Human Performance in Space: Advancing Astronautics Research in China
JOIN AAAS

Get instant access to Science. Support all of the sciences.

The American Association for the Advancement of Science (AAAS) is a non-profit community that is open to everyone, from Nobel laureates to high school students. Ours is a global membership of over 120,000 people who believe in the power of science to make the world a better place.

From the moment you join, you get immediate access to everything that AAAS's award-winning journal Science has to offer, including:

- 51 weeks of home delivery of Science;
- Instant online retrieval of every Science article ever published, from today, dating back to 1880;
- Anytime, anywhere access via the Science mobile site and apps for Android, iPad, and iPhone devices;
- Members-only newsletters; and more.

As a member, you are also making a critical contribution to AAAS's efforts to provide a public voice for all of science. With public skepticism about science increasing, and public funding for research more uncertain than ever, this work has never been more important.

AAAS is hard at work promoting science in government offices, in schools, and in the public commons all around the world—with programs like AAAS Senior Scientists and Engineers, which brings volunteer scientists into public school classrooms, or our sweeping petition drives calling for the preservation of federal R&D funding.

Visit promo.aaas.org/joinaaas and join today. Together we can make a difference.

Human Performance in Space: Advancing Astronautics Research in China

Editor: Sean Sanders, Ph.D.
Assistant Editor: Tianran Hui, Ph.D.; Production Copy editor: Yume Li; Lead Illustration: Jiong Zhang
Guest Editors: Hong Liang, Zhijun Xiao, Jianhui Li; Cover Illustration: Jingying Zh

Since 1880

Section 1: Crew capabilities and physiological changes in space or simulated weightlessness conditions

- 4 Attention, per-personal perception, and visual displays in space
- 5 Human perception with gravity’s imprint
- 7 Effect of gravity on sex hormones
- 10 Alteration of cellular and inflammatory immune responses during long-duration head-down bed rest
- 11 Role of ciliary neurotrophic factor in regulating myoblast plasticity and unloaded muscle atrophy
- 13 MicroRNA: A pivotal player in unloading-induced bone loss
- 15 Space meets time: Impact of gravity on circadian timing systems
- 17 Homeostatic regulation of the sleep-wake cycle by prostaglandin D2 and adenosine
- 19 Investigation of gait pattern in simulated weightlessness
- 21 Traditional Chinese medicine—a potential countermeasure to stressors associated with space missions

Section 2: Human-machine interaction and crew cognitive behavior in space

- 24 Effects of automatic processes on safety performance: Implications for astronauts
- 26 Human factors in manually controlled rendezvous and docking: Implications for engineering better designs
- 28 Exploring brain-computer interfaces for use in space missions
- 30 Factors affecting astronaut manual operation tasks
- 32 Animal behavior assessment technology for space medicine
- 35 Effects of space flight on human emotion
- 38 High-risk decision-making in space
- 40 Effects of weightlessness on cognitive performance in humans
- 41 Psychological adaptations to long-term isolation and confinement: Lessons learned from the Mars500 project
- 42 Space flight operation skills: Effects of operation complexity and training method

Section 3: Human modeling, simulation, and performance evaluation

- 46 Measuring mental workload during emergency operation procedures
- 49 Ubiquitous EEG-based cognitive performance monitoring in astronauts
- 51 Evaluation of EEG oscillation patterns during simple and compound limb motor imagery
- 53 Advancements in space-based network cognitive architecture for human space operation performance modeling
- 55 Application of a human behavior model in space human performance research
- 57 Astronaut performance simulations: An integrated modeling and simulation platform
- 60 Navigational aids for human exploration of deep space
- 62 Virtual modeling and simulation of astronaut motions
- 64 Biomechanical modeling and dynamics simulation of an astronaut’s musculoskeletal system
- 66 Bone density adaptation during long-term space flight: Predictive models and numerical simulations
- 68 Establishment of a 3P model for evaluating operation training efficacy in astronauts
H

uman space exploration was no doubt one of our greatest adventures in the last century. On 12 April 1961, Russian cosmonaut Yuri Gagarin became the first human in space, making a 108-minute orbital flight in his Vostok 1 spacecraft. Since then over 400 astronauts have traveled into space.

The experience and research data accumulated from these space flights have revealed the adverse effects that environmental factors unique to space—weightlessness, extreme temperatures, radiation—can have on humans, including loss of bone density, decreased muscle strength and endurance, postural instability, reduction in aerobic capacity, and psychological problems. Over time, these deconditioning effects can increase the risk of injury as well as impair performance. Research into the means to maintain or improve human performance in space, especially during long-term missions, has therefore been a focus of the space medicine and human factors fields.

Just over a decade after China initiated its manned space program in 1992, we became the third nation to achieve human space flight when Yang Liwei was launched into space aboard the Chinese-made Shenzhou 5 spacecraft on 15 October 2003. Ten Chinese astronauts—eight men and two women—have thus far been into space, resulting in numerous innovations and technological breakthroughs. Initial ground-based studies have been verified and validated by subsequent on-orbit experiments, giving us a more profound understanding of human performance in space. Myriad factors have been successfully studied, characterized, and implemented, including the application of Chinese traditional medicine, to improve human performance in space.

With the launch of China’s space station program, the time that Chinese astronauts spend in space has been extended considerably, generating new challenges in human factor analysis. The National Key Laboratory of Human Factors Engineering is proud to be hosting a National Basic Research Program of China to study the effects of extended duration space flights on humans. It has yielded important research results leading to publications in international academic journals, summaries of which are provided herein. Of broader note, a Chinese national is one of the six subjects from four countries participating in the prestigious international collaboration project called Mars500, a fascinating ground-based experiment simulating a human-led trip to Mars. A selection of results discussing the psychological aspects of this research are also reported in this booklet.

In closing, I’d like to thank Science/AAAS, as well as the editors from Space Medicine and Medical Engineering/China Astronaut Research and Training Center, whose hard work and professionalism have been integral to the production of a top-quality publication. Special acknowledgment goes to the China Manned Space Agency and the Beijing SinoBioway Group, Ltd. for financially supporting the publication of this booklet.

Shangguang Chen, Ph.D.
Academician, the International Academy of Astronautics (IAA)
Deputy Chief Designer of China Manned Space Program, China Manned Space Agency
Director, National Key Laboratory of Human Factors Engineering, China Astronaut Research and Training Center

Advances in human space research – lessons learned and future directions

With the launch of China’s space station program, the time that Chinese astronauts spend in space has been extended considerably, generating new challenges in human factor analysis.

S

pace travel has always fascinated human beings. Since early in our history, we have looked to the heavens for inspiration and guidance, as well as for more practical purposes such as making use of the stars to navigate, and the sun and moon to track the changing seasons.

Our thirst for knowledge and desire to push beyond our innate physical capabilities led to the first human flight in 1903 and, just 58 years later, the first successful attempt to send a human into space.

Our journey beyond the Earth has not been easy. Space provides us with not only technological obstacles, but also significant physical challenges. As a species, humans have evolved in the presence of gravity. This has deeply influenced how we survive and thrive, creating unique hurdles for long-term exploration of space. Microgravity has been found to cause bone loss and muscle atrophy, while the loss of regular day/night cycles in space can negatively impact the body’s circadian rhythms, causing sleep loss and associated decline in mental and physical performance. Even impacts on reproductive fitness have been reported.

As we pursue bold initiatives in space, and as China moves towards launching a permanently manned space station, gaining a clearer understanding of the impact of long-term space travel becomes essential to maintaining the well-being of astronauts. Serious consideration has been given to human travel beyond low Earth orbit—where the International Space Station resides—and beyond the moon, possibly to Mars or the moons of Jupiter. An Earth-based simulation of the psychological effects of a trip to Mars, called Mars500, was carried out between 2007 and 2011 jointly by Russia, the European Space Agency, and China to identify the potential problems that a 520-day manned mission might present.

Can a way be found for astronauts to continue to function at a high level under those conditions? And what can be done to abrogate at least some of the effects of space travel? In addition to attempting to answer these questions, researchers are making improvements to the technical aspects of working in space, such as spacesuit design and human factors engineering. To do this, they are creating highly accurate computerized simulations of how astronauts move and function in space.

Examples of groundbreaking space research currently underway in China are collected in this booklet, providing the reader with a taste of what future space exploration might look like. As Chinese scientists learn about the effects on the body and mind, they are applying their knowledge to modify equipment, improve astronaut training, and fine-tune the selection process for astronauts. Other scientists and engineers around the world will benefit, and can apply the new information to space programs in their own countries.

Sean Sanders, Ph.D.
Editor, Custom Publishing, Science
Crew capabilities and physiological changes in space or under simulated weightlessness conditions

Feng Du, Yan Ge, Weina Qu, Xianghong Sun, Jianhui Wu, Kan Zhang, and Liang Zhang

Abstract

Recent studies have shown that color-coded information not only increases a person’s perceptual discrimination of stimuli, but also involuntarily summons their attention. Du and colleagues asked participants to sort names of colors by a rapidly presented visual stream, mimicking a dynamic information stream on a visual display. They reported that an irrelevant peripheral distractor that matched the target-defining color could automatically capture the attention of test subjects, even when it appeared outside of the area of interest (4, 5). These findings confirmed that color is so psychologically salient that it can override the spatial control of attention. In addition, several recent studies showed that color is a much stronger feature than achromatic features such as orientation and size (6, 7). Thus, visual stimuli that break important information could be consistently color coded to direct attention to that information involuntarily.

However, simply studying the role of color in attention prioritization is likely not sufficient for applying the optimal use of color coding, which requires a deeper understanding of how color-coded information is perceived. For instance, the question of where best to present color-coded information has not been fully answered. However, a recent study showed that an irrelevant distractor that matched a target color was more likely to capture a subject’s attention when presented in the left visual field than the right (5). The effect of varying the interval length between two important color-coded stimuli, which might vary according to the complexity of the information, was also recently examined. Studies demonstrated that humans require an interval of at least 400-500 ms between two sequential stimuli (8, 9) and that our attention control system needs about 500 ms to eliminate the influence of a previous target’s color (10).

The number of colors used to code information should be kept to a minimum to prevent excessive cognitive load in complex cases. This principle is mainly derived from limitations in visual working memory capacity (11). However, when using color as a nonredundant cue to summon important information, visual operators, studies have shown that subjects can easily maintain two colors in their attention control system simultaneously (10). Whether humans can maintain more than two colors in their attention control system simultaneously (11) requires protracted information exchange between the operator and the technology interface. To efficiently transmit visual information to astronauts, visual displays need to be carefully designed and arranged. Here, we have reviewed some recent psychological studies to provide a new perspective on the role human factors play in effective use of visual displays.

Color coding displays

Previous studies have provided useful guidelines for designing the visual displays used in space. Early work demonstrated that using color on displays can facilitate the subject’s ability to search and identify visual information when compared with coding by shape, size, and luminance, irrespective of whether the color coding was redundant or nonredundant (2). Although color was not always better than letters and digits, color coding became increasingly superior to letters and digits as the difficulty of the identification task increased. Moreover, color also helps the subjects to connect spatially separated yet conceptually related elements. For example, Byme et al. designed two sets of visual displays, one containing in motion patterns, and that removing gravitational information compromises visual processing efficacy. To what extent has the Earth’s gravity shaped our attention?

When we observe objects on Earth, they are most often either aligned with gravity or moving under the influence of it. These visual gravitational cues have been conceptualized as an environmental constant that is ingrained into object representations in the brain (1). In order to examine this process, we have studied a specific form of motion, the human gait, which involves a complex set of coordinated activities constrained by gravity. It can be captured by the trajectories of a handful of point lights attached to the major joints of the body (Figure 1). When these point-light displays of walkers in motion, as well as their inverted counterparts, subjects reflexively follow the direction of the motion of the former, but not the latter, and do so by ascribing to the dots when the spatially scrambled (2). The viewer is only aware of the scrambled image of lights as groups of randomly distributed and randomly moving dots and cannot tell which scrambled set is from an upright point-light walker and which is from an inverted one. However, event-related potentials recorded on the scalp of the viewer show an early component characteristic of spatial attention in response to the scrambled upright, but not the scrambled inverted, point-light walkers (3). Put differently, upright point-light walkers with proper gravitational information function as a powerful reflective spatial cue independent of their global configurations. This leads us to infer that the visual processing of point-light walkers involves attention from gravitational cues and in favor of motion patterns congruent with the gravitational environment (4). In line with this inference, we find that viewers are more efficient at locating a scrambled upright point-light walker among an array of scrambled inverted ones rather than vice versa (5), and consistently perceive the motion of a scrambled upright point-light walker as upright in duration than that from an inverted walker of identical physical duration (6). Additionally, they are better at utilizing binocular disparity cues in the perception of point-light walkers as compared with motion patterns carrying no gravitational information (7). Taken together, these findings indicate that our visual system is exceptionally sensitive to gravitational information contained in motion patterns, and that removing gravitational information compromises visual processing efficacy.


Acknowledgments

This study was supported by grants from the National Basic Research Program of China (11CB710100), the key project of the Chinese Academy of Sciences (KZDD-EW-04), the National Natural Science Foundation of China (31200766), and the Scientific Foundation of the Institute of Psychology, Chinese Academy of Sciences (Y402033008).

References


Human perception with gravity’s imprint

Ying Wang1, Wen Zhou2, and Yi Jiang3*

1Key Laboratory of Brain and Cognitive Science, and Key Laboratory of Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing, China.
2Corresponding Author: yijiang@psych.ac.cn

T

T
Another sensory system that works in tandem with vision to represent object identities is olfaction. We have shown that olfactory and visual inputs converge early in sensory representations (8, 9) and that an odor spontaneously guides attention to the corresponding visual object (10). The impact of gravity on airborne odor molecules is likely negligible. However, there are some who believe that gravity could act indirectly on our olfactory apparatus by influencing the distribution of body fluids. Microgravity causes nasal and sinus congestion that likely contributes to the loss of appetite frequently experienced by astronauts. Microgravity also affects the vestibular system, which senses fluid movement within the three semicircular canals in each aural labyrinth, and provides information about movement and balance.

Systematic examination of the perceptual consequences of microgravity is needed for us to further appreciate the role of gravity in our perception. A major challenge lies in the simulation of microgravity within the earth’s gravitational field. Head-down tilt of −6° is a commonly used model. Similar to microgravity, it is generated within the earth’s gravitational field. Head-down tilt of −6° is a commonly used model. Similar to microgravity, it provides information about movement and balance. Systematic examination of the perceptual consequences of microgravity is needed for us to further appreciate the role of gravity in our perception. A major challenge lies in the simulation of microgravity within the earth’s gravitational field. Head-down tilt of −6° is a commonly used model. Similar to microgravity, it provides information about movement and balance.

Systematic examination of the perceptual consequences of microgravity is needed for us to further appreciate the role of gravity in our perception. A major challenge lies in the simulation of microgravity within the earth’s gravitational field. Head-down tilt of −6° is a commonly used model. Similar to microgravity, it provides information about movement and balance.

Systematic examination of the perceptual consequences of microgravity is needed for us to further appreciate the role of gravity in our perception. A major challenge lies in the simulation of microgravity within the earth’s gravitational field. Head-down tilt of −6° is a commonly used model. Similar to microgravity, it provides information about movement and balance.

Systematic examination of the perceptual consequences of microgravity is needed for us to further appreciate the role of gravity in our perception. A major challenge lies in the simulation of microgravity within the earth’s gravitational field. Head-down tilt of −6° is a commonly used model. Similar to microgravity, it provides information about movement and balance.

Systematic examination of the perceptual consequences of microgravity is needed for us to further appreciate the role of gravity in our perception. A major challenge lies in the simulation of microgravity within the earth’s gravitational field. Head-down tilt of −6° is a commonly used model. Similar to microgravity, it provides information about movement and balance.

Systematic examination of the perceptual consequences of microgravity is needed for us to further appreciate the role of gravity in our perception. A major challenge lies in the simulation of microgravity within the earth’s gravitational field. Head-down tilt of −6° is a commonly used model. Similar to microgravity, it provides information about movement and balance.

Systematic examination of the perceptual consequences of microgravity is needed for us to further appreciate the role of gravity in our perception. A major challenge lies in the simulation of microgravity within the earth’s gravitational field. Head-down tilt of −6° is a commonly used model. Similar to microgravity, it provides information about movement and balance.

Systematic examination of the perceptual consequences of microgravity is needed for us to further appreciate the role of gravity in our perception. A major challenge lies in the simulation of microgravity within the earth’s gravitational field. Head-down tilt of −6° is a commonly used model. Similar to microgravity, it provides information about movement and balance.
TABLE 1. The effect of gravity changes on sex hormones.

<table>
<thead>
<tr>
<th>Species</th>
<th>Gravity condition</th>
<th>Changes</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human</td>
<td>Space flight</td>
<td>Reduced testosterone in saliva, urine, and plasma; increased luteinizing hormone; decreased sex drive</td>
<td>11</td>
</tr>
<tr>
<td>Human</td>
<td>Bed rest plus exercise</td>
<td>Unchanged plasma concentrations of steroid hormones including cortisol, progesterone, aldosterone, and free and total testosterone with bed rest alone; reduced level of plasma testosterone with bed rest plus exercise</td>
<td>13</td>
</tr>
<tr>
<td>Human</td>
<td>Bad rest</td>
<td>No significant change in average urine testosterone levels</td>
<td>14</td>
</tr>
<tr>
<td>Monkey</td>
<td>Centrifugation</td>
<td>Significant increase in urine testosterone levels</td>
<td>19</td>
</tr>
<tr>
<td>Mouse</td>
<td>Tail-suspension model</td>
<td>Reduced testicular weight and testosterone levels</td>
<td>17</td>
</tr>
<tr>
<td>Rat</td>
<td>Tail-suspension model</td>
<td>Reduced testosterone, calcirol, and thyroxine levels</td>
<td>16</td>
</tr>
<tr>
<td>Rat</td>
<td>Tail-suspension model</td>
<td>Greater food intake but lower body and testis weight; no changes in testosterone up to three weeks; decreased tissue and plasma testosterone levels after eight weeks</td>
<td>15</td>
</tr>
<tr>
<td>Rat</td>
<td>Post-space flight; centrifugation</td>
<td>Significant increase in secretion of luteinizing hormone and testosterone in urine</td>
<td>18</td>
</tr>
</tbody>
</table>

In a 30-day bed rest study of male subjects under simulated microgravity, the bed rest alone did not change plasma concentrations of steroid hormones, including progesterone and testosterone. However, after intensive isotonic or isokinetic exercise, the participants exhibited reduced levels of plasma testosterone (13). A 45-day bed rest study of male subjects showed increases in the average amount of testosterone in the urine at certain times, but these changes were not statistically significant (14). The discrepancy among the different reports might be caused by the limited number of subjects, individual variance, and different data collection approaches. Despite these discrepancies, the results suggest that sex hormones might be modified under simulated or actual microgravity conditions in humans.

The effects of microgravity or hypergravity were also studied in animals (Table 1). The tail-suspension model has been frequently used in small mammals to mimic the shift of body fluids caused by microgravity (15). In the tail-suspended rats, testosterone levels were reduced from day six, a condition that was reversible after hind limb unloading. The animals suffered loss of bone mineral density in weight-bearing bones by day 12, which was prevented by androgen replacement. It is possible that the bone density changes were, at least in part, due to the decreased serum testosterone (16). In another tail-suspension rat model, suspended animals ate more but gained less body and testicular weight than control animals. After eight weeks of suspension, the tissue and plasma testosterone levels had increased (15). Data from a tail-suspension mouse model also showed that testicular weight and the testosterone levels were significantly reduced by day seven, and showed impairment of spermatogenesis and significantly decreased the movement velocity of motile spermatozoa (17). Microgravity may increase spermatogenesis and sperm functions directly or indirectly through hormonal disturbances. Further work is required to assess this possibility, in terms of both diurnal and ultradian oscillations of gonadal steroids.

Additional studies have suggested that returning to Earth’s normal gravity following space flight might affect sex hormone levels. Centrifugation has been used to simulate a hypergravity state. In post-space flight and centrifuged male Sprague-Dawley rats, urinary excreted testosterone increased significantly (18). Furthermore, in centrifuged male monkeys, testosterone levels in urine during centrifugation were significantly higher than pre- and post-centrifugation (19). In humans, space flight has been shown to affect circadian rhythms (3). SCN, the controlling center of circadian rhythms in the brain, also regulates the diurnal rhythms of gonadal hormone secretion. It is therefore conceivable that gravity changes may affect the circadian rhythms of sex hormone release. Consistent with this view, a study shows that sleep fragmentation in men led to reduced androgen levels and altered diurnal rhythms (20). Additionally, the change in circadian rhythms by reversing the light-dark cycle using a chronic stress model was shown to be a major contributor to reduced levels of estrogen in female mice and a possible cause of abnormal behaviors (4). However, to date, no clear evidence has been collected showing that the state of gravity influences the overall circadian rhythm of sex hormones, in part because sex hormone levels have not been successfully tracked across a full 24-hour cycle.

