possible interventions to regulate behaviour or improve mental health and well-being. Very little is known about the potential chronic after-effects of extended missions (for example depression, post-traumatic stress symptoms).

Figure 6: The crew of the Mars500 isolation study was locked in a simulated space station for 520 days at the Institute of Biomedical Problems in Moscow

Proposed investigations and recommendations

- An integral monitoring system should be developed, based on a broad set of indicators associated with different analytic disciplines, covering cognitive, emotional, physiological, and behavioural aspects of the functioning of the crewmembers, both as individuals and as part of the crew. The large amount of data collected during analogue studies (e.g., Mars 105 or Mars 500) offers a unique opportunity to compare the effectiveness of different assessment methods and to select the most critical indicators, using a meta-analysis to identify the most reliable measures. These indicators should signal or predict changes in thinking, meaning, emotions, and physiological states that are critical for maintaining (crew) performance, or mental health and team cohesion. They may be based on a combination of parameters, which may originate from different disciplines.
- The validity and usability of this integral monitoring should be tested in analogue environments and in ISS or space environments. The research should focus on the changes in : psychological and neurobehavioural aspects of mental health; individual motivation and well-being; Individual and group psychological response to unexpected and threatening events; objective and subjective assessment of crew interactions, cohesion, conflicts and group structure dynamic.
- Other relevant areas for research on monitoring include the advantages and disadvantages of developing self-testing tools, in addition to centralised compu-

ter-based systems, and how such information is best used. For example, how should the data be communicated to crew members? Should it be used for intervention? And if so, how? Who would be allowed to see the data, and who has the authority to make decisions based on it? As with any new tool, programmes of effective training will also need to be explored.

Trans-disciplinary aspects

A monitoring system of this kind would need to be integrated with other monitoring initiatives relevant to Human-Machine Interface and skill maintenance issues. A single monitoring and support system is envisaged that could be used flexibly for all human interactions with both others and the technical systems.

1.3. Conclusions

The overall conclusion of the EG on "group/team processes" is that there is a need for a focused examination of the issues related to team and group processes in extended space operations. While much is already known from previous work, it would be a mistake to apply this knowledge too readily to the unique challenge of a mission to Mars. The potential problems associated with intra-group conflicts, loneliness, disrupted connections with Earth, and obligatory autonomy in managing operational systems need to be carefully managed. In general, crews need to be supported more effectively in both their mission-related activities and the pursuit of their personal goals.

Specific topics identified were:

- Maintenance of team cohesion, wellbeing and performance
- Impact of reduced communication between crew and Earth
- Managing intra-crew differences and conflicts
- Integral monitoring of crew and individual behaviour

Research facilities within the European Community are well equipped to address such problems. There are also many potential Earth benefits from such work, especially in any work context that depends on effective teamwork in dangerous or stressful environments.

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2

Human-Machine Interface

2.1 Introduction

Research on the design of the human-machine interface is fundamental to the overall success of any space mission, determining the nature of crew interactions with the many technical and robotic systems involved in effective and safe progress. In terms of the wider technical state of the art, this is a highly developed area, especially in industrial automation and aviation. Yet, while applications to space missions have been very successful, the greatly extended missions envisaged for future human space exploration will require a step change in sophistication and refinement to allow increased collaboration and trust between human and automation components of the human-machine system team. In particular, the proliferation of automation and robotics may present major problems for crew members, both in monitoring the state of the system and in making necessary interventions.

This is the most general issue identified by the Expert Group focused on Human-Machine Interfaces, requiring fundamental research on the design of robust automation for human-machine cooperation. A particular problem is that the ways in which crewmembers interact with the automation may change during a mission, and through practical experience, virtually nothing is known about how system design can accommodate such adjustments. There are also other more specific issues, including: the nature of human interaction with robots, the use of virtual and augmented reality in simulation training and support; the use of EVA wearable computers to monitor changing operator state in relation to mission goals, and the use of adaptive function allocation strategies to manage changing relationships between crew and computer systems. Much more still needs to be known about the design of decision support systems and dialogue control, and the general problem of how best to promote the high degree of collaboration required. While many of the technological elements are already in place for these developments, there is currently a lack of firm understanding of how to optimise the partnership between crew members and automation technology, and how to allow for context-driven flexibility of optimisation.

2.2. Human-Machine Interface - Key Issues

2.2.1. Key Issue 1: Design of human-automation system

use of virtual and augmented reality in simulation training and support; the use of EVA wearable computers to monitor changing operator state in relation to mission goals, and the use of adaptive function allocation strategies to manage changing relationships between crew and computer systems. Much more still needs to be known about the design of decision support systems and dialogue control, and the general problem of how best to promote the high degree of collaboration required. While many of the technological elements are already in place for these developments, there is currently a lack of firm understanding of how to optimise the partnership between crew members and automation technology, and how to allow for context-driven flexibility of optimisation.

Relevance for long-duration missions

Future space missions will involve automated subsystems with relatively high levels of autonomy and authority (Hoffman & Richter, 2003). Automated systems can be designed at different levels of authority for task completion—between fully manual and fully automated—and different components of information processing that are supported—from perception through decision making to action (Parasuraman, Sheridan, & Wickens, 2000). For automated systems to be used effectively and safely by crewmembers, they will need to be designed by taking human capabilities and limitations into account (Parasuraman & Riley, 1997; Lee & Seppelt, 2009). Human-automation system design refers not to the design of interfaces between the crew and automated systems, but to the functionality of automation and to task allocation between humans and automation.

Human-automation function allocation is an old topic with diverse proposed solutions, beginning with now outdated methods such as the 'Fitts List' of the 1950's to current concepts such as adjustable autonomy (Dorais et al., 1998) and delegation approaches to human-automation interaction (Miller & Parasuraman, 2007). However, many unique aspects of space missions, such as their long duration and delayed or little communication between the crew and ground control, require that additional approaches to function allocation be identified and evaluated to allow for efficient coordination between humans and automation. Even if existing approaches to function allocation are found to be relevant, they need to be validated in the context of automated systems to be used in future planned space missions.

Human-automation interaction protocols and methodologies will need to be specified and evaluated throughout the stages of system design. Particular attention will need to be paid to supporting crewmember handling of off-nominal or critical, unexpected events, i.e. ensuring sufficient crew situation awareness to handle the problem. Trust is a key aspect of effective use of automated systems by humans. The human-automation system design should allow for accurate trust between the extremes of distrust and unconditional trust, and for trust that is appropriate to the use of automation in specific contexts (Lee & Seppelt, 2009). Because of the planned use of rovers and other robots in space missions, human-robot trust also needs examination. Methods to repair loss of trust following system failure in the context of evolving, long-duration missions need to be better understood. Trust maintenance and repair involves not only interaction between the crew and their automated systems, but also between ground control and the mission crew.

As the degree of successful, effective automation of a system increases, due either to a higher level of allocation to machine (vs. human) control or to greater autonomy for decision making and action, crew workload decreases (Wickens et al., 2010), although sometimes the load may only shift to other cognitive demands (Parasuraman & Riley, 1997). At the same time, increased automation can lead to a decrease in situation awareness (SA)—if for no other reason than that the automation is managing some portion of the tasks. The threshold at which the workload-SA trade-off occurs for space missions needs to be identified. Also, what degree of loss of SA due to high degrees of automation is tolerable before safety is compromised?

Because of the length, complexity, small crew size, and limited availability of ground control support of long-duration space flight, automation will be necessary for successful mission completion. A variety of such systems, such as life-support systems, decision aiding and planning tools, planetary rovers and other robots, etc., will be critical to the performance of crew in executing space missions safely and efficiently (Dorais et al., 1998). Such systems will need to be designed so that they operate cooperatively with the crew and support rather than hinder their mission effectiveness. Automation designed without concern for human capabilities and limitations can result in serious degradation in system performance. For example, certain automation designs can reduce crew SA and not provide opportunities for maintenance of cognitive skills. When unexpected events occur, or in instances of system malfunction, the crew's SA will need to be adequate enough to diagnose the problem and their manual skills sufficiently well preserved to allow for effective resolution. Poorly designed automation can lead to problems that can compromise safety and, in the extreme, lead to accidents. Human-automation system design based on well-established human factors principles is therefore essential for the success of long-duration space missions.

Earth benefits and applications

Many current and planned work environments on Earth involve personnel interacting with increasingly highly automated systems. Two examples include the programme for transformation of the air traffic management system to accommodate higher levels traffic more efficiently (NextGen in the US and SESAR in Europe), and the increasing use of unmanned vehicles and robots by the military. Research on effective human-automation design will yield benefits for system efficiency and safety in these and other domains.

Brief review of latest developments

Current knowledge on human-automation system design has been drawn from empirical studies, fieldwork, and accident analyses. The combined evidence from these sources has shown that automation changes cognitive demands on the human operator and imposes new challenges for coordination (Lee & Seppelt, 2009; Parasuraman & Riley, 1997). At the same time, automation impacts crew workload, trust, and situation awareness, in both beneficial and negative ways. The challenge is to identify automation designs that retain the benefits while minimising the costs. At least three major approaches have been identified for reaching this goal, (1) levels/stages of automation, (2) adaptive automation or adjustable autonomy, and (3) delegation approaches. Evidence for the efficacy of these approaches in comparison to “static” automation has been provided in studies of automation as applied in air traffic control and human-robot interaction (Parasuraman et al., 2000; Miller & Parasuraman, 2007).