Conclusions and perspectives
Gravity alteration causes changes in physiology and behavior due to disturbances in circadian rhythms. Many of the changes, including disorders in cognition, muscle mass, strength, and bone density, can also be regulated by sex hormones. It is possible that disturbances in sex hormones may contribute to the physiological and behavioral disruptions resulting from space flight (Figure 1). If this is the case, restoration of sex hormones to normal levels during space flight is expected to alleviate these symptoms and enhance the performance of astronauts. Further studies on the effects of gravity on sex hormones, such as studies on estrogen and carefully tracking of the circadian rhythms of sex hormones, could help to find new ways for astronauts to adapt in space.

References
5. Y. Cu et al., J. Proteome Res. 7, 3984 (2008).

Acknowledgments
The study was supported by the National Basic Research Program of China (2011CB711000, 2011CB944304, and 2012CB947600) and the National Natural Science Foundation of China (81222006). We wish to thank Eugene Yujun Xu for his help in the editing of this manuscript.
Hundres of people have traveled into space since Yuri Gagarin’s first trip in 1961. The evidence accumulated from returning astronauts and other animal species, suggests that space flight affects a wide variety of immune parameters, ranging from organs to cells to molecules. Microgravity, radiation, circadian rhythms disruption, vibration exposure, and physiological and psychological stresses could directly and/or indirectly affect the distribution, differentiation, and function of immune cells. Clinical risks associated with deregulated immune surveillance and immune homeostasis include an increased vulnerability to infections, autoimmunity issues, hypersensitivity, cancer, and delayed wound healing. A thorough understanding of space flight-related immune dysfunction is needed and essential to supporting prolonged space habitation and to enable the development of monitoring strategies and necessary countermeasures to prevent compromise of the immune system.

Due to the limited number of subjects undertaking space flights and technical difficulties in performing on-orbit experiments, compromise of the immune system.

Recently, we performed a 45-day, long-duration HDBR study to evaluate immune system changes, in particular the cytokine response during spaceflight. The results revealed a continuous decrease in immune cell function during HDBR, including a significant reduction in the levels of interferon-gamma (IFN-γ) and interleukin (IL)-17 produced by T cells, a slight upregulation of transforming growth factor (TGF)-β produced by both types of lymphocytes as well as myeloid cells, and an increase of circulating regulatory T (Treg) cells. Such alterations cannot be explained by an increase of memory T cell percentage in the peripheral blood or defects in T cell activation, as no significant changes were found in the production of IL-2, IL-4, and tumor necrosis factor (TNF) α. Whether the increased Treg cell numbers and TGF-β1 levels contribute to the decrease of T helper (Th) 1 and Th17-type cytokines awaits further investigation. Together with the reported changes in the number and function of natural killer cells, reduced cell-mediated immune surveillance is a well-accepted effect of space flight (2). The second finding from this HDBR study was the significant increase in IL-1 and IL-18 secretion by B and myeloid cells upon TLR and TLR3 stimulation. The marginal increase in Th1 cytokines helped occur on day 45, the last day of the HDBR test. It was also noted that the level of these proinflammatory cytokines did not return to baseline even nine days after the completion of HDBR. A similar increase in IL-1 and inflammatory regions in the testes was also found in mice that had been exposed to the space environment for 91 days (3). Although the reason for such an increase is not clear, it may be important since proinflammatory cytokines in the IL-1 family are essential in the onset and development of a complex inflammatory cascade. A potential risk in autoimmune and inflammatory diseases could be associated with such a progressive increase of inflammatory cytokines.

Collectively, numerous immune system alterations have been observed after space flight as well as in ground-based studies, but only some results are similar among various models. Many questions remain, including elucidating the mechanisms involved in key immune system defects, and determining the clinical significance of the observed immune dysfunction as well as quantifying it. Future studies to investigate the effect of microgravity on immune homeostasis in various challenge models and mutant mice can help us gain new insight into these questions and promote the assessment and development of better strategies for countermeasures.

References
2. J. Kelsen et al., Cytokine 59, 403 (2012).

Acknowledgments
This work was supported by the National Basic Research Program of China (2011CB811000).

Role of ciliary neurotrophic factor in regulating myoblast plasticity and unloaded muscle atrophy

Qing Ge* and Xi Xu

Previous studies have demonstrated that a local hypoxic microenvironment, specific miRNAs, and a variety of regulatory factors (such as IL-6 superfamily factors interleukin-6 (IL-6), leukemia inhibitory factor (LIF), and ciliary neurotrophic factor (CNTF)) and transforming growth factor (TGF-β) regulate myoblast plasticity. We have identified miR-22 as an mRNA that is involved in TGF-β1-mediated inhibition of skeletal muscle differentiation. CNTF-β inhibits the expression of miR-24 at a transcriptional level and its role is dependent on SMAD3 (6). We also have shown that hypoxia (2% O2) inhibits the expression of both the myoblast cell line C2C12 and primary myoblasts. In addition, we observed a hypoxia-induced inhibition of the expression of MyoD, Myf5, and myogenin in myoblasts, which we believe might be linked to the hypoxia-induced inhibition of ERK1/2 activity (7). This review aims to summarize our previous studies focused specifically on the role of CNTF regulation of myoblast plasticity and muscle atrophy induced by hind limb unloading (HU) (8-10).

CNTF and myoblast plasticity

CNTF belongs to the IL-6 family of cytokines and was initially identified by its ability to support the survival of parasympathetic neurons in primary explant cultures of the rat retina (7-14). CNTF can also reduce body fat and is a regulator of muscular strength in aging (15-17). Cellular responses to CNTF and IL-6-type cytokines are elicited by different multiunit receptor complexes (the CNTF receptor α (CNTFα), glycoprotein (gp)130, and leukemia inhibitory factor receptor (LIFR)). Binding of CNTF to CNTFα induces heterodimerization of the signal transducing β receptors gp130 and LIFR, which triggers intracellular signaling cascades (18). Recent studies have indicated that CNTFRs are localized predominantly within neural tissue, but are also highly expressed in denervated skeletal muscle where CNTF exerts myotrophic effects (19). We found that the IL-6 family of cytokines (IL-6, LIF, and CNTF) play a critical role in regulating the plasticity of myoblast proliferation, differentiation, and de-differentiation (8, 9), and in protecting skeletal muscle against atrophy (10, 11). Myoblasts derived from adult human skeletal muscle could be induced to redifferentiate in vitro into multipotent progenitor cells (formed myoblast-derived progenitor cells, or MBPCs) by CNTF via the p44/p42 mitogen-activated protein kinase (MAPK) pathway (20). These MBPCs could differentiate into cells that expressed markers specific to neural crest, parasympathetic (CNPase) and cholinergic (tyrosine hydroxylase (TH), neuron-specific enolase (NSE), and choline acetyl transferase (CHAT)) lineages or neural lineages (21-23). CNTF and LIF are able to synergize in promoting survival, proliferation, and differentiation of myogenic precursor cells. Thus, CNTF can regulate muscle fate.
because it can both inhibit myogenic differentiation of myoblasts into multinucleated myotubes and stimulate dedifferentiation of myoblasts into MBPCs. Immunochemistry assay of MBPCs using anti-Myf5, anti-MyoD, and anti-myogenin antibodies and Western blot analysis using anti-phospho (pho-MAPK) or anti-nonphospho (MAPK)-p44/p42 MAPK antibodies to probe extracts prepared from the cells after a treatment without (Con) or with 30 ng/mL CNTF in the absence (30) or presence (30+PD) of 20 μM PD98059 at the times indicated. (F) Phase M assays using anti-phospho (pho-MAPK) or anti-nonphospho (MAPK)-p44/p42 MAPK antibodies to probe extracts prepared from the cells after a treatment without (Con) or with 30 ng/mL CNTF in the absence (30) or presence (30+PD) of 20 μM PD98059 in DM for 72 hours. (N) Western blot analysis using anti-Myf5, -MyoD, and -myogenin antibodies. Extracts were prepared from cells as described in L.

FIGURE 1. Dedifferentiation of adult human myoblasts induced by CNTF in vitro. (A) Immunocytochemistry assay of clonal myoblasts (MBs) and positive controls (Con), neural stem cells (NSC), and hemopoietic stem cells (HSC), using anti-Neulin, anti-CSF1, and anti-CSF5 antibodies. (B) Erogenous CNTF inhibits myoblast dedifferentiation and induces a novel cell population in vitro. Pho, Student’s t-test, n=3. (F, G) Western blot analysis using anti-Myf5, -MyoD, and -myogenin antibodies to analyze extracts from MBPCs, positive control myoblasts (MT) of the myoblasts cultured in differentiation medium (DM) for seven days, and from negative control NIH3T3 (3T3) cells. (H-K) Demonstration of signs of myoblast plasticity in MBPCs. Immunocytochemistry assay of MBPCs and its control myoblasts (MBs) by immunostaining using specific markers for neurons, glial lineages, or adipocytes. NF160, neuronfilament-160; TH, tyrosine hydroxylase; NSE, neuron-specific enolase; c-Kit, bone marrow stromal cell marker; p130, CNTF-induced 130-kD protein; NG2, 2‘,3‘-cyclic nucleotide 3‘-phosphodiesterase; GFRa, glial fibrillary acidic protein; SMA, smooth muscle actin. (L) Western blot assays using anti-phospho (pho-MAPK) or anti-nonphospho (MAPK)-p44/p42 MAPK antibodies to probe extracts prepared from the cells after a treatment without (Con) or with 30 ng/mL CNTF in the absence (30) or presence (30+PD) of 20 μM PD98059 at the times indicated. (M) Micrographs of myoblasts treated without (Con) or with 30 ng/mL CNTF in the absence (30) or presence (30+PD) of 20 μM PD98059 in DM for 72 hours. (N) Western blot analysis using anti-Myf5, -MyoD, and -myogenin antibodies. Extracts were prepared from cells as described in L.

### References


### Acknowledgments

This work was supported by the National Basic Research Program of China (2011CB711000, the National Sciences Foundation of China (31171644 and 81272177), the State Key Laboratory of Space Medicine Fundamentals and Application (SMFA0201 and SMFA0301), and the Advanced Space Medicine-Engineering Research Project of China (2013SF04A1601).
FIGURE 2. A model by which microgravity leads to bone loss. Effects are thought to be mediated through changes in circRNAs, such as miR-214. ATF4, activating transcription factor 4; Ocn, ostocalcin; Alp, alkaline phosphatase; ColII, collagen I; Pten, phosphatase and tensin homolog; Nfat1, nuclear factor of activated T cells; Acp5, phosphatase type 5; Mmp7, matrix metalloproteinase 7.

Space meets time: Impact of gravity on circadian systems

Dongni Wang, Lin Zhang, Yufeng Wan, Xianyong Chen, Xiaoliang Jiang, Hanjie Shen, and Jinshi Guo

circadian timing systems (CTS) are physiological systems that coordinate aspects of physiology and behavior in concert with the 24-hour cycle of light and dark. In response to microgravity, these systems are not synchronised with the Earth’s rotation (1–3). In higher animals, these timing systems consist of a master clock as well as subsidiary circadian clocks located in peripheral organs. These circadian clocks are autonomous and responsible for controlling the endogenous and entrainable circadian rhythms (4). In space, environmental factors that influence circadian rhythms differ dramatically from those on the ground. These differences create challenges for space exploration, as environmental cues—such as an altered day/night cycle and microgravity conditions—impact the physiology, metabolism, and circadian rhythms of astronauts, and thereby their behavior.

Influence of microgravity on circadian rhythms

Since the 1960s, researchers have been able to study the effects of microgravity on circadian rhythms for both model organisms and humans who have been sent into space. Results have indicated that changes in the amplitudes of a variety of circadian variables were observed more often than changes in phases and periods. Space flight has been shown to cause a decrease in physical activity, body temperature, and alertness in humans and other mammals (Table 1). Likewise, hypergravity causes an acute decrease in the average values and circadian amplitudes of deep body temperature (DBT) and locomotor activity (LMA) in rats (8). Moreover, in response to hypergravity exposure, the phenomenon of circadian rhythm splitting was found in DBT and LMA (7). In lower organisms, such as the fungus Neurospora crassa, the conidiation rhythm (timed assay of reproductive growth) has been less robust in tests under microgravity compared with those on Earth (9). Additionally, in space station experiments using the algae Chlamydomonas reinhardtii, the phenomenon of phototropism movement was significantly increased (10). Together, these data suggest that gravitational change might impact the circadian rhythms in different organisms.

To further investigate the effects of simulated weightlessness on diurnal rhythms, volunteers were subjected to a 4-day head-down bed rest position for 45 days (7, 12). Decreases in the amplitudes of the subject’s heart beat and wrist activity (a measure of sleep duration and sleep/wake activity) were observed, while urine and defecation rhythms were also disrupted (11). Elevation of cortisol levels are associated with stress. In bed rest, cortisol levels were unchanged during the first several days of bed rest, suggesting that the levels of stress initially were low to absent. However, overall, cortisol levels were observed from the seventh day until the end of the study (7). Interestingly, increases in cortisol were significantly higher at night, suggesting a possible correlation between changes in cortisol and bone loss. The phase and pattern of the subjects’ heart beat peaks were changed during and after bed rest, and analysis of high-frequency and low-frequency heart activity revealed an overall decrease in the function of the autonomic nervous system (12), which might contribute to the alteration of circadian rhythms.

It should be noted that it is almost impossible to distinguish the impacts of microgravity on circadian rhythms from the other, interweave environmental factors experienced in space. This fact has likely led to the reporting of many contradictory findings. In addition, space flight experiments are limited in both number and size of samples. It is therefore important to utilize multiple simulat- ed approaches to study the impacts of microgravity.

Mechanisms underlying gravity-induced circadian rhythm disturbances

The underlying molecular mechanisms by which gravity may influence circadian rhythms are not well understood. In eukaryotes, at the molecular level, CTSs consist of positive and negative feedback loops. Positive feedback loops are transcriptional units that are able to activate transcription of circadian genes, and the trans- lated clock proteins then progressively repress transcription of the clock genes in a negative feedback manner (5, 6). Negative feedback loops drive a molecular rhythm with a period of approximately 24 hours, controlling the normal daily rhythms of physiological and behavioral traits. In humans, CTSs are comprised of circadian clocks located in the suprachiasmatic nucleus (SCN), which are the circadian pacemaker, and a number of smaller clocks (4, 11). In the SCN, circadian clocks regulate the peripheral clocks through several mecha- nisms, including autonomic innervation, endocrine signaling, and bodily temperature (2).

Few studies have evaluated changes in circadian clock genes in simulated or actual weightlessness environments. Micrograv- ity conditions experienced during a space flight were compared with increased period homolog 1 (Per1) and cryptochrome 2 expression in murine skeletal muscle (12). Similarly, simulated weightlessness using a random positioning machine has shown to alter Per3 expression in FTC-133 thyroid cancer cells (13). Studies investigating the effects of hypergravity on rats have found changes in the expression of the orphan receptor-re- lated orphan receptor a (NiRORa) gene, which encodes a nuclear hormone receptor, and other genes related to metabolism and diurnal rhythms (15). These findings suggest that gravity affects the expression of both clock genes and clock-controlled genes.

In recent years, studies have also shed light on the effect of postural or circadian transcriptional rhythms such as capping, polyadenylation, intron splicing, nuclear export, localization, translation, and turnover, on circadian rhythms (2, 16). Experiments carried out under simulated...
Studies of circadian/diurnal rhythms during changes in gravity.

<table>
<thead>
<tr>
<th>Species</th>
<th>Gravity conditions</th>
<th>Changes</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Space station</td>
<td>Damping</td>
<td>Changes in rhythms of oral temperature and alertness</td>
<td>4</td>
</tr>
<tr>
<td>Macaca mulatta Biosatellite</td>
<td>Decrease in activity, and in skin and auxiliary temperatures; change in periodicity of activity and auxiliary temperature</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Human Orbital flight</td>
<td>Decrease in body temperature rhythm amplitude; decrease in sleep amount and diminished sleep quality; decrease in neurobehavioral performance</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Human Space station</td>
<td>Phase delay in body temperature; shorter sleep cycles and changed sleep patterns</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Rat</td>
<td>Hypergravity</td>
<td>Acute decrease and splitting in deep body temperature and locomotor activity rhythms</td>
<td>8</td>
</tr>
<tr>
<td>Neurupora crassa Space station</td>
<td>Damping</td>
<td>Changes in amplitude of condition rhythm; slight changes in periods of coordination</td>
<td>9</td>
</tr>
<tr>
<td>Chlamydomonas reinhardtii Space station</td>
<td>Elevated amplitude and delayed phase in phototrophic locomotor rhythm</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>Best</td>
<td>Changes in rhythms of sleep, defecation, urination, alterations in phase of heart rate and amplitude of urinal cortisol rhythm</td>
<td>11, 12</td>
</tr>
<tr>
<td>Trigonocella gibas Space station and centrifuge</td>
<td>Changed locomotion patterns and periods of activity rhythm</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 1.** Studies of circadian/diurnal rhythms during changes in gravity.

**FIGURE 1.** Potential mechanisms regulating the effects of gravity on circadian rhythms. Sir Isaac Newton with floating apples denotes a microgravity condition. Clock genes are controlled by daily cycles during space flight. They may be involved in the homeostatic regulation of sleep. Insomnia is a significant problem for astronauts in space due to the effects of microgravity. Below, the roles of PGD2 and adenosine in sleep-wake regulation are reviewed and strategies for novel pharmacological interventions that ensure adequate rest for astronauts are discussed.

**Adenosine as a signaling molecule in PGD2-induced sleep**

PGD2 has been found to be one of the most potent somnogens involved in physiological sleep (2). The PGD2 concentration in rat cerebrospinal fluid shows circadian fluctuations that parallel the sleep-wake cycle and become elevated with the increase in sleep propensity during sleep deprivation, suggesting that PGD2 may have an important function in the central regulation of sleep. A search for the mechanism by which endogenous PGD2 promotes sleep has revealed that adenosine may act as a mediator (2). The subarachnoid space in the mouse basal forebrain is rich in the PGD2 receptor DP1R. Infusing PGD2 into the subarachnoid space of wild-type and DP1R-knockout mice resulted in a dose-dependent increase in the extracellular adenosine concentration in wild-type mice, but not in DP-R-knockout mice (2, 3). The somnogenic effect of PGD2 was blocked by the intraperitoneal injection of 8C7F13, an antagonist specific to the adenosine A1 receptor (A1R), indicating that the increase in adenosine was dependent on the activation of DP-R and that the action of endogenous adenosine at A1R may be a mediator of PGD2-induced sleep (2).

---

**References**


**Acknowledgments**

This work was supported by the National Basic Program of China (2011CB711000 and 2012CB947600) and the National Natural Science Foundation of China (31071122 and 31117119).

---

**Homeostatic regulation of the sleep-wake cycle by prostaglandin D2 and adenosine**

---

**Adenosine as a signaling molecule in PGD2-induced sleep**

---

**References**


**Acknowledgments**

This work was supported by the National Basic Program of China (2011CB711000 and 2012CB947600) and the National Natural Science Foundation of China (31071122 and 31117119).
Sleep-wake regulation by adenosine A<sub>2A</sub> receptor in a site-dependent manner

There are four subtypes of G protein-coupled adenosine receptors expressed in the central nervous system: A<sub>1</sub>, A<sub>2A</sub>, A<sub>2B</sub>, and A<sub>3</sub>. Several lines of evidence indicate that both A<sub>1</sub> receptors (A<sub>1R</sub>) and A<sub>2A</sub> receptors (A<sub>2AR</sub>) play a key role in the effects of adenosine on sleep. In rats, selective A<sub>1R</sub> stimulation or inhibition of A<sub>2AR</sub> may induce sleep by inhibiting the cholinergic region of the basal forebrain. Inhibition of the adenosine signaling pathway via A<sub>1R</sub> in the orexin neuronal regions (5) and histaminergic tuberomammillary nucleus (6) have also been reported to promote non-rapid eye movement (NREM) sleep, which has a critical function in brain detoxification and restoration. However, Methippara et al. reported that A<sub>1R</sub> stimulation or inhibition of adenosine transport can induce wakefulness in the lateral preoptic area, suggesting that activation of A<sub>1R</sub> in other parts of the brain may cause wakefulness (7). These observations indicate that adenosine-mediated effects (through A<sub>1R</sub>) on sleep-wake cycles are site-dependent.

Major role of A<sub>2AR</sub> in sleep induction

Evidence accumulated in recent years indicates that A<sub>2AR</sub> plays a key role in the sleep effects of adenosine. In rats, selective A<sub>2AR</sub> agonists such as CGS21680, administered into the subarachnoid space adjacent to the basal forebrain and lateral preoptic areas, reliably induce NREM sleep, but infusion of A<sub>2AR</sub> agonist CGS21680 to the rostral basal forebrain leads to a considerable increase in expression of c-fos within the shell of the ventral striatum nucleus accumbens (NAc) and the medial portion of the olfactory tubercle (11, 12). Direct perfusion of CGS21680 into the shell of the NAc induces NREM and REM sleep (12). In contrast, selective deletion of A<sub>2AR</sub> in the NAc shell abolished the effects of caffeine on wakefulness (13). These results could be interpreted to indicate that A<sub>2AR</sub> in or close to the NAc shell promote sleep. The NAc has GABAergic projections into a wide range of targets (14), including the ventral pallidum, the lateral hypothalamus, the parabrachial nucleus, and the ventral tegmental area. These may contribute to the sleep effects of A<sub>2AR</sub> activation. For example, the high-affinity A<sub>2AR</sub> agonist CGS21680 produces weak and variable effects (8). When infused into the lateral ventricle of mice, CGS21680 was found to induce both NREM and REM sleep in a dose- and time-dependent manner, while the A<sub>2AR</sub> agonist CPA had no effect on sleep/wake patterns (9).

The effects of caffeine are the opposite to those of adenosine, as its promoter wakefulness, binding to A<sub>1R</sub> and A<sub>2AR</sub> as an antagon-

FiguRE 1. Adenosine A<sub>2A</sub> receptor modulation of the sleep-wake network. Subseriving inhibitory output of the nucleus accumbens (NAc; red, round-headed lines) impacts the activity of neuronal populations in the ventral pallidum (VP), the lateral hypothalamus (LHA), the parabrachial nucleus (PB), and the ventral tegmental area (VTA), which is likely a major source of cortical arousal. The addition sign (+) represents excitatory receptors, the minus sign (−) represents inhibitory receptors. Arrows represent excitatory synapses; round-headed lines represent inhibitory synapses. Lines with two symbols represent repair excitatory (arrows) and inhibitory (round-headed) connections. LC, locus coeruleus; mPFC, medial prefrontal cortex; TMN, tubemammillary nucleus; VPf, ventrolateral preoptic area; BF, basal forebrain; A<sub>2AR</sub>, adenosine A<sub>2A</sub> receptor; D<sub>2</sub>R, dopamine D<sub>2</sub> receptor. Adapted and modified from Lazarus et al. with permission (13).

Sleep pathways induced by activation of A<sub>2AR</sub>

The molecular pathways through which adenosine acts on ex- citatory A<sub>2AR</sub> receptors to produce sleep are not well understood. A<sub>2AR</sub> are predominantly expressed in the striatum and are colocalized with dopamine D<sub>2</sub> receptors. Administration of A<sub>2AR</sub> agonist CGS21680 to the rostral basal forebrain leads to a considerable increase in expression of c-fos within the shell of the ventral striatum nucleus accumbens (NAc) and the medial portion of the olfactory tubercle (11, 12). Direct perfusion of CGS21680 into the shell of the NAc induces NREM and REM sleep (12). In contrast, selective deletion of A<sub>2AR</sub> in the NAc shell abolished the effects of caffeine on wakefulness (13). These results could be interpreted to indicate that A<sub>2AR</sub> in or close to the NAc shell promote sleep. The NAc has GABAergic projections into a wide range of targets (14), including the ventral pallidum, the lateral hypothalamus, the parabrachial nucleus, and the ventral tegmental area. These may contribute to the sleep effects of A<sub>2AR</sub> activation. For example, the high-affinity A<sub>2AR</sub> agonist CGS21680 produces weak and variable effects (8). When infused into the lateral ventricle of mice, CGS21680 was found to induce both NREM and REM sleep in a dose- and time-dependent manner, while the A<sub>2AR</sub> agonist CPA had no effect on sleep/wake patterns (9).

The effects of caffeine are the opposite to those of adenosine, as its promoter wakefulness, binding to A<sub>1R</sub> and A<sub>2AR</sub> as an antago-
Evidence from previous space missions showed that balance control and locomotor disturbances occurred as soon as astronauts entered the weightlessness environment (6). In order to test whether gait pattern was also affected by weightlessness, we set up a horizontal suspension system to simulate the weightlessness environment in order to investigate the differences in plantar force parameters during walking/running exercise between weightless and normal gravity conditions. In this study (2), eight healthy male volunteers walked or ran on a horizontal suspension treadmill (simulated weightlessness, SW) and a traditional treadmill (normal gravity, NG) at three different velocities (3, 7, and 10 km/h). During these tests, an incline measurement system was used to determine the plantar force distribution. We demonstrated that there was no difference in stride time between SW and NG conditions, but the stride time did shorten as the speed increased, and there were significant differences in stride time among three velocities (P<0.01) under both conditions. Notably, the peak force and vertical impact data for SW were significantly lower than that in NG (P<0.05) (Figure 1, page 21). As speed increased, the peak force and vertical impact increased, especially under SW conditions. These results indicated that plantar force characteristics changed under simulated weightlessness, which might go some way to explaining why exercise can’t completely prevent bone loss and muscle atrophy in outer space. These findings suggest that a weightless environment may affect gait patterns in at least two ways: the long-term effect of musculoskeletal changes induced by space flight duration and the impact of the weightlessness environment itself. These results are potentially helpful in designing proper countermeasures to bone and muscle loss in microgravity and for developing bone exercise prescriptions in the future. It should be noted, however, that these conclusions are based only on simulated weightlessness conditions and need to be confirmed in a real-world space environment.

References

Acknowledgments
This work was supported by the National Basic Research Program of China (2011CB111000) and China’s Manned Space Flight Advance Research Fund (SMF11B02 and SMF11A03).

Traditional Chinese medicine—a potential countermeasure to stressors associated with space missions

In space, astronauts experience a unique combination of environmental factors—microgravity, circadian dysrhythmia, isolation, and confinement—as well as high mental and physical workloads. These factors may have harmful impacts on humans in space, even resulting in safety problems (1). It is vital to develop effective countermeasures to offset or minimize these deleterious consequences. The U.S. National Aeronautics and Space Administration together with partner countries have developed various recommendations for these countermeasures, including procedures, training, exercise, and drug therapies (2). In China, in addition to conventional treatments used in Western countries, astronauts are also treated with traditional Chinese medicine (TCM), such as herbal medicine, acupuncture, and massage therapy, to combat the adaptive physical changes they encounter during the preflight, in-orbit, and post-flight segments of past missions (3). More recently, behavioral pharmacology studies have demonstrated that TCM is an effective means to enhance cognitive and emotional function in animals under simulated space flight conditions. Herein, we review the literature about the benefits of TCM for treating physiological and psychological changes during/after long duration space flight, with a particular focus on our research into preventing the decline of cognitive performance during long-duration missions.

Physiological and psychological adaptations to space flight

TCM is distinct from Western medicine in terms of principles, diagnosis, and treatment. Traditionally, TCM’s holistic concepts give special emphasis to the harmonious relationship between

TABLE 1. Measures of gait parameters before and after 45-day head-down bed rest.

<table>
<thead>
<tr>
<th>Item</th>
<th>R-6</th>
<th>R-1</th>
<th>R+10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight (kg)</td>
<td>65.6±5.31</td>
<td>63.10±5.40</td>
<td>64.55±5.69</td>
</tr>
<tr>
<td>Step length (m)</td>
<td>0.74±0.06</td>
<td>0.60±0.07</td>
<td>0.64±0.07</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>1.35±0.12</td>
<td>0.99±0.17</td>
<td>1.10±0.13</td>
</tr>
<tr>
<td>Gait cycle (s)</td>
<td>1.10±0.06</td>
<td>1.27±0.17</td>
<td>1.18±0.07</td>
</tr>
<tr>
<td>Maximum vertical force (N/kg)</td>
<td>1.18±0.194</td>
<td>1.215±0.141</td>
<td>1.194±0.102</td>
</tr>
<tr>
<td>Maximum AP force (N/kg)</td>
<td>0.215±0.061</td>
<td>0.134±0.036</td>
<td>0.183±0.069</td>
</tr>
<tr>
<td>Maximum ML force (N/kg)</td>
<td>0.040±0.012</td>
<td>0.044±0.013</td>
<td>0.052±0.017</td>
</tr>
<tr>
<td>Maximum force of L foot (N/kg)</td>
<td>1.46±0.231</td>
<td>1.533±0.141</td>
<td>1.579±0.096</td>
</tr>
<tr>
<td>Maximum force of R foot (N/kg)</td>
<td>1.457±0.261</td>
<td>1.615±0.162</td>
<td>1.627±0.180</td>
</tr>
<tr>
<td>Impulse of L foot (N.s/kg)</td>
<td>0.578±0.101</td>
<td>0.734±0.079</td>
<td>0.747±0.098</td>
</tr>
<tr>
<td>Impulse of R foot (N.s/kg)</td>
<td>0.581±0.114</td>
<td>0.754±0.072</td>
<td>0.773±0.095</td>
</tr>
<tr>
<td>Loading velocity of L foot (N/kg/s)</td>
<td>7.050±1.474</td>
<td>10.727±3.821</td>
<td>9.546±2.610</td>
</tr>
<tr>
<td>Loading velocity of R foot (N/kg/s)</td>
<td>7.551±1.840</td>
<td>9.194±3.978</td>
<td>9.850±1.834</td>
</tr>
<tr>
<td>Contact time of L foot (ms)</td>
<td>654±39.0</td>
<td>735.8±73.3</td>
<td>718.8±68.9</td>
</tr>
<tr>
<td>Contact time of R foot (ms)</td>
<td>654.7±49.8</td>
<td>719.4±42.2</td>
<td>729.9±31.5</td>
</tr>
</tbody>
</table>

All force and impact data were normalized to body weight. *Corresponding Authors: shanguang_chen@126.com (S.C.) and liuxinmin@hotmail.com (X.L.)
TABLE 1. Chinese herbal formulations used to treat symptoms of stress related to space flight.

<table>
<thead>
<tr>
<th>Symptoms</th>
<th>Formulation name (experimental paradigm, model)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiovascular</td>
<td>circulation disturbance</td>
<td>Gastrodia (angular acceleration and rotation, rat)</td>
</tr>
<tr>
<td>Motion sickness</td>
<td>Taikong Xieli decoction, including Ginseng and Ophiopogon (suspended and suspension adding radiation)</td>
<td>6</td>
</tr>
<tr>
<td>Schisandra chinensis, Rehmannia praepraetra, Rhizoma drynariae, Glycyrrhiza radix, Poria cocos (simulated weightlessness, rat; clinical trials, human)</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Immunological dysfunction</td>
<td>Chinese herbal compound, including Astragalus and Rehmannia (simulated weightlessness, rat); Taikong Xieli decoction, including Ginseng and Ophiopogon (suspended and suspension adding radiation)</td>
<td>9, 10</td>
</tr>
<tr>
<td>Muscle atrophy</td>
<td>Danhuang compounds, including Salvia miltiorrhizae and Astragalus (simulated weightlessness, rat); Qiangji decoction, including Astragalus and Cassia in simulated weightlessness (rat); Rhodiola rosea (simulated weightlessness, rat)</td>
<td>12, 13, 14</td>
</tr>
<tr>
<td>Bone loss</td>
<td>Chinese compound prescription, including Rehmannia praetraecta, Rhizoma drynariae, Puerariae radix, Achyranthis bidentatae (simulated weightlessness, rat); Icariin (Epimedium extract) (simulated weightlessness, rat)</td>
<td>15, 16</td>
</tr>
</tbody>
</table>

Cognitive and emotional dysfunction

| Chinese herbal medicine, including Ginseng, Astragalus, Ligusticum, Pinelliae ternateae, Fructus pisi Dioscoreae, Fructus seu semen amomi (head-down bed rest clinical trial, human) | 17 |

It is demonstrated that the use of traditional Chinese medicine (TCM) can improve cognitive and memory functions in animal models of space flight stress. TCM formulations such as Ginkgo biloba, ginseng, and other adaptogenic herbs have shown promise in enhancing cognitive performance and memory in animal models exposed to microgravity. These formulations are believed to work by modulating the activity of neurotransmitter systems, such as the acetylcholine system, which are involved in cognitive processes. Furthermore, TCM formulations have been shown to exert anxiolytic and sedative effects, which may be beneficial for astronauts coping with the stress of space flight. The use of TCM in space medicine holds promise for developing new countermeasures to treat the negative effects of space flight on astronauts' mental and physical health.
Human-machine interaction and crew cognitive behavior in space

Effects of automatic processes on safety performance: Implications for astronauts

Yaoshan Xu, Yongjuan Li’, Shu Li, and Feng Du

Effects of automatic processes on safety performance: Implications for astronauts

F rom a psychological perspective, astronaut Jing Haipeng emphasized the ideal goal for space mission training: develop good habits at work [1]. A habitual response is a type of automatic process that is fast, unintentional, effortless, and out of one’s conscious awareness [2]. A well-formed automatic process can benefit astronauts in at least two ways. First, an automatically activated process will lead directly to expected behaviors ([1, 2]). Teas led to the automatic process can benefit astronauts at least two ways. First, an automatically activated process will lead directly to expected behaviors ([1, 2]). Second, both automatic processes and resource allocation processes on safety are clearly influential on an employee’s behavioral responses. Therefore, it would be important for instructors to encourage positive safety behaviors and immediately correct poor or unsafe habits in a timely manner to cultivate the right safety habits. In addition, it could be useful for trainers to include intervention programs aimed at correct candidates’ negative automatic psychological constructs.

Automatic processes and safety behaviors

Three of our studies demonstrated that there are several subcategories of automatic processes that can directly activate safety behaviors. First, we explored the roles of habit (habitual responses in certain contexts) and controlled analytical processes or rule-based reasoning (including explicit attitude, perceived control, and social norms) in predicting the intentions of adult professional drivers to wear/observing [7]. Results indicated that the more employees fulfill skilled- and rule-based tasks as an automatic process, the more cognitive resources are available to execute knowledge-based tasks. We also believe that conserving cognitive resources can greatly aid performance. One study examined the effects of situational factors and driving experience on a driver’s future behavior. Situational factors (e.g., behavior of others drivers on the road and historical accident rate information) were manipulated in different driving scenarios, and drivers were asked to indicate their behavior in each situation. The results indicated that the behavior of drivers was increasingly likely to be influenced by situational factors as their level of experience increased. Compared with novice drivers, drivers who have acquired increased automatic skills and responses through practice have more cognitive resources available to devote to situational information, allowing them to perform better. By contrast, novice drivers who have not yet developed automatic driving skills do not have the cognitive capacity to incorporate the available situational information. This conclusion has implications for theoretical studies of safety behavior as well as practical implications for the aerospace field.

Future directions and applications for aerospace

Empirical studies on automatic processes in the aerospace field. Such studies have indicated that astronauts’ safety performance is at least one standard deviation (SD) higher than mean values were regarded as part of the safety-oriented group. The group showed significantly greater ABS than those in the non-safe group. In summary, automatic processes are important and significant supplements to controlled cognitive processes and can aid in predicting safety behaviors. Furthermore, well-honed automatic processes can save cognitive resources, resulting in gaining in performance and preventing accidents. This conclusion has implications for theoretical studies of safety behavior as well as practical implications for the aerospace field.

Acknowledgments

This work was supported by the National Basic Research Program to the China (2011CB110000), the National Natural Science Foundation of China (17011149 and 71377119), and the Chinese Academy of Sciences (KJZD-EW-04).
Manually controlled rendezvous and docking (manual RVD) is a critical technology for space missions. The method applies to the assembly of large orbiting units, reusability of orbital platforms and stations, exchange of crew, and lunar/planetary missions. Manual RVD starts when the two space vehicles are about 150 meters apart and must observe both the target image and numerical data on a monitoring interface and make decisions on how to best maneuver the chase spacecraft. The target spacecraft’s location and attitude is manipulated by two joystick controllers (Figure 1) to complete the RVD task. Human performance in a manual RVD task depends on the design of the human-machine interface and the cognitive abilities of the astronauts, and how well these two factors interact (2, 3). Therefore, researchers are focused on the cognitive demands of manual RVD tasks for astronauts and, based on these demands, looking for ways to alter the ergonomic design of the human-machine interface to improve manual RVD performance.

Human factors in manually controlled rendezvous and docking: Implications for engineering better designs

Chunhui Wang, Ting Jiang, Yu Tian, and Shangguan Chen

In a manually controlled RVD system, astronauts control the chase vehicle using the two joystick controllers. The characteristics of the control system should be designed to best accommodate previously encountered events or objects and use the information provided by the system. We investigated the effects of different control system parameters on the operators’ performance indices (such as operational errors, fuel consumption, control time, and deviation at the moment of docking) during manual RVD tasks. These control parameters included the polarity of the controllers (which defines the spatial relationship between the controller’s movement and the direction that the vehicle being controlled moves), the delay time for the system to respond (the time between the astronaut’s control input and when they see visual feedback from the video interface), and the maximum control of the attitude angle (the vehicle’s orientation). Twenty-two male participants, technicians from the China Astronaut Research and Training Center, completed three series of tests. Our studies revealed that the number of operational errors decreased if the attitude controller moved in the same direction as the active vehicle. The task performance of participants with a system delay of either zero, one, or two seconds was compared. Results showed that, compared with a zero or one second delay, a two second delay led to a significant decrease in the success rate and an increase in the task time. Participants reported that the system felt difficult to control when there was a two second delay. Finally, we compared the participants’ task performance when the maximum control angle of the vehicle attitude was limited to either 0.3 degrees/second, 0.5 degrees/second, or 0.6 degrees/second. The participants’ success rate of the task was significantly better when the attitude was limited to 0.3 degrees/second; however, there was no significant difference between control at 0.5 degrees/second and that at 0.6 degrees/second (2). These results provide a point of reference for the future design of control system parameters.

In conclusion, our research has focused on the human factors involved in evaluating and designing manual RVD tasks. In the studies mentioned above, we evaluated the critical factors impacting human performance of manual RVD tasks, and suggested improvements that can be made to the display interfaces of control systems based on a human-centered design. In practice, our data have greatly facilitated human performance in manual RVD tasks and have successfully supported manual RVD tasks in China’s Shenzhou 9 and 10 space missions.

References
1. Y. Zhang et al., China Science and Technology, 52 (2012).

Acknowledgments
This project was supported by the National Basic Research Program of China (2011CB711100) and the Foundation of National Key Laboratory of Human Factors Engineering (HF2013-2-B-02).
Exploiting brain-computer interfaces for use in space missions

Minpeng Xu1, Feng He2, Changli Wang1, Hongzhai Qi1, Xuexiniao3, Pengzhou4, Lixinzhang5, Shangguangchen6, and Dongming7

HUMAN PERFORMANCE IN SPACE: ADVANCING ASTRONAUTICS RESEARCH IN CHINA

SECTION TWO

Exploring brain-computer interfaces for use in space missions

to the control command without physical motion or relying on the peripheral nervous and motor systems. A BCI system works by collecting a brain signal, decoding the user’s intent, and sending the output to the computer command center. Many research fields are involved in constructing these types of systems, such as feature optimization (1–7), paradigm design (5–7), and others (8).

There are several types of BCIs. Conventional/simple EEG-based BCIs rely on detecting only one kind of change in the dynamics of brain oscillations, such as evoked potential (EP), event-related potentials (ERPs), sensorimotor rhythms (SMRs), or slow cortical potentials (SCPs). Among these types of brain signals, the visual signals such as the visual P300 ERP and the steady-state visual evoked potential (SSVEP) provide the fastest and most reliable EEG-based BCIs (6). The stable P300 ERP appears as a positive deflection in voltage with a delay of about 300 ms from the time of the low-probability visual stimulus onset. It is usually elicited using the oddball paradigm, in which low-probability target stimuli are mixed with high-probability nontarget stimuli. The SSVEP is a response elicited by the visual stimulus modulated at a constant repetitive rate, and is characterized as stationary periodic oscillations with dominant spectral content consistent with stimulus temporal frequency. Recently, a new BCI concept, the pure hybrid BCI, was proposed to improve accuracy and universality by combining two or more different BCI approaches (9). Because the vision-dependent BCI has a higher accuracy and information transfer rate (ITR) than other BCIs that depend on auditory or sensorimotor system, the visual hybrid BCI is quite promising for future space mission applications.