Knowledge gaps and research needs

Designing automated systems to support crew performance in the specific context of long-duration space missions is an important research need. Several taxonomies and frameworks for human-automation interaction design have been put forward. However, current knowledge on human-automation system design is drawn mainly from experience with automated systems in such domains as aviation and process control, and the degree to which these can be extended to and are applicable to space missions is not known. The many unique aspects of space flight require that new approaches be identified and evaluated for efficient coordination between humans and automation. In particular, the differential benefits and limitations of adjustable autonomy and delegation approaches need to be identified. Space mission automation must support crew performance in both routine and mission critical conditions, elicit calibrated levels of trust, and optimise crew workload and situation awareness so that crew members have sufficient resources to respond effectively to unexpected events. Even the definitions of objectives such as “safety” may need to be rethought for long-term space missions, where system shut down may be impossible and even stable states may need to last for months.

Proposed investigations and recommendations

A methodology for human-automation system design specific to long-duration space missions needs to be identified, tested, and verified. Potential investigations might target (but should not be limited to):

- Research on how specific automation designs influence crew trust, workload, and situation awareness in simulations of mission-relevant scenarios.
- Studies should examine several aspects of automated systems that are relevant to space missions, from low-level sensors and automated actuators to decision aids and semi-autonomous robots.
- Since all possible factors influencing human-automation interaction in human-in-the-loop studies cannot be examined, computational modelling studies should be conducted to examine how such factors act individually and in interaction to influence system performance.
- Strategies should be explored for combining predictive cognitive models whose predictions can be tested in follow-up human-in-the-loop experiments. The benefits and costs of specific automation approaches, e.g., delegation-based adaptation, should be tested as part of the verification process.
- The resulting knowledge base should be used to identify relevant dimensions and levels for function allocation strategies under different operational conditions and circumstances.
- Also needing examination are requirements for terrestrial simulators to serve the needs of long-term space mission research.
- The research plan should be systematic and programmatic, beginning with ground-based simulations of progressively more complex scenarios, progressing to flight experiments during LEO, moon, or Mars missions.

Trans-disciplinary aspects

There are strong links with issues related to skill maintenance. High levels of autonomy can lead to atrophy of perceptual and cognitive skills that may need to be exercised by crewmembers when the automation fails or does not provide optimal solutions in a particular context. Good human-automation system design, as well as approaches to function allocation such as adaptive automation, can reduce skill loss.

Also, considering team/group processes, the system design needs to consider not only interactions between individual humans and automation but also between multiple humans/groups interacting with individual automated systems, or machine mediated human-human interactions, or within and between teams processes/interactions (e.g. surface and orbit teams). Automated systems and their interfaces may also be designed for monitoring physical and mental wellbeing.

2.2.2. Key Issue 2: Adaptation to support operator state and mission goals

Relevance for long-duration missions

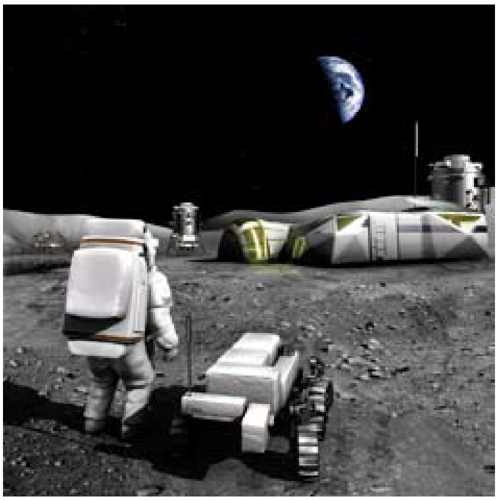

Figure 7: An artist's conception of a possible Moon base, with robots and humans (Credit: ESA)

The state of the operator is an integral part of the effective human-machine system. Major departures from optimal operator functional state (OFS) may significantly compromise mission goals, though such effects may be masked by compensatory recruitment of effort, which protects performance in the short term at the cost of an underlying impairment. There is a need for HMI design to incorporate a system for monitoring of physiological and cognitive changes in OFS, as a basis for adaptive automation and decision support.

Adaptive and adaptable HMI design has increasingly been considered in complex systems design as a possible solution for keeping operators in control; this holds for the short and long run. This enables operators to respond effectively in unforeseen situations. However, it would be necessary to improve HMI design to enable the operator to serve as a link in fail-safe principles. The question remains how HMI design can be developed in order to balance the human requirements for active engagement with those of mission goals and safety? An important aspect in this is to investigate the strength and weaknesses of the assessment of adaptation mechanisms, establish who has access to the resulting data, and the ability to override the adaptation that results. The trust in the system is influenced by the sensor intelligence and reliability.

The relevance for long-duration missions is considered to be large. This holds both for missions in the nearer regions (LEO, moon) and long distance missions (Mars). An important aspect, however, that relatively increases the importance of this work for long distance missions is the impossibility to elicit support from ground personnel via radio communications in missions to Mars. Otherwise most of the issues of complexity, interaction and adaptation are present in the other long-duration missions as well. The problem of enhancing adaptation for enhanced operator support involves a number of related topics: defining the optimal operator functional state; monitoring the physiological and psychological state of individuals and teams; monitoring system performance, e.g., for errors; detecting, identifying, and predicting critical situations/mission situations; developing criteria for OFS breakdown; maintenance of trust in automation; possibilities for adaptive support and task allocation; HMI design to incorporate adaptive and adaptable support; closing the loop by using feedback, either informational or by biofeedback.

Earth benefits and applications

The relevance for Earth applications is large, in particular for aspects such as long-duration interactions with adaptive systems, learning and growing, adaptation to attitude, and real-time user support. Specific applications include: applications in health, rehabilitation and assistive devices; design of human-centred task and interaction interfaces in safety critical systems: process control operations, transportation, manufacturing; Training systems in various fields from health to control systems in hazardous environments. An essential point is that management of most critical systems in the mentioned areas would benefit from a user state assessment.

Brief review of latest developments

Kanas & Manzey (2008) summarised important aspects of physiological (i.e. cardiovascular, sensory-motor, muscular) and psychological adaptation in space, including empirical findings in this area in their important book on space psychology and psychiatry. Miller & Parasuraman (2007) designed a method enabling human-like, flexible supervisory control via delegation to automation. Flexibility in human-adaptable automation can provide important benefits, including improved situation awareness, more accurate automation usage, more balanced mental workload, increased user acceptance, and improved overall performance. Little is known about the cardiovascular effects of mental workload in space, but there are a couple of essential studies on the working of autonomic neural functions and the baroreflex in space. Di Rienzo et al. (2008) studied adaptation to microgravity reflected in changes of blood pressure, heart rate and baroreflex sensitivity (BRS). There are some studies on adaptive designs for task interfaces using real-time EEG with applications in transport industry, experimental implementation in a US Army study on unmanned aerial vehicle operators (i.e. Gunn et al., 2005; Freeman et al., 2004)

Knowledge gaps and research needs

There is a strong evidence base in lab research for the effects of OFS changes, but almost nothing is known from space studies. A major growth point is the development of methods for real-time monitoring of physiological measures and estimating state changes. At present studies are restricted to separate fields (e.g., EEG, cardiovascular) which make estimations quite crude and incomplete. Furthermore, it is insufficiently known in specific working situations what the main causes are of detected changes (e.g. task complexity, time pressure, stress related to crew or ground control interactions etc.) More sensitive measures for identification and prediction of smaller state changes are likely to be required. Also, know more needs to be known about the background and impact of subtle state changes.

Additionally, the consistency and reliability of individual state change characteristics need far more attention. There is an opportunity and need to monitor and detect psychological state changes, and there are preliminary techniques available to do so, but little is known about effective HMI adaptations or interventions, especially in work contexts.

Therefore, questions include defining valid and reliable state predictors (physiological, performance, self-assessment), methods for detecting and predicting high risk states, and developing adequate mitigation strategies (by early detection and prevention, or by adaptive task changes). The main question is how can HMI design be developed in order to balance the human requirements for active engagement with those of mission goals and safety?

Currently available studies refer to potential (general) solutions for adaptive HMI interface design and some adaptation mechanisms, but these approaches are rather limited for individual task support due to lack of criteria and valid, sufficiently sensitive predictors, and tend to focus on larger state changes and shorter time periods than may be required for adaptation in long-duration missions; this holds both for estimation of state changes and task adaptation. Where applications are available, (1) their reliability for identification and prediction of shifts in states is sometimes limited, (2) they exhibit limited sensitivity and diagnostics for the detection of state changes, (3) their suitability for use outside the lab is limited, and (4) their ability to transfer/use across different mission scenarios, task situations is unknown.

There is some knowledge on discrete shifts in interface and task design between normal and abnormal situations, however, effects of human-centred design of transitions between tasks interfaces remain unclear. There is limited knowledge of effects of adaptation dynamics on human information processing, criteria and predictors for adaptation, information requirement for safe and efficient operation. Knowledge is especially limited with regard to long-term effects/applications, domain and situation specific critical states, mitigation strategies, lack of real-time estimates of state changes during prolonged working conditions and (many) repeated working days. Adaptation of interfaces in normal situations is reasonably well-known, but costs when unexpected situations and events occur have not systematically been explored. So, more knowledge has to be gained on the use of adaptive and adaptable interfaces in safety critical and unexpected situations.

Proposed investigations and recommendations

The broad aim is to be able to identify consistent individual patterns of psychophysiological change with continued exposure to natural stress conditions and relate these to control errors and performance breakdown. There is a need to carry out systematic studies of complex H-M task under a fully representative range of ISS living and working conditions and operations; this includes both regular testing over several months to grasp individual response characteristics and their stability.

Studies of adaptive and adaptable human-machine task and interaction interfaces often refer to either generalised (design for all) or individualised (design for single, individual operator) design solutions, while the first aspect has got far more attention than the second. There is a strong need to investigate consequences of human performance and related state changes of individual task adaptation based on (individual) detected state changes. Relevant aspects include the examinations of the short/long-term effects of task adaptation and feedback (since psychophysiological monitoring of operator state will include biofeedback) on overall system performance.

Suggested research topics include but are not limited to:

- Identify the performance effects of adaptive optimisation on non-optimal situations (e.g., is there an automation complacency effect with adaptive automation?)
- Identify the performance and psychological effects of providing user feedback on different types and applications of interface or automation adaptations
- Identify whether and how adverse psychological (e.g., depression) and/or social (e.g., group antipathy and non-cohesion) states can be reliably detected, and what (if any) system adaptations can prove effective in combating them.
- Usability and well-suitedness of adaptivity and adaptable interfaces / systems in safety critical and unexpected situations

Trans-disciplinary aspects

There are links with issues related to skill maintenance in terms of using adaptation to encourage maintenance of skills or training and psychophysiological monitoring of skill maintenance (performance). HMI can also foster team social relationships and/ or effective collaboration

Crew members have a central role in OFS breakdown, and in identifying critical situations; OFS may refer to neurophysiological state assessments.

2.2.3. Key Issue 3: Evolving, problem solving and updating during missions

Relevance for long-duration missions

The sheer duration of a Mars mission, combined with likelihood of encountering unanticipated circumstances and conditions, make it very likely that system functions and components, software, as well as human policy and operational procedures, will all evolve and be updated. These updates could be in response to problems and hardware and software failures or to novel opportunities and upgrades, and might be either optional or unavoidable. They could be initiated and developed by the crew, by ground control, by subsystem developers and contractors or even through autonomous machine learning approaches. Few modern software systems go through two-year lifecycles without patches and upgrades in practice today, and current ISS and Shuttle practice involves extensive review and adaptation of most non-critical procedures to the current state and operations of the vehicle and crew before they are exercised. But it is unclear how such redesign, evaluation and problem solving should be implemented. Who should do the revising (flight crew, ground control, or autonomous machines in either location) under what circumstances? How can crew be kept appraised of revisions, especially when/if they are not involved directly? How can newly-acquired behaviours (especially if autonomously learned or developed by the crew) be validated before being adopted? How can equipment and systems (for validation, crew training, etc.) best support such change?

Figure 8: ISS Mission Control room at NASA Johnson Space Center (Credit: NASA)

How to make such changes and to validate and verify them is a major research challenge. How can operators (whether crew or ground) be trained in the revisions? How can the "transfer of training" problem (inaccurate generalisation or carry over from old learning) be avoided? And the problem of communication changes within the crew, and between crew and mission control—avoiding "cross shift transfer" problem where changes made by one team or "shift" are not communicated adequately to the next shift, while simultaneously avoiding the workload problems occurring around cross-team hand-offs. Crewmembers will need to be able to understand the effect of change on the full range of systems and procedures, and to be able to obtain support for (recording of) collaboration in innovative problem solving technology—related to "design rationale capture" in engineering and software design. There are also bound to be changes in trust at all levels (human-machine, crew-ground and human-human) that have to be managed effectively.

As mission duration increases, the likelihood and the need for significant innovation, revision and evolution of systems and processes increases. The same is largely true for mission complexity—and for mission novelty. The inability to replace failed hardware systems places an added burden which will likely mandate innovative solutions and "workarounds". Traditional engineering approaches wherein a complex system is fully designed and thoroughly tested a priori and then left unchanged during use, might be feasible for short duration, bounded-scope missions, but are already not adhered to in practice in most complex real-world systems such as aviation and process control and (with ISS) space. Of course, complex software systems (e.g., Microsoft Office) used in everyday life undergo upgrades and repairs, sometimes multiple times in a day, and though this process can hardly be said to be seamless, transparent or overly safe.

Earth benefits and applications

As noted above, the problem of managing changes to systems, software and practices is already a component of most complex Earth systems and technologies—with transportation, process control, and military systems being prime examples. While these systems arguably do not experience the problems of managing, supporting and disseminating changes in as severe a form as a long-duration space mission will, they will likely benefit from any advances in research or supporting system design made by a space programme.

Brief review of latest developments

Currently, collaborative problem solving research is nascent, with some good work on processes used by complex design and engineering teams and on collaborative problem solving teams such as military command, NGO disaster relief, fire-fighters, etc. There is extensive research on tools to support collaboration in design and engineering, and various attempts to develop rationale capture tools (primarily in software design teams). Anecdotal evidence from complex process control and shift work exists—including documentation of effects of changes on subsequent shifts and best-practices for maintaining knowledge of changes. Good work is emerging on change detection at the user-interface level in Human Factors.

Knowledge gaps and research needs

While the above characterisation of recent developments in this field shows reasonable progress, limited knowledge exists on the effects of adapting task contexts, procedures and HMI design on long term task performance; essentially no knowledge exists about the optimal rate or magnitude of changes (i.e., software releases) and manners of notification and their effects on human awareness and performance. Effective design rationale capture, especially in high pressure/workload settings among groups using primarily verbal communication, remains an unsolved problem. Nothing is known about these functions in the space context, though anecdotal evidence exists, especially from ISS operations, where sustained operations have necessitated known changes to procedures and probably changes to software after initial installation as well.

Proposed investigations and recommendations

A process of initial identification of analogous Earth environments (e.g., complex process control, military command and control at the battalion or division level, long-term event management, space mission management) and collection/review of effective practices for problem solving and capturing and disseminating of modifications is proposed. A subsequent or concurrent review of the somewhat extensive collaborative problem solving and collaboration support tool literature to identify best practices with relevance to space mission conditions is also recommended. These studies should be followed by laboratory studies of (1) various collaboration environments, group structures and support tools on effective collaboration and problem solving as well as rationale capture, (2) effects of various forms and contents of rationale capture on subsequent performance using/accessing the rationales, and (3) effects of various change notification methods and rates on task performance—all with emphasis on space mission tasks and contexts. While not all such studies need to involve highly trained experts, creative problem solving environments and high stress/tempo operations, at least some of them should. Eventual migration to long duration studies, ideally in naturalistic environments (including high stress and tempo). Note that investigation of solutions/methods in space, while desirable, is considered less critical for this topic because (it is felt) adequate knowledge could be elicited from ground-based analogue studies for reasonable design for space missions.

Potential investigations might target (but should not be limited to):

- Systematic exploration of the effects of frequent small vs. rare but large modifications of an automation and/or user-interface system on task performance
- The effects of various protocols for participation and notification of changes on task performance (e.g., simple notification vs. sign off vs. explicit accept/reject decisions vs. user-initiated change requests)
- The effects of time lag on group collaboration (crew + ground) with special emphasis on creativity, problem solving, and error/problem detection and avoidance.

Trans-disciplinary aspects

There are links with issues related to group and team processes: cross-team and cross-shift communication (of changes); team collaboration and consensus on change/behaviour - How should agreements be made on how a system should appear/behave? What are the limits of individual adaptation vs. group expectation?

There are also clear links with skill maintenance aspects: notification of change, rehearsal, training; transfer of training problems (and their detection).

2.2.4. Key Issue 4: Simulation and virtual/augmented reality (SVAR)

Relevance for long-duration missions

By representing approximations of real and imaginary world work and leisure environments, simulation, virtual and augmented reality (SVAR) provides a tool for and a design methodology of multi-modal interaction in human-machine systems. SVAR should serve an enrichment of system components and functionalities already available and provide a complement or extension through new components and functionalities suitable to improve human performance in actual and future mission scenarios. SVAR can be useful in operations, training and leisure, e.g. remote control interfaces in virtual reality for distant robot operations in reality, augmented reality display for navigation or safety information in real-time, and leisure simulation environments to alleviate sensory deprivation in space. Central to SVAR is the effective and efficient support of multi-sensory human information processing at different stages, i.e. by sharpening and extending perception, by improving decision making through previews and 'what if' scenarios, and by testing action implementation for validation of new tools and procedures. Though SVAR can represent all system components such as materials, tools, procedures, functionalities, and their interactions, feedback about potential gaps between SVAR and reality may be required. The high impact of SVAR on long-term space explorations is due to the capacity and flexibility of SVAR in a broad range of applications and for a comprehensive diversity of tasks. Evidence can already be gained from applications on Earth (e.g., industrial, medical, military operations) and in relation to space (e.g., primarily with regard to training and remote control applications).