FIGURE 1. Typical EEG features of the P300+SSVEP-B system. The top sub-graphs show the temporal waves recorded at sensors Cz and Oz, respectively, while the bottom sub-graphs display the short-time Fourier transform results of target waves for Cz and Oz.

The visual hybrid BCI

We developed a novel, pure hybrid BCI, the P300+SSVEP-B system, which decodes every command using information from both the P300 ERP and SSVEP blocking (SSVEP-B) features (5, 6). The BCI system presents users with a special interaction protocol, in which items for selection provide either oddball or steady-state visual stimuli. Figure 1 shows the typical EEG features of the P300+SSVEP-B system obtained from a participant, namely the P300 ERP, SSVEP, and SSVEP-B features. From sensor Cz (located on the top and center of the skull), an enhanced positive waveform with a latency of about 300 ms can be found in the target response (the brain’s response to the target stimulus under the oddball paradigm), a feature not seen in the nontarget response. From sensor Oz (which monitors occipital lobe activity), an SSVEP of about 10 Hz appeared in nontarget responses, but not in target responses. The absence of SSVEP, called SSVEP-B, was as effective as the P300 ERP in target detection. Thus, the P300+SSVEP-B system provides a second EEG feature, i.e., the SSVEP-B, that is elicited simultaneously with the P300 ERP and can be used to identify the user’s intent. This enhanced the target accuracy (~4% improvement) and system ITR (~15 bit/minute improvement) (5, 6).

Next, we proposed that a potential application for the P300+SSVEP-B system could be to develop a visual parallel-BCI system that was capable of dealing with more than one independent BCI system simultaneously (7). The setup for the visual parallel-BCI system is shown in Figure 2. The command panels from different BCIs were controlled by a field-programmable gate array which sent synchronous triggers to the EEG amplifier. Users would gaze at an object for a specified length of time, during which the EEG amplifier would record and send the EEG signals, together with the trigger signal, to a computer for decoding. The panels belonging to different P300+SSVEP-B systems had different frequencies of steady-state visual stimuli so that the SSVEPs of different systems were able to be discriminated by analyzing the oscillation frequency. Furthermore, the objects in each command panel followed the oddball paradigm, which would elicit both a discriminative P300 ERP and SSVEP-B. Thus, we could decode the user’s intent by analyzing both the EEG temporal waves and its frequency characteristics. The parallel-BCI in this study was four times as efficient as the single P300+SSVEP-B system in terms of delivering command codes, thereby greatly enhancing the system’s ITR (~15 bit/minute improvement).

Conclusions

As a novel communication system, BCI is promising for future space missions. It can facilitate astronauts’ actions with less energy consumption, which is beneficial for both the astronaut and the space mission overall. But before it can be implemented, the BCI system still needs to be optimized for accuracy and flexibility. The visual hybrid BCI is a promising communication tool that possesses the advantages of high speed and accuracy over the conventional system, and provides a promising system for use in space missions.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (61222101, 61172038, 61172043, 30970875, and 909100010), the National Key Technology R&D Program of the Ministry of Science and Technology of China (2012BAI50402), and the Program for New Century Excellent Talents in University of the Ministry of Education of China (NCET-10-0018).
Factors affecting astronaut manual operation tasks

Over 90% of extravehicular activity (EVA) operations require the use of an astronaut's upper limbs; however, there are several factors that limit an astronaut's upper limb mobility, such as their spacesuits and gloves. In addition, the ability to complete an EVA task can also be constrained by the factors during a mission, such as extravehicular activities and space characteristics. Therefore, we have proposed a model to simulate an astronaut's upper limb movement, combined with a basic model of the human body with an anti-torque model of a spacesuit, with the latter providing the limiting conditions. Two different types of human body-based models were built: one that only considers joint torque for motion analysis (the joint-torque model), and another that includes muscle force as a verification model (the muscle-force model). Both models include six degrees of freedom, including three for the shoulder, one for the elbow, and two for the wrist. We have also built three anti-torque models using two types of spacesuits placed under different pressures. Our suit models are based on the Hysteresis Model (3), which describes the relationship between anti-torque and relative static joint angles. Joint torque and muscle force were calculated using an inverse dynamics approach, and the track traced by the tip of each limb at full reach was used as the model's known parameters. First, to determine these "end tracks," we classified typical upper limb movements into 10 line track and 10 curve-track groups, according to the different types of end tracks. We then calculated the torque using the Kane Equation, which has been widely used in astronaut-related simulations (4). Based on our results, we found that astronauts should be particularly careful when changing the direction of their movement, since the joint-torque value can change suddenly. Generally speaking, astronauts should avoid the sudden abduction or adduction of the shoulder, and the hand should ideally move slowly in a straight line path, rather than a curve (Figure 1) (unpublished observations).

Mechanical simulation of astronauts’ hands

We built a model of hand-muscle force based on the two-dimensional static finger musculoskeletal system model using linear programming (5). In this model, the Hill model (13) was used to simulate the muscle force, resistance from the space glove was simplified as surface pressure on the finger, and the external force was modeled as a point pressure (Table 1). Electromyography (EMG) was used to verify the model since actual muscle force was considered as the body's mass. Numerous studies have indicated that thermal protection from EVA gloves (6–8) can decrease the range of motion (ROM) for both the fingers and the wrists significantly (9, 10). This insufficiency can be solved using 2.5 W of heat on the back of fingers (14). Multiple factors combined enhance the effects on astronauts' manual operations, such as glove design, pressure, and outside temperatures are key factors affecting EVAs, and their combined effects have direct impacts on the ergonomics of manual work (15, 16). We have mimicked the conditions in space by simulating different temperatures (-50°C, -90°C, -110°C, -130°C) and pressures (29.6 kPa and 39.2 kPa) using liquid nitrogen and a vacuum pump in a simulation chamber. We then performed a series of manual tasks including maximum grip force tests, fatigue tests, force perception tests, Purdue pegboard tests, and nut tensioning tests. The results showed that: (1) a single factor (glove design, pressure, or low temperature) could decrease the subject's fatigue by up to 50% (P<0.05). If these three factors were considered, working capacity was reduced by 50% of the normal conditions (17, 18). Both the glove design and temperature could decrease the range of motion (ROM) for both the fingers and the wrists significantly (P<0.05), but low temperature had no

### Table 1. Relationship between the distance of thumb from middle finger and the pressure of each joint.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Pressure of each joint (Pa)</th>
<th>MCP</th>
<th>PIP</th>
<th>DIP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.56</td>
<td>0.88</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.32</td>
<td>0.5</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>0.9</td>
<td>1.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>

The ratio of finger length to glove length

<table>
<thead>
<tr>
<th>Finger</th>
<th>Length of finger (mm)</th>
<th>Finger length of glove (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCP</td>
<td>78.6</td>
<td>68.3</td>
</tr>
<tr>
<td>PIP</td>
<td>81.4</td>
<td>73.3</td>
</tr>
<tr>
<td>DIP</td>
<td>83.7</td>
<td>67.4</td>
</tr>
</tbody>
</table>

TABLE 2. Relationship between length of finger length and glove length under 10 kg grip force conditions.

- **FDP**: flexor digitorum profundus; **FDS**: flexor digitorum superficialis; **Es**: extensor digitorum and extensor indicis.
obvious effect on ROM (16) (3). With the glove on, the subject’s perception performance was reduced by 20% (P<0.01); when the pressure was increased, this diminished further to ~60% (P<0.01). There was a significant difference of at least 15°C (9) between the two pressure levels tested (P<0.05). The effect of low temperatures on perception was more apparent than that of pressure, particularly when finger temperature dropped below -15°C (P<0.05) (10). The combination of all three factors reduced perception performance to only ~20%. (4) Both the glove design and pressure could affect the flexibility of fingers and wrists significantly (P<0.05), but low temperatures affected flexibility only after three to five minutes. Increased pressure had a greater impact on manual working capability than the glove design (P<0.05) (10).

Future directions

We have been conducting studies concerning mechanical and heat transfer theories for EVA manual operations for over 15 years. Our research has enabled a better understanding of EVA manual operations and allows us to continue to propose ways to design, improve, and evaluate future EVA spacesuits and gloves.

References


Acknowledgments

This work was supported by the National Natural Science Foundation of China (50406080 and 31171502) and the China Astronaut Research and Training Center.

Animal behavior assessment technology for space medicine

Because of advances in space science and technology, astronauts are now not only required to control the spacecraft, but also conduct specific mission-related tasks (e.g., involving extravehicular activity and scientific research). Astronauts must carry out these tasks while simultaneously facing physiological challenges (hypergravity, microgravity, and circadian rhythm disorders) and stressors from traveling in a spaceship (ambiguous environmental cues, time pressure, rapid changes in circumstances, contact with new cultures and other people, and confined spaces). (1) Adding to these difficulties, crews experience negative effects on their health and performance from being exposed to the space environment, such as altered neurosensory, musculoskeletal, and cardiovascular systems, which result in physiological deconditioning. These space-related stressors induce heavy physical and mental workloads and can have a serious impact on an astronaut's cognitive response times, ability to stay calm and rational, and ability to make accurate judgments and decisions (2).

Since these abilities are particularly important for astronauts to maintain good performance and successfully accomplish mission tasks, scientists hope to reveal the mechanisms underlying the physiological and psychological changes that negatively affect human health and/or performance during space flight. Substantial human trials (for example, head-down bed rest experiments and the Mars500 and NEEMO projects) have enabled the study of various psychological conditions that could affect the well-being and performance of individual crew members as well as the team’s functioning as a whole—all factors that could potentially compromise a mission’s success. However, because these studies have been conducted on human subjects, they must be carried out with certain restrictions due to strict regulations for human test subjects. This can limit our understanding of the underlying mechanisms of the adverse changes seen during actual space flight. Animal testing, a widely used alternative to human testing in basic medical research, has provided us with a number of animal models for studying physical and mental issues related to space missions. In the 1990s, we established an animal behavior assessment technology for studying the physiological and psychological mechanisms responsible for the health and behavioral changes induced under conditions that simulate space-specific stresses, with the goal of finding medical solutions (3).

Research technology overview

Our animal behavior assessment technology consists of three core parts: animal models, testing equipment, and the assessment methods themselves. For simulating space-specific, environmentally induced physiological and psychological impairments, we have developed a series of animal models to study hind limb suspension (HLS), gravity overload (4), weightlessness (5), sleep deprivation (6), resistance on earth (7), circadian rhythm disorders, and chronic mild stress (8). The HLS and gravity overload models are classed ground-based microgravity- and hypergravity-mimicking animal models, respectively. The remaining models aim to duplicate psychological disorders that astronauts might face in space. Moreover, in order to develop a space-specific environment and conduct precise behavioral evaluations, our team independently developed/adapted stimulators and behavior assessment apparatuses. In addition to using the conventional behavioral testing apparatuses such as the Morris water maze (7–9), shuttle box (10), step-down (7–10), and step-through (6, 17, 12), we also developed our own state-of-the-art devices that tested various aspects of cognitive, emotional, and motor functioning. Taking advantage of computer tracking technologies (including methods for acquiring, processing, analyzing, and understanding high-resolution data from the real world) and photogrammetry technologies, we have standardized the visualization, quantification, and analysis of animal behavior.

Compared with other technologies that measure the same behaviors, our devices displayed the following advantages: (1) the ability to freely adjust the monitoring range independent of the animal’s size; (2) the ability to accurately determine several animal behavior parameters simultaneously, such as location, motion trail, direction, distance, and speed; (3) the ability to characterize specific animal behavior in real-time; and (4) the ability to use multiple cameras to assess more detailed and subtle behaviors in three-dimensional space. Here, we briefly present the technologies we have developed (6–12).

Musculoskeletal testing

HLS, a well-established approach for creating a ground-based model of microgravity and musculoskeletal stress, allows researchers to mimic many of the physiological changes associated with space flight in rodents (3). HLS rodents experience many of the same well-characterized neurosensory, musculoskeletal, and cardiovascular dysfunctions that are universally experienced by astronauts during space missions. Although modified numerous times since Moros-Hulton introduced it in the 19th century (13), the apparatus still has a number of shortcomings. First, the spontaneous activity and feeding behavior of animals under suspended conditions have been ignored. Second, the tail used to suspend the animal will often shed for a number of reasons, including the lack of proficiency and experience of the experimenter, potentially leading to a failed experiment if not quickly corrected. For these reasons, we developed a computer-aided, open-field monitoring system for tail HLS in rats. The device provides multiple analogs of space-specific environmental factors,

FIGURE 1. Illustration of animal behavior assessing apparatus and software. (A) A computer-aided open-field monitoring system of hind limb suspension of rats. (B) An intelligent and automatic gait analysis system for mice and rats. (C) A computer-aided operant conditioning analysis system.
such as microgravity, limited space, isolation, and communication restriction (see Figure 1A). Moreover, it contains an intelligent alarm system that automatically sends a warning text message to the nearest station (up to ten stations) and analyzes the vessel in real-time. The system also contains two bottle-feeding setups on the front side of the cage to monitor liquid consumption and assay psychophysics. The processed data is available to be exported as text or spreadsheet files, and includes parameters such as distance moved, speed, duration of movement and sleep, shedding frequencies, and shedding time.

Gait analysis
Gait analysis is defined as the systematic measurement, description, and assessment of quantities that characterize locomotion—such as the degree to which symmetry of motion is maintained by muscular control under gravitational conditions (19). Gait describes the pattern by which an individual or animal walks. In a state of microgravity or simulated microgravity, physiological disorders such as weight loss, muscle atrophy, and bone loss result from off-loading of weight on bones and muscles, which affects walking function and leads to an abnormal gait. We independently developed an intelligent and automated gait analysis system (20) for monitoring mice and fish tracking technology, electrical engineering, and information technology (Figure 1B). The established gait appraisal system, which is suitable for observations of movements of an animal or human, has the advantage of accurately distinguishing normal and abnormal gait, and can specifically identify characteristics of neuromuscular injuries and precisely quantify gait. Thus, numeric comparisons between experimental groups can be performed, making the gait appraisal system broadly applicable for seeking new therapeutic strategies for neuromuscular dysfunction associated with long-duration space missions (21).

Performance testing
Another well-known threat to the success of space flights is the adequate and effective performance of the crew. During space missions, cognitive to environmental factors that induce detrimental effects on both their mood and performance. In order to investigate strategies to counteract the decline in decision-making ability, reaction time, and efficiency at fulfilling specific tasks experienced by astronauts, we developed a series of reward-directed instrumental learning tasks (consisting of instrumental learning and reinforcement learning) that provide a very accurate model of adaptive behavior. It is one of the most elementary forms of behavioral adaptation and reflects a remarkable aspect of adaptability that can be seen in its highest form in human beings. Because a behavior that once generated a positive outcome can later produce a negative outcome in one or even several situations, the individual is capable of predicting consequences and adjust one’s behavior accordingly. This cognitive flexibility allows rapid behavioral changes in the face of a changing environment, conferring a survival advantage. It is a form of associative learning through which an animal learns from the consequences of its behavior. Our improved operant conditioning chambers have been fitted with two food dispensers providing the option for neutral reinforcement—and two retractable levers. Two sets of tri-color LED signal lights are located above the levers as visual cues. Using different colored LEDs (yellow, red, and green), the response (GSR), heart rate (HR), heart rate variability (HRV), and negative affect in response to the threat of drowning and physical injuries and precisely quantify gait. Thus, numeric comparisons between experimental groups can be performed, making the gait appraisal system broadly applicable for seeking new therapeutic strategies for neuromuscular dysfunction associated with long-duration space missions (20).

Emotion assessments
Emotional responses elicited by space-specific environments have frequently been shown to be related to decreases in well-being, as measured in the form of depression, sleep problems, disturbed appetite, and adaptation difficulties (21, 22). To quantify emotional responses, we developed a computer-aided, automated tail suspension test (TST) and a forced swimming test (FST) as reinforcers to reward the student’s most adaptive behaviors (Figure 1C) and a vibrated sensor is used to detect movement, the absence of motion, and the intensity of movements. Up to eight channels can be displayed in real-time, each of which shows a novel object and explore it with its whiskers, nose, and forepaws. These subtle behaviors can be identified and quantified by using different contexts and tasks: discriminating a novel from a familiar object (nonspatial object recognition), finding a mismatch between the past and present, and recognizing objects (spatial recognition), and identifying the order in which objects are presented as well as how recently, relative to one another (temporal order memory) (17).

Cognitive and memory testing
Another important type of cognitive behavior is called object recognition. We have developed a series of object recognition tasks and a computer-aided behavior-assessment device based on the novel pattern of cognitive behavior. We have shown that the rodent is attuned to detecting slight changes in cognition that result from imperceptible psychological alterations. The novelty-preference paradigm exploits a rodent’s innate preferences for novel rather than familiar objects. Quite different from other cognitive behaviors, a rodent’s novelty preference is a delicate, sensitive, and situation-dependent behavior. When novel and familiar objects are presented at the same time, a rodent will readily approach the novel object and explore it with its whiskers, nose, and forepaws. These behaviors can be identified and quantified with the help of computer video tracking and data processing technologies. Moreover, this behavior task can be designed to investigate spatial memory and episodic-like memory by using different contexts and tasks: discriminating a novel from a familiar object (nonspatial object recognition), finding a mismatch between the past and present, and identifying objects (spatial recognition), and identifying the order in which objects are presented as well as how recently, relative to one another (temporal order memory) (17).

Effects of space flight on human emotion
Qing Liu1, Renai Zhao1,2,3, Lichao Xiu1, Xin Zhao2, Chenang Xiao4, and Shangcheng Chen1

both living and working environments can have significant effects on an individual’s emotional state. The impact of extreme work environments, as with space flight, on an individual’s emotional acclimation is an important issue in the field of astronautical engineering. The space flight environment—characterized by microgravity, confinement, and psychological distress—is a mixed threat and confinement—presents challenging conditions under which humans must accomodate, both physically and emotionally. Hence, ground-based models simulating the effects of weightlessness have been developed as a means to study the effects of space flight on emotion regulation. For example, head-down bed rest (HDBR) has been shown to be a reliable simulation model for most of the physiological effects of weightlessness on humans (1–3). We evaluated the effects of simulated weightlessness—induced by a 6° HDBR experimental model on human subjects. We analyzed the participants’ emotional responses through both subjective self-reporting of emotional responses (anxiety, depression, and positive and negative affect) and objective recordings of the participants’ physiology responses, including galvanic skin response (GSR), heart rate (HR), heart rate variability (HRV), and cortisol levels (皮E, ECG).

We first conducted a short-duration (15 day) HDBR experiment with 22 female freshman and sophomore students between the ages of 19 and 24. All participants had no medical or psychiatric history of vision problems or corrective eye surgeries, and were all right-handed and nonathletes (handedness of participants was selected in order to avoid the effects of confounding variables in the participants’ psychological measurements, and aerobic fitness could also influence the psychology and physiology impact of HDBR) and needed to be controlled for a lack of alcohol and anxiety (Inventory (BAI), the Beck Depression Inventory (BDI), and the Positive and Affective Negative Scale (PANAS) to evaluate the psychological effects of microgravity and 5 days prior to the experiment (pre-HDBR), the fifth and the tenth day of HDBR, and five days after the experiment ended. The results showed that the participants experienced a significant change in positive affect (Figure 1A), including clinically salient anxiety and depression (Table 1). However, participants...
did show increases in negative affect, including reduction in vigor and appetite on day 10 of HDBR as well as five days after the completion of HDBR. We also conducted a long-duration (45 days) HDBR experiment in which the BAI, BDI, and PANAS were adopted to evaluate the subjective reporting of emotion in 16 young men between the ages of 20 and 34 at six time points: two days before HDBR; on the eleventh, twentieth, thirty-second, and forthieth day of bed rest; and eight days after the completion of bed rest. In addition, a frontal EEG asymmetry test was administered to record the on-going regulation of emotion (4, 5), and the participants’ GSR, HR, and HRV were assessed as measures of psychological activity. The results showed that there were no significant changes in anxiety or depression, similar to the findings in the previous 15-day experiment (Table 1). In contrast, the negative affect of the participants stayed relatively stable across the study while positive affect, like passion and curiosity, decreased significantly near the end of the HDBR and persisted at these levels until the eighth day after completion of HDBR (Figure 1D). This suggests that prolonged bed rest may have detrimental effects on affect (4, 5).