Carefully designed according to human information processing requirements, SVAR has the potential to convey solutions or serve as a countermeasure for several unique aspects of space missions, far beyond space applications currently available. SVAR can potentially compensate for: the alleviation of sensory deprivation by providing rich stimulation across all stages of information processing for all phases, locations and tasks of the mission; the inability for direct human-machine interaction due to distant, extreme or hazardous environments by facilitating emulation, 'what if' scenario simulation, and remote control; the information complexity in decision-making processes during safety-critical mission scenarios by assisting through SVAR functionalities for information representation; unforeseen or emerging circumstances in the course of the mission by adapting SVAR to new or future situations; the limitations in safe-guards or fail-safe components during long-duration remote/ isolated system operations by SVAR support for verification and validation of changes during the mission; the lack of opportunities for on-the-job training in unavailable or unforeseen environments during the long-term mission by augmenting environments or virtually enriching environments; the limited diversity of social interactions due to small crews during long-term missions by Earth working and living scenarios and functionalities; the lack of privacy by using SVAR to enable individualised pursue of interests.

Specific issues are the need for modelling of environments for different mission stages (pre-flight, flight, post-flight), mission requirements (remote control, verification and validation of updates, skill maintenance), and mission characteristics (nominal and off-nominal, long-duration, confinement) for effective and efficient use in SVAR; design and evaluation of SVAR human-machine interfaces, to facilitate dynamic interaction of multi-sensory human information processing for unique mission characteristics; feedback design for appropriate representation of gaps between SVAR and reality; methodologies for assessment and prediction of SVAR fidelity, immersion and presence for appropriate support of human performance; support for mission cycle (including re-adaptation to earth)

Figure 9: Astronaut Rick Mastracchio uses virtual reality equipment to practice tasks he will perform in space, and virtually interacts with ISS equipment (Credit: NASA)

Earth benefits and applications

Research on SVAR in long-term space exploration is of high relevance for Earth applications: (1) Envisaged SVAR research is required to build on-Earth applications and therefore will also expand methodologies and functionalities already available (e.g., allow for time-lagged remote control using virtual reality, augment human-machine interaction by 'invisible' information on friction or weight, and maintain operator skills through training in SVAR); (2) Required SVAR research needs to address unique aspects of space explorations also relevant for operations under isolated or extreme conditions on Earth (e.g., underwater, arctic, desert, mines) or hazardous operations (e.g., as in some industrial, medical, or military settings); (3) Future research should allow SVAR to further advance from a visualisation and demonstration tool to a long-duration, multi-sensation interaction tool in enriched work and leisure situations and to a design and evaluation methodology for effective human information processing support during all stages of the product life cycle.

Brief review of latest developments

Latest developments indicate SVAR improvements in at least four different areas: (1) The SVAR technology itself (e.g., higher display resolution, wider range of sensitivity of haptic devices); (2) the use of SVAR as edutainment environment and in marketing (e.g., training, gaming, entertaining, advertising); (3) the use of SVAR as a methodology for systems design (e.g., usability studies, verification and validation of design solutions, accident prevention and product safety); and (4) the application of SVAR as a tool or complement in human-machine interaction settings during enriched work and leisure activities. Recent SVAR research also resulted in suitable solutions for SVAR space applications (e.g., remote virtual control of distant robot and virtual reality pre-flight training). Therefore, research activities in Earth and space applications will provide a sound basis for future challenges of long-term space mission.

Knowledge gaps and research needs

Current knowledge suggests that virtual and mixed realities are useful as human-machine interfaces, for human machine interface design applications and for training. Simulated environments have already successfully been used in different areas of application for design representation, for formative evaluation studies, for prospective system design and for training purposes. However, several knowledge gaps have been identified for better use of SVAR in space applications, with the potential to also improve SVAR suitability for Earth applications.

Less knowledge is available about its effective integration as a human-machine interaction interface including the different means SVAR may serve (e.g., methodology, tool, complement). This is partly be due to current limitations to effectively support all stages in information processing in virtual and augmented simulation environments; beginning with the simulation of a broader range of modes of sensation, each in its dynamic variation and across multiple modes also in its interactions.

Although there is already a lot of research on simulation fidelity, immersion, and presence, it remains unclear what level of each would be suitable for what applications or purposes and how to reliably assess sensitive level differences during use of SVAR. Further improvements are required as regards realistic illumination design and workarounds for limitations in transfer of physical / virtual objects from and to virtual environments. Knowledge is also limited about appropriate feedback design, as regards feedback during human-machine interactions as well as feedback about limitations stemming from SVAR being only an approximation of the real world.

Since most existing application research refers to short term uses lasting a working day at best, nothing is known about long-term effects and about long-term applications relevant e.g. for space missions. Consequently, less is known about regimes or procedures to serve appropriate adaptation and re-adaptation for switches between SVAR and reality. The available knowledge is also limited on use of SVAR for training, retraining, and retention, especially as regards long-term duration applications.

Proposed investigations and recommendations

Based on the knowledge available and knowledge gaps identified potential investigations might target (but should not be limited to) the following issues:

- Investigate how multi-sensory interactions in human information processing across different stages for different work and leisure scenarios affect SVAR support for human performance and develop suitable measures for analysis and diagnosis.
- Examine how to diagnose and how to predict the appropriate level of simulation fidelity, level of immersion or feeling of presence for specified work and leisure scenarios for frequent use of SVAR during long-duration missions.
- Investigate human performance effects of long-term and long-duration SVAR applications and effects of switches between SVAR and the real world. Develop recommendations and countermeasures that will effectively avoid negative consequences (e.g., fatigue, human information processing impairments, disorientation, mistrust, simulator-sickness) and supports human performance (in work and leisure activities).
- Because augmented and virtual reality at best will be a simulation of the world, determine how to design feedback on reality gaps (virtual reality to reality deviation) for optimal human performance support
- Determine whether and how SVAR procedures may be used to recall earth-like environments

during long-term missions, to expand a subjective sense of space or sense of habitat variation, to compensate for long-term confinement, and to support skill maintenance and group processes.

- Study how and when human-automation system design, software and hardware changes during the mission and human-robot/agent interaction can be supported by use of SVAR (c.f. Key Issues 1, 3 and 5)
- Identify required qualities of modalities for human information processing for relevant scenarios (earth, LEO, moon, Mars, ground/ crew inside/ outside shuttle) and fill the quality and / or modality gaps
- Investigate new procedures to address more modalities including variations in intensity, type and over time
- Investigate how to best enable and support human-centred design at early stages of product development; better grasp of abnormal situations by simulation (what if when scenarios) (c.f. Key Issues 1 and 5)

Trans-disciplinary aspects

Virtual and mixed realities are useful for training and HMI design applications; what would be the appropriate interaction between training and HMI and group/ team processes? SVAR may serve as a tool for team and group processes management and skill maintenance issues, especially training operational procedures, serving skill maintenance, mitigate micro-cultural differences, but use of VR may increase sense of isolation. Augmented reality displays may serve monitoring of life support information.

2.2.5. Key Issue 5: Robots (HRI), agents (HAI) & human-robot-agent interaction (HRAI)

Relevance for long-duration missions

Due primarily to increased communication lags, long-duration deep-space missions will require increased autonomy on the part of the crew with decreased ground support (cf. Key Issue 1 above). One way in which increased autonomy can be achieved is through increased use of robots (which can deliver the extra "pair of hands" required in many situations and can go where humans can't go, or go as safely—such as exterior space walks for repairs or observations) and agents (which can organise and "bundle" the intelligence and situation awareness required to manage and perform complex functions). Insofar as robots and/or agents are intentionally anthropomorphised in their design and in their use by the crew, they may have the ability to help relieve social monotony, engender loyalty and trust, and provide a "face" around which to organise automation functions. This social aspect implies that HRI/HAI may be useful to influence moods in individuals and teams. Finally, in extreme circumstances, robots and agents may be able to operate and continue at least portions of the mission when humans cannot.

Robots are familiar to science fiction readers everywhere as physical agents that have an autonomous capability to execute tasks with some dynamic decision-making ability and authority, ideally as instructed by or for the service of a human supervisor. Agents, as the term is used here, may be thought of as "software robots" or "softbots"—software-only systems which are otherwise like robots- with the autonomous capability to execute tasks with dynamic decision making authority under the supervision of a human, but to do so without having a physical presence of their own. Both robots and agents maybe be "personified" and/ or anthropomorphic in an appearance, but they do not need to be—and the benefits or consequences of personification in design and in use are a hotly debated topic in the field.

Robots and agents are starting to play increasingly important roles in mission systems technology during the mission and pre- and post missions (see especially NASA and GE's Robonaut2, http://robonaut.jsc.nasa.gov/default.asp, delivered to the ISS on STS-133 in February 2011. During long-duration missions it will be critical for crew members to be able to train for, work and interact effectively with these 'new crew members' in operational environment and during leisure activities. There is little systematic research on the development of the dynamics of the relationship, or on the development of cooperation and communication between the crew and 'new crew members' (i.e. robots and agents), and almost nothing under actual space conditions—though again, the Robonaut2 deployment will begin to change this. In addition there are significant questions about the capabilities, level of autonomy and division of labour that will be appropriate for robots/agents to occupy in a future mission (c.f. Key Issue 1 on Human-Automation System Design).

There are some major questions surrounding the extensive use of robots and agents in space missions. How can humans feel safe and develop trust during interaction with robots and agents? Can efficient and safe means of communication and cooperation between the crew, ground, robots and agents be designed? What are the advantages and disadvantages of personification? How does working alongside robots and agents affect a person/crew's self-reliance? How can robots and agents learn from observation and their interactions with humans? Are they able to develop something like a sense of self-awareness and responsibility? How can robots and agents be used to support leisure activities?

Figure 10: ESA astronaut Paolo Nespoli familiarises himself with Robonaut 2, who was launched to the International Space Station on February 24th, 2011 (Credit: NASA)

Earth benefits and applications

Robots have been in practical use in Earth applications for almost 60 years. The current explosion of new robotic technologies and applications is testament to their on-going and increasing relevance. Robots have been used in manufacturing and industrial processes for decades and tele-operated drones have been used in exploration and maintenance for nearly as long. Recent innovations are increasingly targeting robotic applications for applications in hospitals and care-giving (e.g., medication delivery and even bathing) as well as military applications including armed reconnaissance, bomb disposal and medical evacuation. Viable software agents have an even broader range of applications, especially if they are defined as decision making or aiding software packages apart from personifications. The field is developing rapidly and will almost certainly continue to do so with or without added investment and focus on space applications. As noted below, however, space applications place extraordinary levels of reliance on technology and may drive advances in human-robot and human-agent collaborative work, interaction modalities, and concepts for interaction that involves shared physical proximity and high criticality applications. This, in turn, would have benefits for similar Earth applications—ranging from military to healthcare.

Brief review of latest developments

A range of emerging applications are described in the previous section. Of course, robotic probes have a long history of use in space exploration, most famously the recent Mars rovers and the Rosetta asteroid and comet explorer. While there are certainly advancements in the size, weight, range of motion, battery life and control precision associated with robotic technologies, and the logic and processing power associated with agent technologies, of most interest to this sub-group are advances in human interaction with robots and agents. While there are long-standing research efforts in speech understanding and generation, it seems fair to say that there are significant improvements in these areas and, specifically, in their use in interactions with robots and agents to perform work and leisure activities in recent years. Other modalities of input to robots and agents are being researched and are slowly making their way toward commercial products and work environments as well, including gesture and sketch recognition, facial expressions and bio-metric cues for use as neurophysiological cues. Similarly, increasing work is on-going in establishing protocols for robots which work in the same physical environment with humans, both in terms of exhibited modalities of behaviour (e.g., robot and agent facial expressions, non-verbal gaze and linguistically synchronised gestures and kinesics, posture and gait). Recent studies (e.g., Bickmore, 2010) are showing that there are circumstances (e.g., discussing medical protocols) in which some users prefer working with agents to other humans. Of course, most of this work is being performed in terrestrial labour and leisure environments; comparatively little is focused specifically on space. Specific exceptions include Bluethman et al., (2003) and Jones and Rock (2002).

Knowledge gaps and research needs

There is a small amount of data, both from industrial and space research applications about human-robot and human-agent interaction. However, there are an ever-increasing number of studies in Earth application, such as military and healthcare, which share some similar parameters/conditions to long-duration space missions, e.g. reliance and dependence on equipment for survival, development of trust over long-period of time. Despite the field of industrial robotics, which has existed in industry for half a century, the understanding of issues over an extended period of time in actual use of robots and agents in everyday life is only in its infancy, e.g. automated, aware and interactive homes/restaurants/sports and leisure clubs and robotic helpers. There is a need for a systematic research on the development of dynamics and trustful relationships between the people, robots and agents over long periods of time in safety critical environment. There is a call for to understand how to develop safe cooperation and reliable communication between the crew and 'new crew members' (i.e. robots and agents) with the focus on the use of these technologies under actual space conditions to enable joint human-robot-agent exploration missions.

Proposed investigations and recommendations

Since so much work is on-going in terrestrial applications of HRI and HAI, work in this area should begin with a detailed analysis of space-specific needs, followed by a thorough review of existing and on-going work for applicable lessons learned. This should lead to a more specific identification of those studies and developments that are needed for space applications that are not being filled by existing research lines. In particular, a review of current real-world operations in military and emergency operations, hospitals, etc. for lessons learned and concepts of operations, followed by efforts to project these results to space applications, followed by analogue and space-based studies to validate the understanding and concepts. The early investigations would focus on development of concepts, systematic research approaches and methodology to first study how humans react to and communicate with robots and agents in laboratory settings; followed by studies of more complex interactions in diverse and collaborative routine work environment and extended to safety-critical and unexpected scenarios.

Potential investigations might include (but should not be limited to):

- comparing effects of a range of personification alternatives on human performance in space-relevant tasks (in lab or earth-based simulation environments);
- developing a set of guidelines for the preferred modalities of interaction/communication (speech, gesture, joystick, etc.) for a range of space conditions and tasks;
- developing protocols for division of authority and resource usage.

Initial applications will need to be tested in similar-to-space extreme environments, such as military, medical and nuclear domains, e.g. battle conditions, surgical theatres, oilrigs, deep-sea, disaster relief operation. Finally, improved concepts of robots and agents as crew members, their communication and cooperation skills will then need to be tested in support of LEO and Moon missions (pre/post and during missions), before these technologies are imbedded in long-duration missions.

Trans-disciplinary aspects

Robots and agents may be used in monitoring and maintaining crew health (use of life shirts, encouragement of exercise – robots and agents as personal trainers); and crew individual and group psychological well-being. Also, robots and agents have a role to play in training and skill maintenance; as mediators in group dynamic processes; and in exercise management to support compensation for bone and muscle loss.

2.3. Conclusions

The general conclusion of the Expert Group on 'human-machine interface' is that much more work is needed to design and implement effective human-machine systems for use in long-distance space exploration. Although much of the technology and methodology is already well developed, exploration missions impose unique demands on both human operators and automation. In particular, research and development need to focus on designing systems that accommodate the need for flexible and adaptive use of automation. Specific themes identified were:

- Design of human-automation system
- Adaptation to support operator state and mission goals
- Evolving, problem solving and updating during missions
- Simulation and virtual/augmented reality (SVAR)
- Robots (HRI), agents (HAI) & human-robot-agent interaction (HRAI)

European capability is considerable in these areas, with research activity already at a high level. Such work is expected to have extensive benefits for Earth-related problems, notably in work environments involving interaction with highly automated systems, such as process control, transportation and medicine, and the increasing potential of virtual reality and robots for many Earth applications.

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3

Skill Maintenance

3.1 Introduction

One of the major problems for the involvement of humans in the management of complex mission tasks is the need to maintain necessary levels of operational skills during prolonged missions. Such issues have not previously been identified as a special source of problems for humans in space, but this is a serious oversight. Maintaining essential skills under long-duration conditions is made even more difficult by the necessary provision of high levels of automation, so that crew intervention may often be required only when faults occur with automatic control systems, or when infrequently scheduled manual sequences need to be activated. Specific concerns lie in the need to carry out unscheduled medical interventions or emergency operational trimming procedures, which—by definition—are rarely practised. Here, as with other less critical situations, there is a need not only for in-flight top-up training, but also effective computer-based support tools, integrated with relevant systems.

Figure 11: Andrè Kuipers inside a Soyuz TMA simulator during a training session at the Gagarin Cosmonaut Training Centre in Russia (Credits: ESA - S. Corvaja, 2010)

The key research needs identified by the Expert Group on 'skill maintenance' are for the development of effective tools and training procedures, for both individual crewmembers and the crew as a team, and for both ground-based preparation (e.g., simulation training) and on-going in-flight support (refresher or top-up training). However, research on the design of effective training and skill support has generally been piecemeal and fragmented. Training for performance of complex tasks needs to be flexible enough to facilitate the effective transfer of acquired skills to unusual operational conditions (unexpected events, novel problems, emergencies). There is also a need to develop countermeasures against the temporary loss of skill under compromised operator functional states associated with the presence of environmental stressors, fatigue, sleep disruption, monotony and boredom, all of which can lead to impaired decision making and operational performance. While the knowledge base for such problems is already well developed on Earth, little is known about the impact of the extreme conditions of long space missions. Effective control of disturbances of operator state—essential for long-duration space exploration--will require modelling of performance on an individual level, e.g. by collecting extensive baseline data on individual crew members before and during missions.

3.2. Skill Maintenance - Key Issues

3.2.1.Key Issue 1: Risks for operational effectiveness from infrequent or non-use of skills

Relevance for long-duration missions

One of the major problems for the involvement of humans in the management of complex mission tasks is the need to maintain necessary levels of operational skills during prolonged journeys. This problem is of increasing importance the longer missions become, and are a major risk for interplanetary travel. One reason is the (necessary) provision of high levels of automation, so that crew intervention is required only when faults occur with automatic control or when infrequent scheduled manual sequences need to be activated. Other activities may be required only occasionally, or during specific phases of the mission (e.g., hand controlled docking of a space craft) while others (catching free floating objects with a robot arm, telemetrically controlling a rover and its specific tools for surface exploration) are fundamental to mission goals. Because of the threat posed by skill neglect there may be a need for skill maintenance support to be designed as part of an on-board application.