Environmental changes experienced during space missions affect circadian rhythms and may cause sleep problems. Sleep deprivation has been used as an analog to measure the effects of sleep loss in space (6, 7). To investigate circadian disturbances on an individual’s emotional acclimation, we designed a 72-hour sleep deprivation experiment to be carried out in social isolation. We used the Profile of Mood State (POMS) and PANAS tests to assess the subjective emotional changes in astronauts during the ages of 18 and 30, during either 72 hours of social isolation or 72 hours of sleep deprivation. The participants’ objective electrophysiology responses, including GSR, HR, HRV, and frontal EEG asymmetry were recorded. The results showed that, after 72 hours, participants experiencing sleep deprivation were more likely to have a lower positive affect than those only in the social isolation (Figure 1C) as well as an increase in negative moods, such as fatigue and panic, and an increased HR, decreased HRV, and negative alpha values, indicating increased right frontal lobe activity that is associated with the experiencing of negative emotions (5) (Table 1). Taken together these results point towards a detrimental affect of sleep deprivation on the emotional state of individuals (7).

In order to confirm our ground analog findings, we studied psychological changes in astronauts during actual space flight. The 13-day Shenzhou 9 space flight involved three astronauts (two male and one female) aged 34 to 46 years old. To evaluate the astronauts’ emotional state during the flight, we collected their subjective responses using the positive affect scale and their physiological responses using the frontal EEG asymmetry test at four time points: 25 days before the orbital flight (pre-flight), the 6th day or 7th day of the orbital flight (Ontrack1), the 10th or 11th day of the orbital flight (Ontrack2), and three days after the orbital flight (post-flight) across a 13-day space flight (N=3, 2 males [A, B] and one female [C]).

**TABLE 1.** Studies demonstrating variation in subjective emotion reports and electrophysiology responses during actual and simulated space flight conditions.

<table>
<thead>
<tr>
<th>Index</th>
<th>15-day HDBR</th>
<th>45-day HDBR</th>
<th>72-hour sleep deprivation</th>
<th>13-day orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anxiety and depression</td>
<td>No significant changes (7)</td>
<td>No significant changes (8)</td>
<td>Compared with social isolation, subjects experienced an increase in negative moods, like fatigue and bewilderment after sleep deprivation (6)</td>
<td></td>
</tr>
<tr>
<td>Proﬁle of mood states (POMS)</td>
<td>Compared with pre-HDBR, the subjects’ GSR decreased significantly under HDBR and did not return to baseline, even after the HDBR (2)</td>
<td>Compared with social isolation, subjects showed a significant decrease in GSR after sleep deprivation (6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanic skin response (GSR)</td>
<td>Compared with pre-HDBR, the subjects’ GSR showed a significant decrease in GSR after sleep deprivation (6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heart rate (HR)</td>
<td>Compared with pre-HDBR, the subjects’ HR decreased significantly as soon as HDBR started, then increased slightly, but did not return to baseline after the HDBR (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High frequency of HR variability (HF)</td>
<td>Compared with pre-HDBR, the subjects’ HR showed an increase in HF variability after the HDBR (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low frequency of HR variability (LF)</td>
<td>Compared with pre-HDBR, the subjects’ LF showed a significant decrease at the end of HDBR and did not return to baseline after HDBR (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF/HF ratio</td>
<td>Compared with pre-HDBR, the subjects’ LF/HF decreased significantly after sleep deprivation (6)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 1.** Variation tendency of positive affect under space flight and ground analogs.

(A) Participants’ positive affect at four time points: five days before the rest (pre-HDBR), the 6th day and the tenth day during the rest period (HDBR5 and HDBR10), and five days after the completion of the HDBR (post-HDBR) across 15 days (N=22 females). (B) Participants’ positive affect at six time points: two days before the bed rest period (pre-HDBR), the eleventh, twentieth, thirty-second, and fourthieth day during the bed rest period (HDBR11, HDBR20, HDBR32, and HDBR40), and eight days after the HDBR completion (post-HDBR) across 45 days (N=16 males). *p<0.05, compared with the scores of positive affect on PANAS pre-HDBR. (C) Participants’ positive affect in the pre-test and post-test under 72-hour social isolation and 72-hour sleep deprivation conditions (N=12 males). **p<0.05, compared with the social isolation condition. (D) Participants’ positive affect at four time points: 25 days before the orbital flight (pre-flight), the 6th day or 7th day of the orbital flight (Ontrack1), the 10th or 11th day of the orbital flight (Ontrack2), and three days after the orbital flight (post-flight) across a 13-day space flight (N=3, 2 males [A, B] and one female [C]).

**References**


**Acknowledgments**

This work was funded by the National Basic Research Program of China (2011CB711000).
High-risk decision-making in space

Lilin Rao, Chengming Jiang, Zhuyuan Liang, Yuan Zhou, and Shu Li*

S pace missions are full of risk and uncertainty. Astronauts may occasionally be confronted with high-risk situations, such as the five program alarms that went off during the last seven minutes of the Apollo 11 landing, and the false fire alarm on board the Shenzhou 7 mission during a spacewalk. Thus, making the right decisions in emergency situations is critical for the success and completion of the mission.

The correspondence between French mathematician Blaise Pascal and lawyer Pierre de Fermat concerning the so-called Gambler’s Ruin problem led to the birth of probability theory, which later gave rise to expected value (EV) theory in the field of decision-making under risk (1). The EV theory assumes that the attractiveness of a bet or offering certain payouts with certain probabilities can be represented mathematically. At present, prospect theory, which is the most successful implementation of EV theory, is the dominant theory that describes how people choose between probabilistic alternatives that involve risk (2). The prospect theory states that people make decisions based on a weighting and a summing process, i.e., that the attractiveness of a bet is given by the sum of the potential subjective utilities (rather than the objective payoff) weighted by the corresponding outcome weighting functions (rather than the objective probabilities). However, there is much debate about whether decision-making under risk is guided by a weighting and summing process, as the five program alarms that went off during the last seven minutes of the Apollo 11 landing, and the false fire alarm on board the Shenzhou 7 mission during a spacewalk. Thus, making the right decisions in emergency situations is critical for the success and completion of the mission.

In this context, we designed a series of experimental studies to investigate how decision-making under risk is actually conducted in space environments. In the first study, we conducted a questionnaire survey to assess the self-reported risk-taking behavior of astronauts in space. The results showed that astronauts tend to take more risks in space than on Earth, especially when the task requires making decisions under uncertainty (3). In the second study, we investigated the risk-taking behavior of astronauts during spacewalks using an eye-tracking task (4). The results showed that astronauts tend to take more risks during spacewalks than during regular space missions, which might be due to the high level of uncertainty and the need to make rapid decisions in space (5).

In summary, our studies have shown that decision-making under risk is critical for the success and completion of space missions. Future research should focus on understanding how astronauts make decisions under risk in space environments and how their decision-making strategies can be optimized to ensure safe and successful space missions.

Table 1. Summary of the process test of high-risk decision making.

<table>
<thead>
<tr>
<th>Process Tested</th>
<th>Task</th>
<th>Method</th>
<th>Dependent measurement</th>
<th>Moderating variables</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deriving of probability functions</td>
<td>Russian roulette problem</td>
<td>Behavioral experiment</td>
<td>Willingness to pay, perceived happiness</td>
<td>None</td>
<td>6</td>
</tr>
<tr>
<td>Probabilistic decision task and single-case choice task</td>
<td>Behavioral experiment</td>
<td>Reaction time, proportion of choice</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weighing</td>
<td>Single play risky choice task, multiple play risky choice task, and proportional choice task</td>
<td>Eye tracking</td>
<td>Eye movements between outcomes and probabilities</td>
<td>Computational difficulty</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Preferential choice task and judgment-based choice task</td>
<td>Functional magnetic resonance imaging (fMRI)</td>
<td>Connectivty strength between brain functional areas</td>
<td>None</td>
<td>10</td>
</tr>
<tr>
<td>Summing</td>
<td>Single play risky choice task, multiple play risky choice task, and proportional choice task</td>
<td>Eye tracking</td>
<td>Eye movements between largest (or smallest) outcomes</td>
<td>Computational difficulty</td>
<td>8, 11</td>
</tr>
<tr>
<td></td>
<td>Preferential choice task and expected value choice task</td>
<td>Event-related potential (ERP)</td>
<td>P300 component of ERP</td>
<td>Difference in the minimum outcome dimension between two options and computational difficulty</td>
<td>12</td>
</tr>
<tr>
<td>Expectation-maximizing</td>
<td>Preferential choice task and judgment-based choice task</td>
<td>fMRI</td>
<td>Activity of brain areas</td>
<td>Decision conflicts</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Vital/near loss decision task</td>
<td>fMRI</td>
<td>Activity of brain areas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experienced feelings of decision process</td>
<td>&quot;Imposed decision rules&quot; task</td>
<td>Behavioral experiment</td>
<td>Behavioral result, emotional reactions, and acceptance of imposed decision rules</td>
<td>None</td>
<td>15</td>
</tr>
</tbody>
</table>

References
17. C.-W. Lee et al., J. Exp. Psychol. Appllic. 8, 75 (2002).

Acknowledgments
This research was partially supported by the National Basic Research Program of China (2011CB715000), the Knowledge Innovation Project of the Chinese Academy of Sciences (KSCX2-EW-2-J), and the National Natural Science Foundation of China (31170976, 31300043, and 71071150).
Effects of weightlessness on cognitive performance in humans

Xin Zhao¹, Renlai Zhou¹,²,³,⁎, Qing Liu¹, Xiaoqiu Chen¹, Shanzhuang Chen¹

1 Department of Psychology, School of Social and Behavioral Science, Nanjing University, Nanjing, China
2 Beijing Key Lab of Applied Experimental Psychology, School of Psychology, Beijing Normal University, Beijing, China
3 Training Center, Beijing, China

It is important to study the effects of weightlessness on human cognitive performance, in large part because efficient human space exploration relies heavily on astronauts’ ability to think clearly. As a result, investigating how weightlessness affects cognitive functioning and performance in humans has become a major area of research. Studies have elucidated that changes in weightlessness might have a significant impact on various cognitive functions (3–9). One study found that effects of space travel on an individual’s behavior, as indexed by simple reaction time and choice reaction time (3). More recently, Eldis et al. reported no memory search deficits for individuals exposed to weightlessness conditions (4). Similarly, research from the Russian Space Agency has documented no significant changes in cognitive functioning of astronauts, as indexed by reaction times and accuracy, collected both during and after space flight (5). Similar results have been obtained with simulated weightlessness studies conducted on Earth. We found no working memory (WM) impairment for subjects under a 15–45 day head-down bed rest (HDBR) study (6). Liu et al. used the same WM task in a 45-day HDBR experiment and reported similar results to Zhao’s study (7). Shabtai et al. tested eight male participants on attention, spatial memory, tracking ability, and three other cognitive measures during a 17-day HDBR study, none of the participants showed a decline in cognitive abilities during the rest state (8). Train et al. found no cognitive impairment in their study of six male volunteers in a 28-day simulated weightlessness experiment (9). Based on the above observations, scientists have postulated that there are no cognitive effects under long-term weightlessness conditions because of our ability to adapt. These studies were conducted only one day after weightlessness exposure, so rapid adaptation is without a doubt a predominant mechanism. The adaptation theory suggests that changes in gravity might affect an individual’s sensorimotor behavior (10). The initial exposure to weightlessness leads to decreased accuracy and speed of an individual’s spontaneous movements, such as locomotion, eye-hand coordination, and spatial orientation. Modern theories attribute such deficits to the effects of weightlessness on the vestibular system (1, 2). Specifically, the changes in gravity alter a person’s sensory inputs to the central nervous system leading to changes in response output, which disrupt the balance between the sensory input and the response output (11). Although the human sensory system’s vulnerability to changes in gravity is well documented, empirical studies have only pointed to such a change in sensory-motor performance (12). The sense of weightlessness effects on the vestibular system, higher cognitive functioning remain intact because of our adaptive ability. However, the situation appears to be more complicated than previously thought. According to a recent study by Chen et al., volunteers did not show recognition memory deficits during a 15-day HDBR study, but did show time-based prospective memory (PM) impairment, even when researchers controlled for emotion-inducing factors (12). Chen et al. found similar results during a 45-day HDBR experiment under similar conditions (13). Why is time-based PM affected during long-term weightlessness conditions? This might be related to the effects that changes in gravity have on the circadian rhythm and observed deleterious effects on individual circadian rhythms during a 45-day HDBR study (14). Time-based PM is a type of PM in which memory is triggered by a time-related cue indicating that a given action needs to be performed (12). Time-based PM is not only influenced by sensory input, but is also closely related to the circadian system and observed deleterious effects on individual circadian rhythms during a 45-day HDBR study (14). Therefore, it seems possible that the time-based PM deficits observed in our series of studies are partially due to the adverse effects of changes in gravity on subjects’ biological rhythms (12, 13). The effect of weightlessness on human cognitive functioning is not necessarily an all-or-nothing phenomenon, but rather might be adaptive impairments have been found in humans as a result of weightlessness because of our adaptive ability. However, the situation appears to be more complicated than previously thought. According to a recent study by Chen et al., volunteers did not show recognition memory deficits during a 15-day HDBR study, but did show time-based prospective memory (PM) impairment, even when researchers controlled for emotion-inducing factors. Since astronauts experience long periods of isolation and confinement during interplanetary space flights, researchers believe that it is important to investigate how these factors might affect mental health (1). In order to study how the space environment impacts humans, the Institute for Biomedical Problems (IBMP) of the Russian Academy of Science (RAS) organized and implemented a high-fidelity ground simulation experiment called Mars500 as a collaborative effort with international agencies, including the European Space Agency (ESA), the Aeronautic Center of China (Chinese Aeronautic Research and Training Center), and the Canadian Space Agency (CSA). The project, which ran from June 3, 2010 to November 4, 2011, simulated a mission to Mars with six volunteer astronauts (three Russian, one French, one Italian, and one Chinese). The crew was isolated in a habitat in Moscow with complete and continuous isolation for 320 days (Figure 1). In order to create the experience of a realistic mission, the special conditions of a Martian flight were simulated, including a diurnal weekly work schedule for the astronauts, lags in communication with mission control, and a mid-mission landing on a simulated Mars surface. In addition, the crew carried out 105 scientific studies in a number of areas including the simulation of physiology, psychology, biochemistry, hygiene, and ergonomics. Detailed information about all crew members and the project are available online (1). Over the course of the project, the Mars500 crew exhibited psychological adaptations similar to the “third-quarter phenomenon,” which has been observed in long-duration space missions (2). This phenomenon might affect mental health by reducing motivation and increasing stress and anxiety (3). The third-quarter phenomenon occurs during the final weeks of a mission when the crew members experience increased stress (4). The Psychological adaptations to long-term isolation and confinement: Lessons learned from the Mars500 project

Yue Wang¹, Bin Wu, Ping Wu, Zhiming Gu, Min Liu, Xianwen Gong, and Xiaoping Du

Psychological adaptations to long-term isolation and confinement: Lessons learned from the Mars500 project

As astronauts adapt to microgravity conditions and one’s motivation to achieve excellent performance under extreme environmental conditions are also factors that likely influence outcome.

References

Acknowledgments
This work was supported by the National Basic Research Program of China (2011CB711000).

Psychological adaptations to long-term isolation and confinement: Lessons learned from the Mars500 project

Yue Wang, Bin Wu, Ping Wu, Zhiming Gu, Min Liu, Xianwen Gong, and Xiaoping Du

As astronauts adapt to microgravity conditions and one’s motivation to achieve excellent performance under extreme environmental conditions are also factors that likely influence outcome.
third quarter because of the realization that the mission is only half complete, and they may still have many tough issues to grapple with ahead; however, there is no objective data from the Mars500 project to justify this interpretation.

In addition to the psychological effects, researchers have also investigated the physical effects the astronauts experienced during the Mars500 project. Belavy et al. studied the impact of prolonged confinement on the participants’ physical activity, adaptation, and motivation (7). Physical activity, as measured by the average acceleration of mass (“activity temperature”) using the acti-belt device, decreased progressively over the course of isolation. Concurrently, measures of jumping power and single-leg hop force decreased during isolation. Moreover, no significant change in motivational state was observed during isolation, suggesting that reductions in lower-limb neuromuscular performance were unrelated to motivation. Schröder et al. found that exercise had a positive effect on the astronauts’ mental state and cognitive performance when completing tasks during the Mars500 simulation as well as during space missions. However, this group suggests that the neurocognitive performance could not be enhanced by all types of exercise. It likely depends on the subjects’ interests and attention. Their work demonstrated a bias on valence rating for unpleasant stimuli with time, i.e., the crew tended to assign positive ratings to negative pictures especially between days 36 and 421 of the mission. This behavior was in line with the crew member’s POMS mood scores and the increasing levels of S-hydroxytryptamine and noradrenephrine detected in plasma, expressing disorder, providing evidence in support of the third quarter phenomenon (6). The analysis and publication of data on global DNA methylation status and expression of genes thought to be involved in depression are currently underway.

In summary, isolation and confinement-two necessary components of long-term space flight missions—prove to be both psychologically and physically challenging. Many of the studies coming out of the Mars500 project suggest that the multinational crew members each exhibit psychological adaptations that changed over the 520-day confinement and mimicked the patterns described by the third quarter phenomenon (6). These results imply that attention needs to be paid to the structure and planning of future space missions that experience, such as a journey to Mars, is the most critical period, described by the third-quarter phenomenon. These results imply that attention needs to be paid to the structure and planning of future space missions that experience, such as a journey to Mars, is the most critical period, described by the third-quarter phenomenon. These results imply that attention needs to be paid to the structure and planning of future space missions that experience, such as a journey to Mars, is the most critical period, described by the third-quarter phenomenon. These results imply that attention needs to be paid to the structure and planning of future space missions that experience, such as a journey to Mars, is the most critical period, described by the third-quarter phenomenon. These results imply that attention needs to be paid to the structure and planning of future space missions that experience, such as a journey to Mars, is the most critical period, described by the third-quarter phenomenon.

Emergency malfunction procedures: Skill acquisition

The predictive value of the operation complexity measurement

Emergency malfunction procedures (EMPs) necessitate that astronauts carry out a number of coherent steps to handle a specific spacecraft subsystem malfunction. In order to optimize EMP training, we developed an operation complexity measure for analyzing the effects of operation complexity and training methods on skill acquisition for these two types of space flight operations. We discuss these studies as well as their implications for astronaut training and future studies below.

Emergency malfunction procedures: Skill acquisition

Yijing Zhang1, Meng Wang2, Pengjie Li1, Bin Wu1, Weifen Huang1, Shangguang Chen1*

Space flight operation skills: Effects of operation complexity and training method

We focused on key to effectively train astronauts to perform space flight operations has been drawing increasing attention from researchers since the mission began. The first phase of the experiment was conducted after the crew entered the isolation phase, and the second phase was tested experimentally. The experimental tasks included seven EMP units with complexity values ranging from 0.8 to 1.7. Ten subjects participated in the experiment and each of them performed the seven operations 18 times. We used both objective indexes (operation time and error rate) and subjective indexes (NASA-TLX) in the experiment. The regression analysis showed that the average operation time, subjective complexity rating, and subjective workload could be predicted well from the operation complexity value (r=0.876, 0.802, and 0.698, respectively); and the error rate could only be partly explained by the operation complexity value (r=0.343) (2).

The complexity measure was verified by the operation time in 189 trials with Chinese astronauts. A regression analysis showed that complexity values were significantly correlated with the average operation time (r=0.918, P<0.001) (3). Following validation using both experimental and training data, our operation complexity measure has been applied to astronaut training in China and has been further shown to be a suitable way to evaluate the complexity of procedural operations and predict operation times (4).

Feedback and imagery theory: Effects on training

We designed an experiment to illustrate the high-complexity operation skill acquisition process. As the training method changed from the routine method to the compounding-feedback method to the integrated method, the average operation time to complete the complex tasks decreased significantly. In addition, the average number of errors for the low-complexity level operations did not change significantly during the different training methods. The routine method is based on traditional training methods and includes two basic parts: learning the theory and then practicing the operation. This method was introduced in astronaut training practice as a general training method for simple operations (5). The compounding-feedback method is based on feedback theory and error management. This method includes two forms of training: feed-forward and feedback. Feed-forward focuses on error prevention by giving operators information ahead of time about the correct procedures they must have occurred from the operation experience of Chinese astronauts. Feedback focuses on error-correction through trial and error by letting operators make mistakes and learn from their own errors. The integrated method consists of compounding feedback, mental imagery, and group discussion. Compounding feedback can improve the reliability of operations, mental imagery can help the operators construct a mental representation of the operation procedure by building an operation-inspired psychological model, and group discussion helps operators learn by “brainstorming” (5).