From another point of view the maintenance and training tools of mission important skills provide an approach for monitoring and diagnostic analysis of the state and workability of the astronaut but could be extended to monitoring of crew cooperation and crew performance. Real tasks, including work sample tests are accepted by the crew and do not tend to be rejected by them even after numerous repetitions. But further research and development is required to identify valid and reliable monitoring methods. Currently plans for such monitoring are not incorporated into the technically oriented development phase of training systems. An effective skill updating system is also required for long-term space exploration missions.

Earth benefits and applications

Skill maintenance has a large significance for Earth applications with naturally long breaks between episodes requiring skill utilisation. There is an obvious relevance for safety critical systems. There are numerous complex work situations such as in process control operations, the military, aviation, and civil protection services where skills have to be maintained over long time periods and which may rarely be called upon. For some situations it may be ethically impossible to train staff under real conditions. A particularly apposite example is when emergency rescue or disaster teams are required, or in medical emergencies, when highly skilled team members are obviously required but the situations rarely occur.

Brief review of latest developments

While there are numerous findings in the literature about skills and skill acquisition, research on the deterioration and retention of (particularly complex) skills are less prevalent, confined largely to tasks with high visuomotor challenges, such as those associated with aviation. Few researchers have analysed cognitive tasks involving complex decision-making or problem solving (e.g., Sauer, Hockey & Wastell, 2000). Farr (1987) provides a good overview of older work, but little has been added since. In terrestrial medical research an analogous problem has been investigated, that of the maintenance of resuscitation skills in medical environments. This requires both manual and cognitive skills. The results demonstrate the primary vulnerability of the cognitive components in that complex skills may decay within three months (Kaczorowski, Levitt, Hammond, Outerbridge, Grad, Rothma & Graves, 1998).

For relatively simple skills the typical finding, as demonstrated by Manzey (1998) for simple tracking, is for no obvious deterioration over a long period of space flight. The only known study of long-term retention of complex skill in space was conducted by Salnitski, Myasnikov, Bobrov and Shevchenko (1999), and involved the manual docking of a spacecraft on a space station. The manual control of a spacecraft represents a very difficult task, requiring the simultaneous control of actions in six degrees of freedom, a situation never experienced under terrestrial conditions. The task primarily challenges complex cognitive processes, and cannot be reduced to a simple sensorimotor coordination task. It involves three dimensional perception of own position and movement from a 2d-screen; decision making about possible pathways; complex (6df)-control of 6 independent engines for turns around own axes and moves in space; limitations in fuel consumption; but no marked time constraints. Both US astronauts and Russian cosmonauts described the manual docking of a spacecraft as a very exciting and emotionally challenging task.

The practical relevance of the topic is evidenced by the research of Salnitski and his colleagues (Salnitski et al, 1999; Salnitski, Dudukin & Johannes, 2001). The docking procedure is trained only on simulators and rarely practiced in real-life situations. Even with well-trained cosmonauts, the reliability of these skills decreases without practice after a period of more than three months on a space flight. Hand controlled docking is required only if the automatic docking system fails due to a technical fault in the sensor systems (measures of distance, relatively speed etc.) or if a transport spacecraft (Progress) has to be re-docked to an alternate docking port to vacate the previous port for the approaching Shuttle. Finally, in most instances of manual docking, the astronaut is performing this operation in reality for the first and only time. It is obvious that a high level of psychological strain may play a critical role in such a situation. The crashed docking during the MIR23-Mission (Ellis, 2000) is an unfortunate example of what can go wrong. Salnitski et al. (2001) developed a common concept for evaluating the reliability of an operator's skill. Besides taking into account all indicators of docking quality, the assessment of the psychophysiological state during the docking manoeuvre plays an important role for the prediction of the expected real docking success.

Knowledge gaps and research needs

While there is an extensive terrestrial empirical base for skill acquisition, as well as for forgetting in simple tasks, very little is known about the pattern of skill loss with disuse for more complex tasks. There is only limited knowledge of methods for monitoring and assessing potential skill deterioration for different types of skills. Also, very little is known about the rates and level of skill loss for task knowledge and procedures that are shared between members of teams or crews. Finally, almost nothing is known about patterns of skill learning and deterioration in space missions.

Proposed investigations and recommendations

Proposed studies include:

- Development of skill maintenance and training systems (inventing new techniques and technologies) with embedded monitoring of performance and psychophysiological state for strain assessment; embedded testing of fundamental cognitive skills. A primary objective to start with is to be able to identify how and when performance and operator functional state are being compromised by infrequent or non-use of skills. This will enable the appropriate monitoring of performance associated with the introduction of diagnostic methods to alert operators of the need for additional training;
- Systematic investigation of performance of a range of skills over a long period (2 years), to allow the identification of possible differential deterioration of different types of skill over time;
- Comparison of maintenance and learning under standard Earth conditions and in ICE and space environments. This will be necessary because of the interaction between learning, performance and the space environment, for example in terms of the effects of adaptation to microgravity, bone and muscle changes over time.

Trans-disciplinary aspects

The embedding of training and monitoring methods into the operational system will need to be designed in relation to several of the issues related to human-machine interfaces.

3.2.2. Key Issue 2: Need for different training methods for the acquisition and maintenance of different types of skill

Relevance for long-duration missions

Long transfer phases between Earth and other planets require the crew 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. In addition, with longer space flights there is an increased probability that crew members have to react to unforeseen incidents in which the trained skills need to be flexible applied. High-performance skills vary in their dependence on different cognitive, perceptual and motor components, and are thought to benefit from specific training regimes. Even for skills that are superficially similar (e.g., those used by process operators to manage chemical plants or transport systems) there are variations in the dependency on rules/procedures or knowledge/real-time decision making. Training methods vary in a number of ways (e.g., specific/general skills, whole/part skills, use of feedback, and spacing of practice). From the point of view of preserving these different kinds of skill under the stress and low practice condition of extended missions it would be advantageous to examine the relative effectiveness of different strategies for the range of skill types experienced during missions – not only during acquisition but for later use.

Figure 12: ESA astronaut Frank De Winne trains inside the Cupola module mock-up in the Multi-use Remote Manipulator Development Facility (Credit: ESA/NASA)

In addition, the tasks which have to be performed by the crew members may be distinguished in terms of their status as part of planned activities, differing in frequency of implementation and time until first requirement. For example, while the skills for performing the tasks during take-off are implemented at the beginning of the journey to Mars (meaning a smaller retention interval), skills relevant to landing manoeuvres on Mars are needed at the earliest 6-8 months after the take-off (a very large retention interval). In addition to these tasks, for which it is possible to estimate when they have to be performed, other skills have to be implemented unexpectedly; e.g. trouble shooting in the case of a technical problem or medical emergency. Both conditions of skill application are relevant to consider in the proposed research and need to be addressed differently; e.g., in terms of just-in-time training for predictable skill applications with long retention intervals and other forms of training for addressing the unexpected troubleshooting applications.

Earth benefits and applications

Many high reliability organisations such as nuclear power plants, chemical plants, oil platforms or refineries, hospitals or commercial aviation, are characterised by highly specialised production departments which have to operate on a highly dependent (reliable) level. Whether or not they actually perform reliably is demonstrated in non-normal or abnormal situations which are either (a) technical problems that arise and need to be addressed by the human operator (troubleshooting) or (b) important/dangerous and infrequent events, such as the shut down every five years of a plant for a general technical inspection. Within the time period before the infrequent event, skills are likely to degrade through long periods of non-use and the extensive use of highly automated processes. This means that for Earth applications, the unexpected and immediate skill application as well as the infrequent use of special skills is also relevant, but just-in-time training might be easier to conduct.

Brief review of latest developments

Generally it is assumed that training methods vary in their effectiveness in a number of ways (e.g., specific/general training, whole/part task training, quality and quantity of feedback, spacing of practice; Pashler, Rohrer, Cepeda & Carpenter, 2007; Schmidt & Bjork, 1992), but there are a small number of isolated studies directly addressing skill learning, retention, and relearning (e.g. Arthur et al., 2007; Ginzburg & Dar-El, 2000), or very long intervals of non-use (Pashler et al., 2007; Shute & Gawlick, 1995).

A comprehensive analysis by Arthur et al. (1998; extended by Leonard, 2007) showed that skill retention depends on the nature of task (physical, natural, speed-based versus cognitive, artificial, accuracy-based) as well as the conditions of retrieval. Additionally, research by Pashler et al. (2007) and by Roediger and Karpicke (2006) shows that skill maintenance can be positively affected by retrieval practice. But so far only relatively simple tasks have been investigated, such as learning word pairs, mathematical problem solving, perceptual categorisation learning, or fact learning (e.g. Pashler et al., 2007). These are obviously parts of the complex skills needed for longer space flights, but have not so far been investigated in combination.

Current research on process control (Burkolter, Kluge, Sauer & Ritzmann, 2010; Kluge, Sauer, Burkolter & Ritzmann, 2010) shows that training methods differentially affect task components after 12 weeks of non-use. Practising routine drills, for example, supports the use of procedural knowledge within closed loop tasks, leading to fewer decrements in performing fixed sequences for reacting to a technical problem. However, skills in stabilising a technical system manually (using system knowledge or open loop control) were not affected by different training methods.