Effects of operation complexity and training method on skill acquisition

To study the effects of operation complexity and training methods, we designed an experiment that would take into account both within-subject and between-subject variables. Twenty-eight participants were divided into three training-method groups and underwent three training phases, conducted with a one-week interval between each. All the participants were asked to perform all the operations for 8 to 10 times at each training phase. The operation tasks were classified into two complexity levels (within-subject variables): low complexity (three EMPs with complexity values ranging from 0.9 to 1.1) and high complexity (three EMPs with complexity values ranging from 1.5 to 1.7). The three training methods used varied for the three participant groups (between-subject variables): the routine method, the compounding-feedback method, and the integrated method. We measured the operation time, operation errors, and NASA-TLX values (the dependent variables) to determine how the training method and the operation complexity level affected skill acquisition (5).

Our data showed that the different training methods had varied effects only on the two complexity levels at different phases of training. As the training method changed from the routine method to the compounding-feedback method to the integrated method, the average operation time to complete the high-complexity operation did not change significantly. In addition, the average number of errors for the low-complexity level operations did not change significantly during the different training methods. However, compared with the routine method group, both the compounding-feedback and the integrated training methods resulted in a significant decrease in average error rates for the high-complexity EMP operations (P<0.006 and 0.034, respectively). The mental demand and the total value of the NASA-TLX measurement also showed a decrease in the error rate associated with training the phase 1 to phase 3). Additionally, semi-structured interviews were conducted among participants on the effect of the training and the results showed that the compounding-feedback method and the integrated method were more effective in preparing the participants to complete high-complexity operations than low-complexity operations (5).
Manual rendezvous and docking skill acquisition

Defining operation complexity: Control interfaces and initial deviation

A space rendezvous between two spacecrafts is an orbital maneuver where both vehicles arrive in the same orbit, at the same velocity, and finally become physically connected. In order to accomplish this orbital maneuver, the spacecraft maneuvers with a manually controlled rendezvous and docking (RVD) module that is located in the lower-left quadrant of the spacecraft.

The control system’s interface for a manual RVD operation involves one monitoring screen and two joystick controllers: a translation controller to control the x, y, and z axes of the spacecraft and an orientation controller to control the yaw, pitch, and roll (Figure 1). As a continuous operation, this reduces the cognitive load, and cognitive models, leading to lower error rates for operation performance. Using both experimental and training data, we determined that there is negative correlation between operation time and operation complexity (2-4). Therefore, the complexity measure can be used to evaluate the design of space flight tasks and to plan astronaut training for ground and in-orbit tasks. In the future, we would like to consider other issues in complexity measurement, such as the effect of sleep deprivation and of being in an isolated environment, two factors that astronauts experience during space flight.

Our research went one step further and investigated the effects that different training methods have on operations of different complexity. From these studies, we found that the type of training method used has a larger effect on discrete operations than on continuous operations. Our results also indicated that physiological indexes, like HRV, can be used as a marker for which training phase an astronaut is in (7, 9). This research area shows promise for providing objective and quantitative measures of proficiency, however, exactly how HRV can be applied to estimate skill proficiency requires further study.

To facilitate better operation performance, we determined that training methods designed using cognitive analysis and error-prevention techniques can help operators build better cognitive models, leading to lower error rates for operation performance compared with traditional methods. However, this positive effect is limited in that operators do not benefit from these training methods during the initial training phase due to the operation complexity (5). In our training methods, we did not focus on the duration of skill retention, but rather evaluated its effectiveness in terms of achieving better performance. For long-duration space flight, however, skill retention is a more important issue and deserves further research. The studies reviewed here reiterate the point that great care needs to be taken when designing training programs. The characteristics of a task and the cognitive process required for that task are two necessary components to consider when building a solid mental model for operations that resist skills decay.

References
Measuring mental workload during emergency operation procedures

Qin Gao1, Yang Wang2, Fei Song3, Zhizhong Li1, and Xiaolu Dong1

SECTION THREE

HUMAN PERFORMANCE IN SPACE: ADVANCING ASTRONAUTICS RESEARCH IN CHINA

3

Human modeling, simulation, and performance evaluation

standard procedures play an important role in managing the safety of employees in high-risk environments, such as those working in aeronautics or nuclear power plants. Emergency situations in particular have provisions for a set of well-designed emergency operation procedures (EOPs), which are necessary for reducing the mental workload of operators and for preventing the degradation of operation competency. Most studies examining the design of computerized EOPs in nuclear power plants measured mental workload using subjective measures, such as the National Aeronautics and Space Administration task load index (NASA-TLX) (1). A major limitation of subjective measures is that they can only assess the overall experience of the workload of procedures, and cannot reflect changes in workload during the execution of procedures. In addition, the subjective nature of such measures makes them vulnerable to personal biases, such as memory deficiencies and cultural differences (2).

To develop a set of continuous and objective measures to assess the workload at each procedural step and to determine the peak workload in nuclear power plant EOP tasks, we compared six physiological mental workload measurement methods, including three eye response measures (pupil size, blink rate, blink duration), three heart variability measures (parasympathetic/sympathetic ratio (LF/HF), total power (TP), and the standard deviation of R-R intervals (R-R std)), and an analytical method, the GOMS, operators, methods, and selection (GOMS)-kaytestro level model (KLM)-based workload index. By integrating these six physiological measures, we constructed a model that can predict the overall mental workload accurately.

To collect the data, we invited eighteen male undergrad-

uates from Tsinghua University to perform an EOP for a steam generator tube rupture (high complexity) and an emergen-
cy shutdown EOP (low complexity). Within each procedure, the complexity of the steps required for the task varied. The degree of complexity for each step was quantified using a visual/auditory/cognitive/psychomotor (VAC/P) model (3). Participants were required to complete at least 20 trials of each EOP and had to succeed in all of the final five trials to complete the first session.

Eye responses: Blink rate, pupil size, and blink duration

Blink rate was sensitive to both the procedural workload (Table 1) and the peak workload (Table 2). The suppression of blink rate observed during the step with the greatest complexity (the peak complexity step) appeared to be caused by the need to acquire visual information as required by the task (4). The increase in blink rate after the peak complexity step may reflect a release of mental resources in stimulus-related cognition (5). In addition, the change in the blink rate over time mirrored that of step complexity, but with a certain latency, as shown in Figure 1. This was in agreement with previous findings that a peak of blink bursts follows a high cognitive load (4, 6, 7).

A change in pupil size during the EOPs significantly correlated with the step error rate, but not with both the step complexity or the step operation time (Table 3). This finding indicates that the pupil dilation seen in our experiment might not be from need for increased cognitive processing, but rather reflects increased attention and arousal caused by errors (8).

Blink duration was found to lengthen significantly after the peak complexity step (Table 2). Further analysis showed that blink duration increases over the time period of both EOPs. This finding was consistent with a previous study that found that blink duration was dependent on the time spent on tasks (9).

Cardiac responses: HRV, LF/HF, and TP

Cardiac responses were used only for measuring the proce-
dure’s workload. These responses seem more sensitive to the accumulative workload than the eye response measures. All three measures showed a significant (HRV and TP: P < 0.05) or marginally significant (LF/HF: P = 0.07) increase in the high-complexity EOP relative to the low-complexity EOP (17).

Revised GOMS-KLM method

Regression analysis between the GOMS-KLM time estimation and the actual operation time showed that the model was effect-

tive and sufficient. The subsequent workload measure, defined as the proportion of the actual operation time for each step deter-

mined during the experiment to the estimated time it should take to complete the step, was found to correlate significantly with the error rate (Table 3) (17). An obvious advantage of the GOMS-KLM method over physiological measures is that it requires no special equipment, only a timer.

TABLE 1. Comparison of overall mental workload for low- and high-complexity procedures using average physiological responses during a specific time interval while subjects performed the procedure. Analyzed with a Student’s paired t-test (for methods, see 11).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>EOP complexity</th>
<th>Mean</th>
<th>SD</th>
<th>t</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pupil size (average percentage change)</td>
<td>high</td>
<td>0.016</td>
<td>0.17</td>
<td>1.52</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>0.071</td>
<td>0.18</td>
<td>0.002</td>
<td>0.05</td>
</tr>
<tr>
<td>Blink rate (times/second)</td>
<td>high</td>
<td>0.22</td>
<td>0.14</td>
<td>4.43</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>0.13</td>
<td>0.09</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>Blink duration (second)</td>
<td>high</td>
<td>0.12</td>
<td>0.04</td>
<td>1.34</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>0.13</td>
<td>0.06</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>LF/HF (ratio)</td>
<td>high</td>
<td>2.96</td>
<td>0.04</td>
<td>1.96</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>2.11</td>
<td>0.04</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>TP (ms²)</td>
<td>high</td>
<td>2464</td>
<td>1144</td>
<td>4.88</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>1352</td>
<td>733</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>R-R std (ms)</td>
<td>high</td>
<td>52.22</td>
<td>12.83</td>
<td>2.81</td>
<td>0.01*</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>43.75</td>
<td>13.11</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

*significant difference between high- and low-complexity tasks (P < 0.05). Note that the negative value of mean pupil size was due to the difference between the blue screen background for the baseline test and the grey background for the formal experiment. EOP, emergency operation procedure; SD, standard deviation; t, t-statistic from Student’s t-test; LF/HF, parasympathetic/sympathetic ratio; HRV, heart rate variability; TP, total power; R-R std, standard deviation of R-R interval.

FIGURE 1. Mental workload required for each step measured in relation to the step’s complexity scores. Mental work- load measured using the GOMS KLM method. Blink rate, pupil size, and blink duration were measured as well as opera-
tion time and error rate of each step. All measures are shown in standardized val-
ues. 1 refers to low-complexity steps and H refers to the high-complexity steps.

Integrated mental workload index

No single physiological measure correlates well with the NASA-TLX scores. This indicates that single physiological measures may not provide adequate information to assess the overall mental workload perceived by participants in a complex task such as an EOP. To predict the overall perceived mental workload, we used the so-called group method of data handling (GMDH) to integrate the six physiological measures, namely pupil size (x₁), pupil rate (x₂), blink duration (x₃), LF/HF (x₄), R-R std (x₅), and TP (x₆), into a synthesized index to predict the overall mental workload measured by NASA-TLX (Y). The data of the first 16 participants were used to construct the model using GMDH Shell software. The results indicated that all physiological indices were significant predictors and the model is expressed by the formula below (11). The constructed model can explain 76.8% of the variance in NASA-TLX.

Y = 20.06 - 1.176x₁ - 5.732x₂ + 0.860x₃ + 7.275x₄ - 5.766x₅ + 4.617x₆ - 3.043x₁ - 2.935x₂ + 2.312x₃ + 3.346x₄ + 1.812x₅ + 0.7055x₆ + 3.624x₁ + 0.5816x₂

The predictive ability of the model was validated using the data from participants 17 and 18. The results indicated that the model provides a valid and accurate prediction of the overall mental workload measured (17).

Summary

We determined that individual physiological measures, such as blink rate and blink duration, can serve as a way to evaluate each step’s workload and to identify when the peak of the workload occurs in EOP studies. Moreover, we found that a...
TABLE 3. Correlation between workload measures and performance measures for each step.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Period</th>
<th>Mean</th>
<th>SD</th>
<th>t</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pupil size (average change)</td>
<td>(t1-15s, t1)</td>
<td>-0.045</td>
<td>0.17</td>
<td>0.59</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>(t1, t1+15s)</td>
<td>-0.010</td>
<td>0.17</td>
<td>0.69</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>(t1-15s, t2)</td>
<td>-0.015</td>
<td>0.17</td>
<td>0.66</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>(t1, t2+15s)</td>
<td>-0.016</td>
<td>0.18</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>Blink rate (times/second)</td>
<td>(t1-15s, t1)</td>
<td>0.23</td>
<td>0.14</td>
<td>3.45</td>
<td>0.003*</td>
</tr>
<tr>
<td></td>
<td>(t1, t1+15s)</td>
<td>0.15</td>
<td>0.16</td>
<td>3.45</td>
<td>0.003*</td>
</tr>
<tr>
<td></td>
<td>(t1-15s, t2)</td>
<td>0.18</td>
<td>0.16</td>
<td>3.45</td>
<td>0.003*</td>
</tr>
<tr>
<td></td>
<td>(t1, t2+15s)</td>
<td>0.29</td>
<td>0.15</td>
<td>3.45</td>
<td>0.003*</td>
</tr>
<tr>
<td>Blink duration (second)</td>
<td>(t1-15s, t1)</td>
<td>0.074</td>
<td>0.050</td>
<td>0.64</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>(t1, t1+15s)</td>
<td>0.070</td>
<td>0.043</td>
<td>0.64</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>(t1-15s, t2)</td>
<td>0.096</td>
<td>0.059</td>
<td>0.64</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>(t1, t2+15s)</td>
<td>0.12</td>
<td>0.071</td>
<td>0.64</td>
<td>0.53</td>
</tr>
</tbody>
</table>

*significantly different (P<0.05), r, correlation coefficient can explain 76.8% of the variance in NASA-TLX.
FIGURE 2. Mobile EEG sensors. Real-time EEG data fed from the mobile sensors (right) can be seen on a nearby monitor (left).

TABLE 1. Recognition rate (%) of three complex mental tasks.

<table>
<thead>
<tr>
<th>Subject number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-CSP</td>
<td>70.82</td>
<td>81.79</td>
<td>63.14</td>
<td>64.28</td>
<td>67.85</td>
<td>74.11</td>
<td>71.61</td>
<td>68.93</td>
<td>71.96</td>
<td>66.25</td>
<td>70.07</td>
</tr>
<tr>
<td>Multi-GE CSP</td>
<td>70.00</td>
<td>80.54</td>
<td>63.14</td>
<td>62.32</td>
<td>65.00</td>
<td>73.75</td>
<td>73.39</td>
<td>66.07</td>
<td>72.50</td>
<td>65.54</td>
<td>68.73</td>
</tr>
<tr>
<td>Multi-TR CSP</td>
<td>73.67</td>
<td>84.11</td>
<td>62.07</td>
<td>64.64</td>
<td>66.07</td>
<td>75.00</td>
<td>75.00</td>
<td>68.75</td>
<td>71.07</td>
<td>63.93</td>
<td>79.43</td>
</tr>
</tbody>
</table>

TABLE 2. Recognition rate (%) of seven mental tasks.

<table>
<thead>
<tr>
<th>Subject number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band-pass filter</td>
<td>83.63</td>
<td>71.06</td>
<td>61.09</td>
<td>75.23</td>
<td>79.58</td>
<td>71.36</td>
<td>76.59</td>
<td>78.91</td>
<td>61.09</td>
<td>78.56</td>
<td>73.71</td>
</tr>
<tr>
<td>EMD</td>
<td>87.69</td>
<td>73.24</td>
<td>65.72</td>
<td>81.2</td>
<td>84.77</td>
<td>78.64</td>
<td>81.33</td>
<td>84.40</td>
<td>69.39</td>
<td>84.56</td>
<td>79.09</td>
</tr>
</tbody>
</table>

Evaluation of EEG oscillation patterns during simple and compound limb motor imagery

Hongzhi Qi1, WeiBo Yi1, Xin Zhao2, ChunHui Wang2, XueJuan Jiao2, ShuangGuang Chen2, and Dong Ming3

SUMMARIZE

The feasibility of recognizing complex limb imagery using appropriate techniques was first tested on three forms of complex MI tasks (standing up from seated position, left-foot combined with homologous hand movement, and right-foot combined with homologous hand movement). The experiments were divided into three sections, consisting of 30 trials each (10 trials for each complex MI task). The EEG signals were then processed using band-pass filter and empirical mode decomposition (EMD) to recognize these three forms of complex limb imagery. The percentage recognition rate was computed by averaging all results from each of the testing sets using a tenfold cross-validation strategy. As shown in Table 1, the highest recognition rate is 87.69% and the mean is close to 80%.

To further extend the experimental design, we added additional tasks: simple limb MI (left hand, right hand, feet), compound limb MI (both hands, left hand combined with right foot, right hand combined with left foot) and compound limb MI (both hands, left hand combined with right foot, right hand combined with left foot). The experiments were divided into nine sections, involving eight sections consisting of 60 trials each for six MI tasks (10 trials for each task) and one section consisting of 60 trials for the resting state. The percentage recognition rate was obtained using the same strategy as above. Table 2 shows the recognition rate of these seven mental tasks using three algorithms modified from the mathematical concept known as common spatial pattern (CSP), namely multi-class CSP (multi-CSP), multi-class CSP based on generalized eigenmode (mgCSP) and multi-class-stationary Tikhonov regularized CSP (multi-TRCSP).

It can be seen that the highest recognition rate is over 84% and the mean is ~70%. These results lay the foundation for designing a multi-modal BCI system that can provide an accurate classification of EEG signals during a compound limb MI task.
a better BCI system with the application of compound limb MI in the future. Simple limb MI can induce event-related desynchronization (ERD), namely amplitude suppression of EEG within two frequency ranges (8–13 Hz and 14–30 Hz) over sensorimotor areas. However, compared with simple limb MI, the induced ERD has broader frequency bands during MI of left/right hand combined with contralateral foot. On the other hand, larger cortical areas are activated by compound limb MI. As presented in Figure 1, imagining simultaneously using both hands results in equal activation of bilateral hand areas. In addition, imagining simultaneously using upper limb and contralateral lower limb contributes to the activation of an increased number of cortical areas, including all sensorimotor areas, the frontal cortex, and the posterior parietal cortex.

**Critiques**

The frequency bands of ERD with hand imagery are not exactly the same as that with foot imagery. Therefore, imagining simultaneously using different limbs could elicit different frequency ranges, which may result in ERD with broader frequency bands in the amplitude component of the power spectrum of the EEG, and a high PSE entropy (PSE) as a parameter to characterize the frequency band different frequency bands, which may result in ERD with contralateral foot. From these results, compound limb MI appears to be distinctly different in both frequency and spatial domains compared with simple limb MI. Such a difference can be detected using our proposed algorithms and can be applied as a means to discriminate between different kinds of imagined movements.

**Conclusion**

The work reviewed here strongly suggests that compound limb motor imagery can be applied to build a multimodal MI-based BCI system. Moreover, in terms of different purposes and situations, different types of compound limb motor imagery can be designed and employed in order to complete complex tasks in space.

**References**


**Acknowledgments**

Research discussed in this paper was supported by the National Natural Science Foundation of China (61222021, 6172008, 6171423, 30970875, and 90920105), the National Key Technology Research and Development Program of the Ministry of Science and Technology of China (2012BAI34402), and the Program for New Century Excellent Talents in University of the Ministry of Education of China (NCET-10-0818).

**FIGURE 1.** The topographical distribution of six mental tasks. Red areas indicate the activated areas during six types of MI: left hand, right hand, feet, both hands, left hand combined with right foot, right hand combined with left foot are represented by LH, RH, F, BH, LH&RF, RH&LF, respectively.
Advantages in modeling complex cognitive processes. QN’s queuing mechanisms provide natural multitask coordination methods at the local server level without the need for task-specific execution rules or utilization provides an index for mental workload. On the other hand, ACT-R’s advantages are the symbolic knowledge representations (declarative knowledge and procedural knowledge) and sub-symbolic computations that allow the modeling of complex cognitive processes such as memory retrieval, decision making, and sentence comprehension (5). Here, symbolic knowledge refers to a cognitive architecture’s information stored in the form of symbols (such as the fact that the sum of three and four is seven), and sub-symbolic computer science confirms that the details of symbol processing (such as the algorithms determining reaction time and correct rate values). Integrating the two complementary architectures gives QN-ACTR the upper hand in modeling human performance in space operations, which often contain multitask and complex cognitive processes. Previous studies using QN-ACTR have modeled human performance in space tasks in a wide range of different complex multitask scenarios, including movement of vehicle lane position and speech comprehension dual-tasks, transcription typing with reading comprehension and dual-task components, and diagnostic decision making with concurrent memorization tasks. These examples have demonstrated the modeling capabilities and the types of multitask scenarios that previous methods have had difficulties modeling.