Knowledge gaps and research needs

Kanas and Manzey (2008) refer to training that prepares astronauts for coping with the psychological demands of space flight, also called non-technical skill. But there exists only limited knowledge of the following: how training approaches affect the way of maintaining different skills; effective sequencing, spacing and composition of training methods; effective retrieval practice; advantages and disadvantages of training of flexible vs. specialised skills; the effect of the training of general versus specific problem solving procedures; how training of one skill saves training and rehearsal time of another (and how much it depends on there being shared aspect of both tasks); use of recall and recognition cues, such procedural aids and decision aids, or online help systems, rehearsal techniques, etc.; the extent to which skills and skill maintenance can be allocated among crew members, or whether every crew member needs to be trained to meet predefined performance criteria in order to build up shared knowledge and skill redundancy within the group.

Proposed investigations and recommendations

High-performance skills vary in their dependence on different cognitive, perceptual and motor components, and are known to benefit from specific training regimes. Even for skills that are superficially similar (e.g., those used by process operators to manage chemical plants or transport systems) there are variations in the dependency on rules/procedures or knowledge/real-time decision making. Therefore, the major need is for a formal analysis of which skills are required after a period of non-use, and how long these practice gaps are for different activities. These skills and their associated periods of non-use may then be ranked in terms of the duration of their period of non-use, and investigated in combination with a cognitive task analysis to systematically investigate the pattern and extent of forgetting.

Based on such findings, investigations (training experiments including pre-flight training and assessment on the ISS) are needed of the effectiveness of different training approaches:

- evaluation of advantages and disadvantages of part-task training, whole task training, emphasis shift training, procedural training;
- the spacing and most effective forms of retrieval practice for different types of complex cognitive and psychomotor skills, including comparison of different training schedules and spacing;
- possible advantages of over-training (beyond nominal 100% criteria of performance) in protecting skills against decrement with non-use.

From the point of view of preserving these different kinds of skill, under the stress and low practice conditions of extended missions, it would be advantageous to examine the relative effectiveness of different strategies across the full range of skill types experienced during missions.

Trans-disciplinary aspects

The Expert Group did not identified obvious overlaps with other topics.

3.2.3. Key Issue 3: Use of on-board top-up training to maintain and enhance skills

One way of overcoming the impairment of skills with disuse or lack of operational practice is to provide supplementary (top-up) training, but there are currently no accepted criteria for deciding how best to achieve this. Different perceptual motor competencies, cognitive and executive control skills, and even individuals, may require different schedules and types of refreshment. Specific questions refer to the timing, intensity and design of refreshment training in relation to the skill – how specific or varied it is in use, and how much it is constrained by environmental input. A second issue concerns on-board implementation; how can training platforms and refreshment procedures be designed into the system, using either integrated learning modules or self-managed, off-line tools?

Relevance for long-duration missions

Many mission relevant skills are trained only on simulators prior to a real space flight (e.g., docking training). In professional aviation the use of full scale or part task simulators is a standard, but this is not possible as an on-board application. The need to develop training capabilities and platforms that can be implemented on board and enable training and refreshment of skills, tasks and procedures is an important challenge for long-duration space missions and is made possible by contemporary developments in the use of virtual reality technology for skill training (Gopher et al 2010). It is equally relevant to a large variety of long duration, high demand and rich technology tasks performed on earth. All of them have in common the need to acquire and maintain high competency in a wide and diversified set of skills, interact with and be comfortable in the operation of advanced engineering systems, cope with dynamically changing demands and respond to emergency and low frequency events. It is also the case that in space missions as well as in many of these tasks errors are costly, hence there is a low tolerance for errors (e.g. flight control, nuclear power plant control rooms, submarines, etc.). The challenge is to develop modules and formats of training that can be incorporated on board and be accessed during and along with mission performance. The present age of sophisticated, high-powered, computer- and AI-supported operational systems, makes it possible and desirable to include an accompanying integrated training module in the basic design configuration of the system. Such a training and simulation module will enable crew to move readily between training and operational modes in system operation. This mode may enable the technological age re-instantiation of the "on the job training" concept. It should be recognised that a prime instigator for the development of separate task simulators and training environment was the limited ability to conduct training on the real system

Earth benefits and applications

There would be benefits for a variety of industries, in terms of workability, maintenance of proficiency, and the retraining of professionals (continuing professional development).

Brief review of latest developments

With the advancement of computer technology simulators becoming more hybrid and dynamic systems, visual field and audition have become increasingly driven and generated by computers. Contemporary developments in sensors and display capabilities and the exponential increase in computation speed and storage capacity led the way to the development of multimodal virtual environments. In these environments, the operator is immersed, experiencing multimodal sensations and interacting with virtual objects including other humans (Riva 2006, Sanchez-Vives, Slater, 2005). Vision and audition have routinely been included the study and design of simulators. The new important addition is the inclusion of haptics—the ability to feel and exercise force, touch, texture and kinematic sensations. Haptic technology is developing rapidly and haptic interfaces are now being incorporated into many virtual worlds. It is reasonable to expect that the multimodal, virtual reality platforms will dominate the next generation of training simulators. An example for this development is the current collaborative skills project of the EC 6th Framework Programme on multimodal Interfaces for capturing and transfer of skills (Avizzano 2008; Avizzano et al, 2010; Gopher et al. 2010; Ruffaldi et al, 2010). The goal is to design, develop and validate training systems where haptic technologies are introduced in the interaction with the training virtual scenarios; in this, the paradigm of knowledge acquisition plays a central role.

Figure 13: ESA astronaut Christer Fuglesang uses virtual reality hardware in the Space Vehicle Mockup facility at the Johnson Space Center to rehearse duties he will perform on the ISS (Credit: ESA/NASA)

In this context specific (complex) tasks have been identified suitable to become the focus of training scenarios based on the application of robotics and virtual environments technologies. These tasks belong to different application domains – sport and entertainment, surgery and rehabilitation, industrial maintenance and assembly – and specific training scenarios and demonstrators have been associated to such domains.

Knowledge gaps and research needs

Training simulations, virtual reality, computer based trainers and training environments have all have been developed to serve task and systems but have not been constructed as an added integral component of the operational system to combine operation and training and enable on the job training. Performer training and system operation have been developed independently and analysed separately. Training is conducted in a separate environment, in preparation for operational performance (e.g. Kaiser, & Schroeder, 2003). The main argument here is that with the long-duration space missions and the present state of technology, it is possible and necessary to include "on the job training" together with the operational system design. It is anticipated that such an approach will be beneficial for both operational effectiveness and skill training and reduce their costs.

Proposed investigations and recommendations

A number of fundamental sets of studies are required to develop this area to the point where it can be useful for space exploration, particularly for dynamic, high demand tasks, where there is a high degree of uncertainty and variability in details of the task profile, and low tolerance to error. In many tasks of this type forgetting of skills is exacerbated by the long-time intervals between the recurrence and repeated use of some task segments, emphasising the need for continuing training that can be readily available and easily accessed:

- There is a sufficient level of technology and AI capability on board to justify and support the incorporation of skill training modules. A major research goal is to develop formal methods of achieving these aims within the normal operation and conduct of the mission. Research needs to be carried out on how to embed training modes, scenarios and options, within and in support of each main system and operational segment.
- A major programme of work is required on optimal ways of using virtual and augmented reality capabilities to support complex skills. Methods need to be established for determining how and what performance measures and comparison formats should be added for performance, both on the real system and in the training environment (analogous to transfer of training studies). This would allow the evaluation of learning progress as well as possible deterioration in competence.

Trans-disciplinary aspects

Provision of on-board training has a direct relevance for the management of communication delays and changes in crew cognition.

3.2.4. Key Issue 4: Protection against effects of stressors on skill learning and effective long-term skilled performance

Relevance for long-duration missions

The effective performance of skills can be threatened by compromised operator functional states, such as those produced by the need to combat stressors. Such states are intrinsic to space missions, induced by the extreme physical environment, isolation and confinement, danger and the requirement to maintain mission goals under all situations. Effects of stress states are not always obvious because of the typical operation of an adaptive strategy which protects primary goals through increased effort, but there are likely to be hidden costs which can compromise safety margins. In addition, stressors such as noise or threat have been found to make learning more specific and rigid, with reduced flexibility for responding under unfamiliar circumstances.

Earth benefits and applications

The terrestrial applications of the proposed research are many and varied. There is a massive potential application to stress management; coaching/learning environments; specific healthcare and medical systems; the training of medical skills for disaster situations; and operator support in safety critical systems. In terms of the advantages of developing appropriate countermeasures there is potential application to work in extreme stress environments, with appropriate application to stress management, emergency/terrorist measures, accident management, and escape training.

Brief review of latest developments

There is widespread knowledge about the short-term effects of stressors across a range of well-learned skills. However, very little is known about the effects of such stressors on skill acquisition and the long-term maintenance of skills, for both Earth and for space simulation; almost no knowledge of performance under stress in space; and limited knowledge of methods to protect crew members against stress effects. Kanas and Manzey (2008) identified various factors that have

Environmental factors	Individual state factors	Psychosocial factors
Noise	Sleep deprivation	Isolation
Radiation	Disturbance of sleep patterns	Confinement
Microgravity	Fatigue	Social interaction
Vibration	Health and well-being	Communications
Light/dark cycle	Physiological adaptation	Boredom/monotony
Task demands	Psychological adaptation	

Table 1. Potential threats to skill maintenance in space missions

the potential to cause performance impairments during space flight (see Table 1).