The component task knowledge and multitask scheduling methods obtained from the previous studies can serve as a knowledge base and guide HPM of space operations that share similar fundamental cognitive task components and multitask demands. In addition, the visualization capabilities of QN-ACTR allow intuitive analyses of human mental processing and human-computer interactions, as modellers can see how a model’s mental modules, such as what the model’s eyes and hands interact with the display-control interface (6). In an on-going study whose purpose was to develop and test an AC-RT model of a MCC task, human experimental data were collected from manual RVD simulation experiments. The operator was asked to control a chase vehicle using two joysticks with six degrees of freedom and dock the chase vehicle with a target vehicle. Based on the empirical results and task cognitive analyses, a manual RVD model was proposed with production rules (i.e., procedural knowledge) that could be grouped into three major phases to complete the task.

The first model visually attended the scene to perceive the target and chase vehicle. Second, the model decided to focus on one of the six degrees of freedom. In the third phase, the model issued maneuvers along the focused dimension or along one of two orthogonal directions for orthogonal deviation between the two space vehicles. The model then returned to the first phase to start the next cycle, repeating until the docking was complete. Under this general framework, many modeling details need to be tested in order to determine if they fit with the human results. For instance, how long does it take to perceive the visual information? How large is the perceptual error? How does an operator decide which dimension to focus on first? When does an operator stop focusing on one dimension and move to the next? In addition, although most of the human subjects focused on one dimension at a time, there were cases in which they issued multiple maneuvers simultaneously in multiple dimensions, a situation not covered by the model. It seems that there are more questions than answers for now, but we believe that these questions will guide future experimental and modeling work. Multidimensional freedom of movement in space makes the modeling of spacevehicle control much more difficult than modeling, for instance, driving a car. Currently, the model can compute docking tasks with only one or two dimensions containing translational or rotational differences. The model fitness therefore still needs improvement, especially when maneuvers are required in multiple translational and rotational dimensions.

Our work modeling manual RVD tasks has generated insights regarding the fundamental procedural knowledge required for task performance in future space studies in a wide range of more complex scenarios, such as the addition of concurrent verbal communication. Since the QN-ACTR architecture is a general framework for human performance, including multitask performance, a multitask model may be created from the combination of each individual task component model. In addition, the QN-ACTR cognitive architecture provides a platform to examine the effects of many cognitive factors such as mental workload and fatigue on human space operation performance, utilizing previous modeling methods from the literature on both QN and ACT-R.

In summary, the QN-ACTR modeling approach emphasizes integration and quantification. The model building process may be helpful to human factors researchers in identifying mental capabilities and knowledge required for human operators to complete complex tasks in space. The QN-ACTR model could serve as predictive as well as interface evaluation tools for human performance engineering applications in space. We also plan to apply the computational modeling methods developed to human space operation tasks in the future.

References

Acknowledgments
This research was supported by the National Basic Research Program of China (2011CB711000).
Using the HBM, we explored how performance is affected by various cognitive factors. The cognitive parameters for the RVD task could be easily changed, and we could therefore quickly generate the corresponding performance. The major cognitive modules we drew from our study were: (1) The most significant factor causing task failure was excessive and imprecise operation of the controlling joysticks when trying to adjust for distance deviations in attitude of the chase craft, leaving little time to correct the error. (2) The operators’ control performance was mainly determined by their perception accuracy and control accuracy. Perception accuracy refers to the accurate sense of translational and rotational motion speed. Control accuracy refers to accurate manipulation of the joystick. The chase craft’s forward speed was determined mainly by the task requirement, safety, and the precision of the translational and rotational acceleration; (3) Selection of which degrees of freedom (three translational dimensions and three rotational dimensions) needed to be adjusted first was an important factor in RVD task performance. For example, selecting the dimension to adjust that had the largest discrepancy between current and target values would produce a very different performance results compared to simply selecting a single translation or rotation dimension, it is necessary to get a better understanding of astronauts’ capabilities during long-term space flights. Being able to predict an astronaut’s limitations is important for planning whether tasks are reasonable and can be successfully completed during a mission. Computer models can be used to learn from and even predict human performance, eventually replacing humans in simulations. The most accurate models can be programmed to model human interaction with complex systems to achieve human-out-of-the-loop (HOOTL) simulations. HOOTL describes a computer-based process in which computer models of human performance are used to simulate a human agent interacting with the computer-generated representation of the human’s operating environment. Such computer modeling can be used to replace human-in-the-loop (HITL) simulations, another research method to study human performance with complex systems in which human participation is still required. The costs of HOOTL simulations are greatly reduced compared with HITL since no experimenters, subjects, or essentially any testing time is needed. In addition, such computer modeling can be used to evaluate system designs at early stages of development.

To support studies of astronauts’ physical and mental capacity during space flight, we established the Astronaut Modeling and Simulation System (AMSS), an integrated simulation platform for modeling human capabilities and analyzing performance. The AMSS provides an experimental test bed for studying an astronaut’s ability to perform specific operations during long-term space flight.

### The Integrated Simulation Platform

Astronaut performance simulations: An integrated modeling and simulation platform

Shangquan Chen, Yuqiu Liu, Chunhui Wang, Bohu Zhou

**Abstract**

As an astronaut’s ability to successfully complete specific tasks during missions is of crucial importance for space flight. As China moves toward the construction of its own space station, it is necessary to determine the knowledge required to complete an RVD task in space and mission planning. Computer models can be used to learn from and even predict human performance, eventually replacing humans in simulations. The most accurate models can be programmed to model human interaction with complex systems to achieve human-out-of-the-loop (HOOTL) simulations. HOOTL describes a computer-based process in which computer models of human performance are used to simulate a human agent interacting with the computer-generated representation of the human’s operating environment. Such computer modeling can be used to replace human-in-the-loop (HITL) simulations, another research method to study human performance with complex systems in which human participation is still required. The costs of HOOTL simulations are greatly reduced compared with HITL since no experimenters, subjects, or essentially any testing time is needed. In addition, such computer modeling can be used to evaluate system designs at early stages of development.

To support studies of astronauts’ physical and mental capacity during space flight, we established the Astronaut Modeling and Simulation System (AMSS), an integrated simulation platform for modeling human capabilities and analyzing performance. The AMSS provides an experimental test bed for studying an astronaut’s ability to perform specific operations during long-term space flight.

**Keywords**

- Human performance simulation
- Astronaut modeling
- Computer-based simulation
- Space station construction
- Task performance prediction

**References**


**Acknowledgments**

This research was supported by the National Basic Research Program of China (2011CB711000).

**Natural Key Laboratory of Human Factors Engineering, China Astronaut Research and Training Center, Beijing**

**Corresponding Author:** shangquan.chen@hrb.ac.cn (S.C) and chunhu@tju.edu.cn (Y.L.)

### Section Three

A simulation software called Micro Saint Sharp (http://www.microsaintsharp.com) that connects the HBM, the RVD simulator, and a UDP link. The simulator sends information to the HBM via a UDP link. This information can be interpreted by the QN-ACTR architecture within the HBM in order to determine the most appropriate speed during training. Testing different speeds using the model could allow for observation of performance results that may improve the understanding of the decision-making process. The model not only generated a prediction about performance, but also provided actual performance output. This can be used to provide task performance feedback, such as monitoring task completion time.

The present model still lacks some basic psychological capabilities and constraints on human cognition that are necessary to fully replicate the cognitive processes used by the human operator, solving memory retention and retrieval processes, visual encoding, motor programming, and execution. Bottom left is a visualization of the QN-ACTR architecture. Upper right shows the interface simulating a realistic environment for the RVD simulation. Bottom right shows the completion of the task.

To visualize the cognitive process, the QN-ACTR architecture was used to implement an HBM able to model complex cognitive behavior patterns to interpret human performance during a task. This computational architecture was built in discrete event simulation software called Micro Saint Sharp (Delphi (C, C# Sharp) development environment for network, communication, and database management (Figure 2)). The management and scheduling module associated with the user interface layer provides the main interface entering task-specific parameters and algorithm parameter configurations as well as selecting and calling down layer modules. The following modules are included in the functionality layer: the cognitive simulation module, the biomechanical simulation module, the human performance evaluation and analysis module, the three-dimensional (3-D) visualization module, and network communication module. The cognitive simulation module is responsible for simulating the human thought process and cognitive workflows, while the biomechanics simulation module performs biomechanical analysis of the operator completing specific tasks in space. Task performance prediction and analysis is carried out by the performance analysis module, and the 3-D visualization module provides task-specific images necessary to visualize task execution processes in real-time. The network communication module controls communication and data sharing among the multiple modules within the platform. Finally, the database module controls the extraction of data from simulations and performs data processing functions such as adding, modifying, deleting, querying, or browsing the data (1, 2).

### Simulating Cognition and Predicting Workload Capacity

Simulating cognition requires the use of basic cognitive modeling principles to build cognitive architectures. ACT-R (Adaptive Control of Thought-Rational) is a cognitive architecture that represents the human mind as a production rule system (3). It assumes two types of knowledge representations: declarative chunk-based representation and procedural rule-based representation. The declarative knowledge that a person might use when they solve a problem. Production rules represent procedural knowledge that contains the body of the function that is carried out when the body of the rule is executed. ACT-R has a sophisticated declarative memory-like system based on chunk activation. The activation of a chunk reflects its general usefulness across the past and all similar contexts, which controls the probability of it being retrieved and its speed of retrieval. The main advantage of ACT-R is that it can describe the higher cognitive processes involved in learning, memorization, decision making, and problem solving.

Wu and Liu from the University of Michigan developed a simulation model of a memory-based system for cognitive abilities for information processing, called a queuing network (QN). The QN cognitive architecture represents the human mind as a queuing network, which has its basis in neuroscience (4). The network nodes are defined as servers dealing with specific information entities, similar to major brain areas handling certain information processing functions. When servers in the network are similar to the neural pathways connecting different brain areas. ACT-R and QN are two complementary but different cognitive
FIGURE 2. A software block diagram of AMSS.
The 3-D visualization software for task processing was developed using an object-oriented graphics-rendering engine and was based on the manual RVD task conducted during the Tian-gong 1 and Shenzhou 9 space flights. For the visualization of RVD tasks, a 3-D model of an astronaut as well as the Tiangong 1 and Shenzhou 9 space crafts were established. The entire task process was displayed on the output from the cognitive simulation modules. The output from the motor module of QN-ACTR was synchronized with the astronaut hands and surrounding them. Our comparative analysis revealed that the VVM provided an overview of the scene, which facilitated the construction of a cognitive map of the environment. The AG aid provided a guidance interface to the users to see where the destination was and how to get there before navigation, but the users were at risk of forgetting what they had seen in the animation. With the HSC aid, the user needed to interpret the help information from the system and align the exocentric direction (north, south, east, west) with their own, egocentric mental map direction (forward, back, left, right). This integration process required a lot of cognitive resources, degrading the user’s performance. Therefore, our study revealed that by providing visual spatial information on multiple scales (both overview and detailed), the user could integrate the spatial information efficiently and thus improve their navigational performance (2).

In another study, we used a simulated driving task to test two other types of navigational aids: the simulated global positioning system (SGPS) and the dual-scale exploration aid (DSEA). The SGPS aid was similar to most commercial GPS systems which have single-scale visual information: a localized map with a highlighted, recommended route. The DSEA aid (DSEA) was constructed as a dual-scale model with two windows: the overview window that displayed an overview of the user’s position and destination, plus the detail window, similar to that in the SGPS, but without the recommended route. The DSEA user should therefore be able to explore the environment according to either the overview or the detailed information. The results suggested that in the situations that required quick, one-time access to the destination, using the SGPS aid was more helpful. In such situations, the users did not need to actively explore the space and construct a cognitive map, but rather they just needed to passively follow the instructions to arrive at the destination. Therefore, the user’s performance was improved by following the visualizations from SGPS. However, in situations that required repeated access and where memorizing the route’s overall structure was important for future access, DSEA was superior. Users had the freedom to analyze the route strategy, plan the detailed route, and execute the navigation task with the help of both detailed local route information and an overview of the route’s structure. These active explorations helped the user to construct a cognitive map of the environment, and facilitated his/her future access to the same destination (3).

Navigational aids for human exploration of deep space

In the last several decades, a great deal of interest in the research of deep-space exploration has been generated. Through the development of new space technologies, astronauts (or human-piloted rovers) may one day be able to explore the surface of distant planets. Earth-based mission control will be limited during deep-space explorations due to the communication delays caused by the distance between the Earth and the spacecraft (1). Astronauts could therefore have difficulty navigating remote surfaces due to the lack of input from control and of landmarks to reference in an unfamiliar environment. It would be necessary to provide navigational aids to the astronauts to improve their situational awareness during surface explorations. These aids would need to provide spatial information about the region and would serve to reduce both the stress and mental workload of navigation for the astronauts.

Our research team carried out a series of studies in virtual environments to compare the effectiveness of different types of navigational aids at improving situational awareness and spatial knowledge about the ground environment. Three different types of aids were compared: a human-system collaboration (HSC) aid, an animated guide (AG), and a view-in-view map (VVM) (2). For the HSC aid, the exocentric direction of the destination was calculated and provided to the user in realtime (for example, “now your destination is to the north”). The AG provided the user with a short animation video before they started toward their destination. The animation started with an aerial view of the starting point and then gradually descended to a street view as the navigator proceeded toward the destination. Before the animation started, the user could acquire an overview of the area and see the landmarks around the destination. The VVM provided an overview map displaying the position of the user relative to the destination throughout the navigation process. The user could acquire real-time spatial information from the overview map as well as getting the local details of the three-dimensional environment surrounding them. Our comparative analysis revealed that the VVM had significant advantage over the other two aids in terms of the success rate of reaching the destination and the overall navigation time (Figure 1). The VVM offered the user a special overview of the environment as well as detailed information of the real-time environment, which facilitated the construction of a cognitive map of the environment. The AG aid provided a guidance interface to the users to see where the destination was and how to get there before navigation, but the users were at risk of forgetting what they had seen in the animation. With the HSC aid, the user needed to interpret the help information from the system and align the exocentric direction (north, south, east, west) with their own, egocentric mental map direction (forward, back, left, right). This integration process required a lot of cognitive resources, degrading the user’s performance. Therefore, our study revealed that by providing visual spatial information on multiple scales (both overview and detailed), the user could integrate the spatial information efficiently and thus improve their navigational performance (2).

In all of these studies, we used a simulated driving task to test two other types of navigational aids: the simulated global positioning system (SGPS) and the dual-scale exploration aid (DSEA). The SGPS aid was similar to most commercial GPS systems which have single-scale visual information: a local detailed map with a highlighted, recommended route. The DSEA aid (DSEA) was constructed as a dual-scale model with two windows: the overview window that displayed an overview of the user’s position and destination, plus the detail window, similar to that in the SGPS, but without the recommended route. The DSEA aid provided a guidance interface to the users to see where the destination was and how to get there before navigation, but the users were at risk of forgetting what they had seen in the animation. With the HSC aid, the user needed to interpret the help information from the system and align the exocentric direction (north, south, east, west) with their own, egocentric mental map direction (forward, back, left, right). This integration process required a lot of cognitive resources, degrading the user’s performance. Therefore, our study revealed that by providing visual spatial information on multiple scales (both overview and detailed), the user could integrate the spatial information efficiently and thus improve their navigational performance (2).
In a follow-up experiment, we combined the features of the above DSEA with SGPS to form a dual-scale GPS (DGPS) information (user to memorize the information shown in the previous window between the two scales (temporally divided). Although few two separate windows simultaneously (as in DGPS, discussed above), the overview map window and a detail window. The overview map window provides the user's current location, the destination, and the recommended route for successfully finding their way. The detail window was the same as SGPS. Our comparative analysis revealed that users of DGPS needed less time to navigate to the destination, independent of whether the navigation task was easy or difficult (Table 1). Furthermore, DGPS gave the participants a clear description of the overall route in the space environment, but may be useful to investigate for further investigation must be conducted before the dual-scale navigational aid can be used for modeling astronaut operations and maintenance activities in the space station, and to evaluate astronaut operational performance in space (1-3). Based on skeletal- driven technology, a virtual astronaut model that meets the requirements on anthropometry, joint range, and floating was constructed. First, a figure mesh was built modeled on a real astronaut. It included the dimensions of the body, positions of joints, and the space suit. The figure was then combined with a skeleton model to create a model closely mirroring real human topology. Finally, the body size and joint range of the virtual astronaut were set according to anthropometry data. The virtual astronaut can be scaled to any specifications that are required for human simulation.

Virtual astronaut modeling

Virtual human simulation can be used for modeling astronaut operations and maintenance activities in the space, which can aid human factors research. The virtual astronaut, which accurately reflects anthropometry data and behavioral characteristics in microgravity, can also be used to analyze ergonomics design problems of the space station and to evaluate astronaut operational performance in space (1-3). Based on skeletal-driven technology, a virtual astronaut model that meets the requirements on anthropometry, joint range, and floating was constructed. First, a figure mesh was built modeled on a real astronaut. It included the dimensions of the body, positions of joints, and the space suit. The figure was then combined with a skeleton model to create a model closely mirroring real human topology. Finally, the body size and joint range of the virtual astronaut were set according to anthropometry data. The virtual astronaut can be scaled to any specifications that are required for human simulation.

Parameterized action simulation for virtual astronaut

Parameterized action simulation (used the Jack software package) of astronaut operations is usually very costly. A parameterized action simulation was therefore conducted to simulate the different motions and operational activities of an astronaut. Although an astronaut's operational and maintenance actions vary, they typically involve approaching an object and then operating that device. These actions were classified into two types, moving and operating, and covered 11 elementary motions. Each motion was defined by a set of parameters in the task simulation such as posture, hand shape, tool, and duration. Tasks could be combined as required to describe more complex actions (4). Functions describing parameterized actions were developed using the Jack software and displayed on a graphical user interface. The virtual astronaut was then programmed to simulate movement or operational activities using those parameterized action functions (5). Through this process, the simulation speed and efficiency of Jack was significantly improved.

Simulating space flight using the virtual astronaut

It is technically difficult to simulate an astronaut's actions in microgravity. An effective way to solve this problem is to establish a human kinematic model under weightless conditions, collect human motion data, and use this information to program a virtual human model. A method was applied to convert the Biowin hierarchical (BVH) data files containing joint motion capture data to a format compatible with the Jack software. First, the joint structure differed between the Jack skeleton and the BVH data; a simplified version of the skeleton was generated based on the BVH data. Next, a mapping matrix was created, allowing joint positions and angles to be mapped between the Jack skeleton and BVH data. Finally, since certain joints in the Jack software such as the elbow and knees had only one degree of freedom while BVH had three, the rotational data was distributed to other joints, such as the shoulder (6-8). Figure 1 shows an example in which the elbow joint was mapped. Using this method, the virtual astronaut built in Jack could be driven by motion capture data.

Simulation-based reach zone analysis

To facilitate the research of collision detection, a point-by-point scanning algorithm was used to generate the spatial surface of an average human's reach zone and visual field (9). Major degrees of freedom for human arms and the horizontal and vertical ranges for human eyes were used to set the initial scanning point motion. Then, each point's coordinates were determined at various sampling intervals. Afterwards, the reach zone and visual field were stored for further analysis. Using an algorithm, one could specifically optimize the degrees of freedom of a human's arm reach and vision, which could then be used to compute a variety of reach zones and visual fields, such as the maximum reach zone or comfortable reach zone, based on arbitrary joint ranges. An example of a real-world application of this information is the positioning of the handrails in a space station based on the position and movement of an astronaut (Figure 2).

Conclusions

We have studied the key issues of modeling and simulating astronaut motions and have successfully built a virtual astronaut simulation and analysis platform. Future work will attempt to more accurately simulate astronaut motion while freely floating in space and will apply this analysis to determine fatigue and safety during space operation.

References


Acknowledgments

This work was supported by the National Basic Research Program of China (2011CB710000), and the Advanced Space Medicos-Engineering Research Project of China (2011Y5005000).
Biomechanical modeling and dynamics simulation of an astronaut’s musculoskeletal system

Gang Tang1, Dongmei Wang2, Kai Xiao3, Chunhui Wang4, and Shangguan Chen1*

Biomechanical modeling and dynamics simulation of an astronaut’s musculoskeletal system

Biomechanical modeling and dynamics simulation of an astronaut’s musculoskeletal system is a field that aims to understand the mechanical behavior of the musculoskeletal system during spaceflight. This involves developing models that can predict muscle force and bone remodeling, and analyzing how these changes affect the performance of astronauts. The research described below was conducted to develop a comprehensive biomechanical model of the musculoskeletal system that can be used to predict changes in muscle force and bone remodeling during spaceflight.