However, the outcomes of a huge amount of experimental work on the effects of various stressors on single-task performance suggest that degradation of simple tasks is unlikely to be observed under normal conditions. 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, Bock & Comfort, 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, Lorenz & Polyakov, 1998). Adaptation to the new environment appears to erode these effects.

Primary-task performance has been described as being protected under 'normal' circumstances, 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.

An important question for space flight is whether crew members can be trained to deal more effectively with stress states, and reduce the threat to operational skills. In other words, are there any effective countermeasures against impairment under stress? An approach known as stress exposure training (SET) has been proposed as a training intervention to reduce anxiety and improve performance under stress (Driskell & Johnston, 1998). SET involves instruction in the likely impact of stressors, and allows the practise of task skills under conditions that are increasingly similar to those expected in operational situations. SET has proved effective in protecting operators by preparing them for performing under stress (e.g., Driskell, Johnston & Salas, 2001). However, it is possible that training skills and preparing operators to perform under stress may require specific knowledge of the situations and tasks likely to be faced by them in space, which may not always be possible.

Knowledge gaps and research needs

Creating real or simulated emergencies in laboratory situations is not easy and it is often impossible to predict the nature of potential natural emergencies accurately. Although there is a wide literature on the effects of single stressors on certain types of performance, these tend to be limited to relatively low levels of stress and few studies have examined the effects of multiple stressors on performance and state outcomes. More evidence is also needed on the efficacy of SET from lab-based studies and military/industrial/healthcare applications. There is currently no knowledge of effects in space or space simulations.

Very little is known about the transfer of skills learned during simulation training to their use in new stressful environments. Despite the considerable body of research on the effects of environmental stressors on performance, there is little of direct relevance to this question.

Proposed investigations and recommendations

The main recommendations are:

- that a systematic investigation should be conducted of the effects of a combination of stressors on a range of skills on Earth and in low Earth orbit. In order for this programme of research to be effective it will be important that an appropriate methodology is developed for studying skill decrement in relation to performance and the costs of managing performance. This will require a multi-measurement approach, in which performance and changes in operator functional state are monitored in relation to the manipulation of multiple stressors;
- In terms of the development of appropriate countermeasures, studies need to be conducted to evaluate the effects of stress exposure training (SET) for different applications and environmental situations. A study using the ISS would provide an ecologically valid environment, with initial SET training on Earth (with control group receiving dummy training). The study would examine the transfer of SET training during the preliminary Earth phase (between different kinds of stressors and tasks), then during ISS mission, and during follow-up back on Earth. A suitable sample size would need to be built up from several cohorts. It is important that such a study has many relevant outcome measures. It will be necessary to demonstrate both the effects of stress and the effectiveness of SET.

Trans-disciplinary aspects

Training for stress management has a clear link with that for crew cognition and would best be treated as part of the same pre-mission programme.

3.2.5. Key Issue 5: Management of sleep and work/rest schedules to prevent skill impairment by sleepiness and fatigue.

Relevance for long-duration missions

Space flight presents particular challenges for sleep and a number of studies have indicated that sleep is impaired by suboptimal work/rest schedules, unsuitable temporal light patterns, noise, stress, microgravity and other factors. Sleep disruption, circadian resynchronisation, and the resulting fatigue and sleepiness will, in turn, impair the performance of operational skills. The occurrence of such disruptions can make the crew dysfunctional in one or two days. Maintenance of effective sleep is thus a key goal for extended space missions.

Earth benefits and applications

Risk management related to fatigue, sleep and circadian disruption is relevant to all areas where human performance, and particularly the guarantee of a certain level of performance, is critical. Medical applications, nuclear plant management and the transport industry are among the most obvious applications, but also shift work and other irregular working regimes in non-risk related places. Fatigue and sleepiness may seem like topics which have already been investigated extensively, however, in terms of countermeasures, there is a serious lack of research supporting evidence based applications. Another important benefit for Earth application is the contribution to the measurement of fatigue and fatigue-like states. This is highly relevant for clinical research on chronic diseases, where fatigue is the main symptom affecting quality of life, such as cancer, chronic fatigue, multiple sclerosis and others. These affections could also benefit from the countermeasures identified to be relevant for space flight.

Brief review of latest developments

While sleep loss and circadian influences are known to have remarkably strong effects on alertness and behavioural efficiency, relatively few studies have demonstrated such effects on real-life performance.

This is a problem because laboratory results cannot be readily generalised to operational environments. However, a number of studies have shown that poor or shortened sleep is a predictor of fatal accidents at work, and that accident risk is considerably increased by irregular work hours (Åkerstedt, 2002).

Figure 14: Sleeping cabins on-board the ISS are built into the floor, walls and ceiling, providing astronauts with privacy and a fixed place to sleep (Credit: ESA/NASA)

Spaceflight research indicates that the overall quantity and quality of sleep in astronauts is markedly reduced in comparison to terrestrial sleep (NASA, 2008). Sleep structure changes are variable, with generally more awakenings and intra-sleep wakefulness, and sometimes a decrease in Slow-wave sleep (SWS) during the flight (Frost, Shumate, Salamy & Booher, 1976; Gundel, Polyakov & Zulley, 1997; Dijk, Neri, Wyatt, Ronda, Rie, & Ritz-De Cecco, 2001). Sleep disturbances in space depend on a combination of factors such as mission imperatives, confinement, promiscuity, noise, workload, the loss of stable circadian zeitgebers and circadian misalignment. For example, workplace stress, fatigue and sleep deprivation were identified by NASA as contributory factors in the Mir-Progress collision (Ellis, 2000).

A number of countermeasures have been implemented in order to improve sleep comfort, including carefully timed bright light exposure (Fucci, Gardner, Hanifin, Jasser, Byrne, Gerner et al., 2005). Current research mainly focuses on actigraphy-data driven scheduling tools: for example, splitting sleep and implement napping strategies under conditions where continuous night rest may not be compatible with operational requirements (Mollicone, Van Dongen, Rogers & Dinges, 2008). An additional promising method is physical activity, which is regarded as a standard non-pharmacological intervention for sleep disorders (Hauri, 1993). Exercise is particularly effective when other zeitgebers (notably the light-dark cycle) are missing, as will be the case during a long-duration exploration flight. Indeed, the observed decrease in SWS during space missions (Gundel et al, 1997; Dijk et al, 2001) has been attributed to reduced physical activity during spaceflight, and thus a reduced influence of sleep homeostatic processes. Biofeedback can also be used as a self-regulation method of sleep management (through control of relevant physiological systems: cardiac activity, respiration, muscle tone or cortical activity (Egner and Gruzelier, 2004).

Knowledge gaps and research needs

While a great deal is known about sleep and its performance effects in terrestrial environments, relatively little is known on how sleep is affected by long space missions, and what effects these may have on skill use in such situations. Research needs can thus be summarised as follows: (1) detailed physiological assessment of sleep during spaceflight, with clear identification and diagnosis of sleep impairments; (2) Impact of sleep and circadian disruption on skill maintenance during spaceflight/confinement; (3) modelling and prediction of performance decrements due to sleep impairment, circadian disruption and demanding work schedules; (4) a better understanding of fatigue – in particular the joint effects of fatigue from sleep disruption and from mental and physical work – with clear predictions of its impact on performance; (5) a focussed search for more effective countermeasures.

Proposed investigations and recommendations

- The impact of sleep and circadian disruption on skill maintenance needs to be fully understood and carefully quantified. This implies a need for measurement tools. Fatigue and skill maintenance are concepts intuitively grasped by everybody, and yet hard to measure in an ecologically valid way because of their multidimensionality. A major goal is to try to model their impact on performance;
- More effective countermeasures or combinations of interventions need to be identified. These already include sleep scheduling (including napping and split-sleep strategies), exercise regimen, biofeedback, phototherapy, nutrition and drugs. Effects of countermeasures should be assessed, to issue recommendations with regard to the adequate combination to be applied during long-duration space mission. Such studies need to be carried out in ISS or ICE settings, which share the relevant features of sleep discomfort, isolation, confinement and circadian disruption.

Transdisciplinary aspects

There are evident links with integrative physiology – these should be explored further (exercise as countermeasure => bone loss and amyotrophy, cardiovascular deconditioning). There is also a link with HMI issues and habitat – design of mission environment (both hardware and software).

3.3. Conclusions

The broad conclusion from the Expert Group is that the problem of skill maintenance should be recognised as a major focus for space-related research on human behaviour. This area has been overlooked in previous human space programmes, though it is likely to have a major role in the success of very long-duration missions. Maintaining operational skills requires both a better understanding of how to develop effective training and methods of providing on-board refreshment of skills. A third focus for research is to understand and manage the threat from environmental stressors, fatigue and sleep disturbances.

Specific topics identified for further research were:

- Risks for operational effectiveness from infrequent or non-use of skills
- Need for different training methods for the acquisition and maintenance of different types of skill
- Use of on-board top-up training to maintain and enhance skills
- Protection against effects of stressors on skill learning and effective long-term skilled performance
- Management of sleep and work/rest schedules to prevent skill impairment by sleepiness and fatigue

A high level of European capability exists in all these areas, though it is at present not focussed on space issues. The potential benefits for Earth activities are almost unlimited, since the programme would ensure better learning, retention and utilisation of complex skills, and a greater resilience of human performance under conditions of threat and stress.

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4

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