The objective of the studies described below was to develop biometric and biomechanical models of the musculoskeletal system using kinematics and dynamics analysis theory, theoretical calculations of muscle force, and on bone remodeling theory. In this paper, a musculoskeletal biomechanical model and dynamics simulation of astronaut behavior during long-term spaceflight has remained elusive.

The objective of the studies described below was to develop a biomechanical and biomechanical model of an astronaut’s musculoskeletal system based on kinematics and dynamics analysis theory, theoretical calculations of muscle force, and on bone remodeling theory. In this paper, we discuss our progress in musculoskeletal biomechanical modeling and simulation software.

Developing simulation software

We are currently developing biomechanical simulation and analysis software using the C++ programming language and the biomechanical model described above. The software includes a kinematic analysis module, a kinetic analysis module, a muscle drive force prediction module, and a bone remodeling module. The four software modules form a comprehensive system that allows for parallel processing. Our software can be used to simulate various types of space missions, such as comparing the effects of different maneuvers on the body, postural analysis, and predicting the effects of different maneuvers on the body. The software can also be used to analyze tasks that require a high level of precision and accuracy, as well as record the state of an astronaut’s strength and endurance at a particular time.

Summary

Our musculoskeletal biomechanical model and dynamics simulation is great potential for enhancing space flight research, including for predicting musculoskeletal system performance, assessing risk, and developing optimal techniques to counteract the predicted effects of microgravity.

References


Acknowledgments

This work was supported by the National Basic Research Program of China (2011CB911000), the National Natural Science Foundation of China (31300783 and 41373574), and the Shanghai Maritime University Research Project (20130747), and the Shanghai Top Academic Discipline Project Management Science & Engineering.

SECTION THREE

Human Performance in Space: Advancing Astronautics Research in China

Biomechanical modeling and dynamics simulation of an astronaut’s musculoskeletal system

Gang Tang1, Dongmei Wang2, Kai Xiao3, Chunhui Wang4, and Shangguan Chen1*

 increase bone mineral density (BMD) and muscle atrophy is a common occurrence in astronauts returning from long-duration spaceflight. Additionally, muscle atrophy is a common occurrence in astronauts returning from long-duration spaceflight.

It is also noted that the astronauts were considered to be the major factor impacting the measured values. In our study, the heights of the astronauts remained unchanged. We also computed the joint coordinate system (JCS) coordinates of the MAPs for the bones and muscle fiber lengths and tendon lengths were calculated according to the relative location of the MAPs in the body. The features of the subject are then reproduced in the model (19).

The following studies were performed for each muscle: the RSA test was designed to estimate the RSA of the muscle for which ground motion data were available; the RSA test was performed with the subject in a standing position, and the positions of the anatomical landmarks were obtained using a motion capture system while the subject was moving. To reduce the chance of errors when determining the anatomical landmark


Acknowledgments

This work was supported by the National Basic Research Program of China (2011CB911000), the National Natural Science Foundation of China (31300783 and 41373574), the Doctoral Fund of the Ministry of Education of China (20110171110051), the Shanghai Maritime University Research Project (20130747), and the Shanghai Top Academic Discipline Project Management Science & Engineering.

References

Bone density adaptation during long-term space flight: Predictive models and numerical simulations

Zhouchui Le, Dongmei Wang*, Gang Tang†, Chunhui Wang‡, and Shanguang Chen*1

Bone density adaptation during long-term space flight: Predictive models and numerical simulations

B

Bone is a living tissue that is capable of modifying its structure in response to environmental changes, known as adaptive bone remodeling. For instance, during space flight, there’s a reduced load on astronauts’ bones due to weightlessness. This lessened load can shift the bone resorption/growth balance towards more resorption, resulting in bone loss. If researchers were able to accurately predict when bone remodeling will occur, measures could be developed to counteract these effects and retain bone mass, which is critical for crew members’ health and safety during and after exploratory missions (1). In order to explain how the mechanical environment influences bone remodeling and to be able to predict changes in bone density and structure, several different bone remodeling models have been proposed in the literature. Depending on the assumptions upon which they are based, these models can be classified into two main categories: phenomenological and mechanistic. Phenomenological models provide a quantitative description of the bone response under a given stimulus, whereas mechanistic models try to consider both biological and mechanical factors as well as including current knowledge about bone cell activity. Both of these models have specific advantages and limitations (2–6).

Phenomenological models of bone remodeling

Phenomenological models attempt to predict when bone remodeling will occur through the analysis of the direct relationship between a mechanical stimulus and a bone’s structure. In this model, however, biological processes underlying a bone’s remodeling are not considered. Several pioneering studies postulated that remodeling takes place to maintain a homeostatic equilibrium between a strain-induced stress state and the bone’s deformational parameters. Deviation in the mechanical state would stimulate local changes in bone density (2). The rate of this change for the apparent bone density at a particular location (dp/dt), with ρ and ρb as described above, can be described as an objective function that depends upon a particular stimulus at the location (x,y). This generic relationship can be specified using the following equation:

\[
\frac{dp}{dt} = B[S - k(1±\omega)] \quad 0 < p < p_b
\]

where B is the remodeling coefficient, S is the mechanical stimulus, k is the reference stress, or the dead zone size, and \(p_b\) is the maximum bone density. Whether bone formation or resorption occurs depends on the stimulus, S. If S is greater or less than the reference stimulus k by only a small amount, then bone remodeling will not occur, this is called the dead zone (u). This remodeling equation has been widely used for predicting adaptive bone changes after prosthetic implantation, and the results have been compared with the bone density estimates determined via computed tomography (8, 9). The results of these numerical simulations are strongly dependent upon a set of parameters that are based on remodeling equations, for which the values vary between individuals and are difficult to define precisely. Therefore, our group attempted to elucidate how the bone density distribution is affected by the different parameters that govern the remodeling process. As a preliminary step, we constructed a finite element (FE) mesh of a proximal femur and used the forces at different phases of the gait cycle as the load conditions to simulate the bone’s daily life. The results indicated that we could account for how the amount of gravitational force can affect bone remodeling. We then made several bone remodeling predictions using different sets of parameters, such as varying the FE mesh grid density, initial bone density, width of the dead zone, reference stimulus values, and remodeling coefficients. Finally, we compared the numerical predictions with existing in vivo data. The FE simulations led us to several conclusions. First, varying the parameters within physiological limits had very little qualitative impact on the bone density distribution in the intramedullary canal and Ward’s triangle, or on the typical cancellous (porous) density patterns in the femoral head, which are four markers of bone density changes. Second, the reference stimulus values of the physiological equilibrium state, which reflected normal physiological states, determined the density value of trabecular bone in the interior of the femur. Finally, the time-dependent remodeling coefficient depended on the rate of bone metabolism and had a strong influence on how quickly the iteration algorithm converged on a solution, which in turn determined the speed of the remodeling process. Based on a similar concept that bones maintain a state of equilibrium, several studies were conducted to investigate remodeling as a continuous process of simultaneous damage and healing. Prendergast and Huiskes proposed that any one remodeling stimulus cannot exclusively be attributed to either microdamage or strain, but rather that both operate together in a process that aims to both maintain mass and simultaneously avoid failure (10). Several groups have proposed models that simulate the bone remodeling process using strain-damage-coupled algorithms (11, 12). These models have been used to study different mechanoregulatory approaches based on different combinations of strain and damage stimuli for bone density regulation, and have successfully predicted some aspects of bone remodeling.

Mechanistic models of bone remodeling

Mechanistic models are more complex than phenomenological models since they try to elucidate the effect of the mechanical environment on the underlying biological mechanisms involved in bone remodeling. Researchers using these models are not only interested in predicting the long-term behavior of bones under loading, but also in predicting the rate of bone remodeling and the role that bone cells play at each stage of the adaptation process. There are two different cell types involved in the remodeling process: osteoclasts (which resorb bone) and osteoblasts (which deposit bone). The mechanistic model proposed by Hasewood et al. assumes that the bone remodeling process is carried out by groups of cells called basic multicellular units (BMUs) (13). Another proposal, developed by Hernandez et al., also takes into account the biological and metabolic factors that are directly related to BMU activity, including the mineralization period, focal bone balance, and activation frequency (14). However, these models have limiting assumptions, including the need for a hypothetical function relating the BMU activation frequency to disease and damage. The nature of the disease and damage that activates remodeling, and the mechanisms by which these effects are related, are still unknown. To determine the actual function, further research would need to be done. Moreover, although bone cells are generally considered to function as BMUs for bone remodeling, Dunlop et al. proposed that BMUs were not sufficient to explain the adaptation of the bone remodeling process to changing conditions (15). Therefore, they have suggested that bone resorption and deposition should be described as two separate stochastic processes, and the determinist view where a sequenced to occur in a completely predictable fashion must be replaced by probabilities of bone resorption and formation. The precise role of bone cells in bone remodeling is complex and requires further study.

Summary and perspectives

Because bone structures can functionally adapt to the influence and regulation of mechanical factors, such as an increasing or decreasing load, establishing a numerical model and quantitatively analyzing the bone remodeling process has significant clinical value. Mathematical models of bone remodeling are normally implemented using FE programs that enable numerical quantitation of various problems related to bone remodeling; however, most of these models have been based on phenomenological rather than mechanistic factors. Phenomenological models can be useful for predicting bone remodeling, information which can be used to improve implant designs or treat some patients, but mechanistic models are likely to reveal effects and relationships missed by phenomenological models. Mechanistic models can simulate time-dependent and more detailed effects, both of which are conducive to determining the turnover, loss, and adaptations that an astronaut’s bones undergo during long-term space flight.

References
16. J. W. C. Dunlop et al., Calcified Tissue Int. 85, 45 (2009).

Acknowledgments
This work was supported by the National Basic Research Program of China (2011CB711000), the National Natural Science foundation of all nations of China (39500122 and 31300383), and the Doctoral Fund of the Ministry of Education Jointly Funded Project (2012312110004).
Establishment of a 3P model for evaluating operation training efficacy in astronauts

Bin Wu,1,2*, Meng Wang,3 Pengjie Li,1 Yijing Zhang,1 Jing Zhao,2 Yue Wang,1 Min Liu,2 Yangjiai Bai,2 and Weifen Huang1

With the development of the Chinese manned space program, the types and complexity of operation tasks required of astronauts has increased significantly. To reduce the number of human errors and ensure the success of missions, it is essential that astronauts develop the best operational skills possible. Scientifically valid, ground-based training forms an important foundation for training program design, training efficiency development, and mission crew selection (1). Based on many years of training research and experience, we have established an integrated evaluation system and a model for effective astronaut operation training.

Basic principles and model development

Although the performance results for subjects undertaking experimental operation tasks are generally equivalent, some operators appear to exert more effort in gaining and applying the requisite skills than others, indicating differences in their skills and/or proficiencies. Differences in certain physiological, biochemical, psychological, and behavioral indexes may go some way to explaining this.

We have proposed three synthetic indexes (3P) to assess the effects of astronaut operation training protocols: the performance index, the physiological/biochemical index, and the psychological/behavioral index. The integrated evaluation, or 3P model, can be expressed as follows:

\[ \text{Performance index} = \alpha_1 \times \text{psychological/behavioral index} + \alpha_2 \times \text{physiological/biochemical index} + \alpha_3 \times \text{performance index} \]

where \( \alpha_1, \alpha_2, \alpha_3 \) are weights determined using survey questionnaires and expert evaluation.

Validation and application of the 3P model

In almost two decades of astronaut training in China, we have always emphasized the usage of performance indexes when evaluating the efficacy of operation training, utilizing a combination of qualitative and quantitative evaluation methods. We have successfully built a standardized assessment method for astronaut operation training that has been applied and tested through the training of astronauts involved in the Chinese manned space missions Shenzhou 5 through 10.

Recently we evaluated the assessment of mental workload and physiological indexes using a manual rendezvous and docking task. The results showed that: (1) differences in training significantly influenced the subjects’ heart rate, heart rate variability, eye movement indexes (blinking frequency, blink time, and size of pupils, among others), EEG readings (δ, θ, α2, β1, β2, and γ1 waves), and their subjective evaluation of mental demands; (2) mental demands could be quantitatively evaluated using physiological indexes, which were highly correlated to the results of subjective indexes (\( R = 0.785 \)); (3) an improvement in skill level significantly (\( P<0.01 \)) increased various mood indicators including activation, arousal level, and attentiveness, while also decreasing situational awareness rating technique (SART) scores that measure the impact of the complexity in a given situation (\( P<0.05 \)); (4) improvement in skill level led to an increase in the mean time of the operator’s visual focus and a decrease in the frequency of blinking, decreasing the size of the pupils, and the total width of saccade (\( P<0.01 \)); and, (5) there was a significant difference in the distribution of errors when comparing inexperienced and experienced operators at various task difficulty levels (\( P<0.01 \)).

We also carried out studies to assess the effect of operation training on spaceship panel tasks. By observing special simulation panels, the subjects performed a series of operations such as pushing buttons and switching valves on/off, based on fixed procedures in order to solve potential emergencies and faults (such as decreased oxygen pressure or atmosphere pressure). Seven evaluation indexes were selected and their weights determined using survey questionnaires and analyzed using a fuzzy analytical hierarchy process method. The evaluation model can be represented as follows:

\[ P = 0.1526V_s + 0.3558V_e + 0.1416V_{hr} + 0.0834V_s + 0.0625V_e + 0.0625V_{hr} \]

where \( V_s \) is the operation time, \( V_e \) is the number of errors, \( V_{hr} \) is the mean heart rate, \( V_{de} \) is the standard deviation of NN (beat-to-beat) intervals, \( V_s \) is the subjective workload, \( V_{hr} \) is the number of times that the manual was consulted, and \( V_{hr} \) is the number of times that the simulation was viewed.

It can be seen that the weights of the performance index, the physiological/biochemical index, and the psychological/behavioral index were 0.5084 (the coefficients sum of \( V_s \) and \( V_{de} \)), 0.2832 (the coefficients sum of \( V_e \) and \( V_{hr} \)), and 0.2064 (the coefficients sum of \( V_s \) and \( V_e \) and \( V_{hr} \)) respectively. These results were in good accordance with previously published work (unpublished observations).

In summary, we have proposed a 3P model to evaluate the effect of astronaut operation training on proficiency. It has been applied and verified in training programs for space vehicle emergencies, manual docking, and spaceships environment control system failure. We continue to accumulate additional data for this model on extravehicular activity, experimental skills in space, and other training programs. We hope to further validate and perfect this model in the future.

References

6. P. J. Li et al., Oral presentation at the 8th China Human Ergonomics Society Conference, Beijing, China, Nov 2012.

Acknowledgments

This work was supported by the Manned Spaceflight Program of China, the Advanced Space Medico-Engineering Research Project of China (2009YS411005 and 2014YS440001), and the National Natural Science Foundation of China (81372126 and 71001092).
Bioeconomy

SINOBIOWAY GROUP

Sinobioway Group is one of the three main corporations affiliated to Peking University. It is concerned with bio-industry development and the establishment of bio-economy systems. Sinobioway Group has invested in six key business areas: bio-medicine, bio-agriculture, bio-energy, bio-environment protection, bio-service, and bio-manufacturing. The corporation has accomplished significant achievements and has become the flagship of bio-industry in China. It is predicted to become one of the top competitors in the world.

Sinobioway constructed and implemented the world’s first bio-economic system, including industry, research, and finance systems. Furthermore, Sinobioway is making great efforts to achieve its goal of creating a leading enterprise, nurturing an excellent team, and initiating an industrial revolution. The dream is to become a flagship in the bio-economy era, and to contribute to the sustainable development of China, thus attaining the ‘Chinese dream’ of the great rejuvenation of the Chinese nation.

Sinobioway Bio-Medicine Group

Sinobioway Bio-medicine Co., Ltd, is the foundation company of the Sinobioway Group, and focuses on the development of vaccines, biotechno-
cal drugs, and traditional Chinese medicine. The mission of the company is to provide affordable drugs for all Chinese. Sinobioway has several bases around China. (These bases are subsidiary companies that engage in research, manufacturing, and marketing.)

- The Xiamen base focuses on the development of nerve growth factor products, cytokine drugs, and peptide drugs. It produced the first mouse-injected nerve growth factor, NOBEX, to be launched in the market.
- The Xi’an base was the first to be developed in China based on the research awarded the 1986 Medical or Physiology Nobel Prize. Sinobioway’s Xiamen PKU Biopark covering 190,000 square meters is currently under construction. It will be the world’s biggest nerve growth factor production base.
- The Jiangsu base produces mainly recombinant human insulin. The aim of the company is to produce 500 kg of insulin and 10 million vials of insulin formulations within 2 years, and to produce 60 million vials within 5 years. It will eventually produce the majority of the world’s lowest priced and best-quality recombinant human insulin.
- The Hebei base focuses on the development of monoclonal antibodies. The facility is currently under construction, and when completed will cover 266,668 square meters. It will manufacture biosimilars of the top 10 best-selling antibody drugs on the market. The first antibody drug will be produced in 2016; all 10 antibody drugs will be manufactured at the base by 2025.
- The Yantai base focuses on antibiotics and antiviral drug development. The base currently covers 76,000 square meters, with a footprint of 50,000 square meters. The facility is compliant with International GMP Standards. Its recombinant mAbs platform is on the market and holds the top position in the domestic interferon market.
- The vaccine base in Beijing engages in research and development, manufacturing, and marketing of human-use and veterinary vaccines. The base has successfully developed a Hepatitis A and B vaccine, the “inactivated SARS Vaccine,” and the first influenza A (H1N1) vaccine. Phase III clinical trials for SIV vaccine are now complete. A number of other treatment vaccines are in the pipeline.

The Origin of Bioeconomy in the World:

[Images of various facilities and research centers]
Sinobiway Bio-Energy Group has invested $500 million in the project to plant 300,000 acres of energy plants with a production capacity of 100,000 tons of biodiesel and 100,000 tons of methanol fuel. Annual sales are predicted to reach $10 billion within 3 years. Sinobiway Bio-Energy Group is also socially responsible, as it routinely increases farmers’ income, acts to improve environmental conditions, and works towards a low-carbon economy.

Sinobiway Bio-Agriculture Group was co-founded by Sinobiway Group, Peking University, the Institute of Genetics and Developmental Biology of CAS, the Institute of Biotechnology of CAAS, and the Beijing Academy of Agriculture and Forestry Sciences. With a focus on national development, market demand, and technology innovation, Sinobiway Bio-Agriculture Group has adopted an entrepreneurial operation model. It has successfully established both scientific research and management systems, and developed a platform for plant genetic research and crop improvement with international standards and competitiveness.

The group has become a fundamental base for biotechnology innovation and industries via its combined “industry, university, and research” approach. The company presently has four national level research centers.

Sinobiway Bio-Agriculture Group is currently implementing a “three-step strategy” from “big” seed industry to “big” agriculture, and “big” industry. It aims to provide solutions to the key industry problems facing China as it undergoes rapid urbanization, and contributes to the positive changes in rural areas.

**Development plan and strategy**

- **Big industry**: 1 Trillion
  - Three characteristics
    - New agricultural technology for all developments
    - Modern science and technology applied in agriculture
    - Integration of primary, secondary, and tertiary industries to create a new industry

- **Big agriculture**: 100 Billion
  - Agriculture
  - Forestry
  - Livestock
  - Fisheries
  - Traditional Chinese medicine

- **Big seed industry**: 10 Billion
  - The plant seed industry
  - Soybean, corn, sunflower, rape
  - Mung beans, vegetables
  - Animal husbandry industry
  - Wood-based industry

Based on a bio-economy system, Sinobiway aims to create a bio-agriculture flagship, and significantly contribute to China’s food security.
The National Key Laboratory of Human Factors Engineering (HFE) is one of the premier research divisions within the China Astronaut Research and Training Center. Committed to solving human-related problems in manned space systems and optimizing human performance in space flight, research at the HFE laboratory includes anthropometry, human-machine interactions, human reliability and error analysis, human-machine interface design for controlling manned space vehicles, human movement and cognitive behavior in space, human workload and performance evaluation, virtual astronaut modeling and simulation, and advanced technologies for spacesuit design and regenerative life support systems.

With the remarkable progress of China’s manned space programs over the past 20 years, many achievements both in theoretical innovations and technological breakthroughs have been made in the HFE laboratory. Some of the highlights are:

- Creation and development of man-machine-environment system engineering theory
- Establishment of human system integration requirements and standards for manned spacecraft
- Verification and evaluation of human-machine interfaces and the operational habitability inside the crew cabins of manned space vehicles
- Successful application in recent Chinese manned space missions of research into the factors affecting human performance in space
- Design and development of Chinese spacesuits including an extravehicular suit and regenerative life support systems for China’s space station program.