Review of NASA's Evidence Reports on Human Health Risks

2014 LETTER REPORT

Committee to Review NASA's Evidence Reports
on Human Health Risks

Board on Health Sciences Policy

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The serpent has been a symbol of long life, healing, and knowledge among almost all cultures and religions since the beginning of recorded history. The serpent adopted as a logotype by the Institute of Medicine is a relief carving from ancient Greece, now held by the Staatliche Museen in Berlin.

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"Knowing is not enough; we must apply.
Willing is not enough; we must do."
—Goethe

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COMMITTEE TO REVIEW NASA'S EVIDENCE REPORTS ON HUMAN HEALTH RISKS

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Although reviewers listed above have provided many constructive comments and suggestions, they did not see the final draft of the report before its release. The review of this report was overseen by **GLORIA LEON,** University of Minnesota, who served as the Coordinator and **MARCIA J. RIEKE,** University of Arizona, who served as the Monitor.

Appointed by the Institute of Medicine, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Board on Health Sciences Policy

December 30, 2014

Mark Shelhamer, Ph.D.
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Dear Dr. Shelhamer:

The Institute of Medicine (IOM), at the request of the National Aeronautics and Space Administration (NASA) and with guidance from the IOM's Standing Committee on Aerospace Medicine and the Medicine of Extreme Environments (CAMMEE), has established the Committee to Review NASA's Evidence Reports on Human Health Risks. This letter report is the second in a series of five reports, following the IOM's 2013 letter report (IOM, 2014).[1] The committee will provide an independent review of the more than 30 evidence reports that NASA has compiled on human health risks for long-duration and exploration spaceflights. This 2014 letter report builds on the work of the 2008 IOM report and examines seven evidence reports:

1. *Risk of Adverse Health Effects Due to Alterations in Host-Microorganism Interactions* (Chatterjee et al., 2012),
2. *Risk of Crew Adverse Health Event Due to Altered Immune Response* (Crucian et al., 2009),
3. *Risk of Inadequate Human-Computer Interaction* (Holden et al., 2013),

[1]The 2013 letter report discussed the risks from dynamic loads (Caldwell et al., 2012); unpredicted effects of medication (Wotring, 2011); and intracranial hypertension and visual alterations (Alexander et al., 2012).

4. *Risk of Inadequate Design of Human and Automation/Robotic Integration* (Marquez et al., 2013),
5. *Risk of Incompatible Vehicle/Habitat Design* (Whitmore et al., 2013),
6. *Risk of Inadequate Critical Task Design* (Sándor et al., 2013), and
7. *Risk of Performance Errors Due To Training Deficiencies* (Barshi, 2012).

COMMITTEE'S TASK AND OVERARCHING ISSUES

To review the seven NASA evidence reports, the IOM assembled a 12-member committee with expertise in aerospace medicine, occupational health, radiation medicine, human performance, systems engineering, human-computer interaction, internal medicine, physiology and cardiovascular health, immunology, behavioral health and sociology, task simulation and training, and biomedical informatics. Committee biographical sketches are included in Appendix B. The committee's task, detailed in Box 1, was to review each evidence report in response to nine specific questions. In summary, this report examines the quality of the evidence, analysis, and overall construction of each report; identifies existing gaps in report content; and, provides suggestions for additional sources of expert input. This report also builds on the 2008 IOM report *Review of NASA's Human Research Program Evidence Books: A Letter Report*, which assessed the process for developing NASA's evidence reports and provided an initial and brief review of NASA's original evidence report.[2]

The committee approached its task by analyzing each evidence report's overall quality, which included readability; internal consistency; the source and breadth of cited evidence; identification of existing knowledge and research gaps; authorship expertise; and, if applicable, response to recommendations from the 2008 IOM letter report previously described.

It is difficult to characterize and compare the quality of evidence cited in individual evidence reports. In the 2008 letter report, the IOM

[2]The original evidence book was "a collection of evidence reports created from the information presented verbally and discussed within the NASA HRP [Human Research Program] in 2006" (NASA, 2013a).

BOX 1
Review of NASA's Evidence Reports on Human Health Risks
Statement of Task

NASA has requested a study from the Institute of Medicine (IOM) to provide an independent review of more than 30 evidence reports on human health risks for long-duration and exploration spaceflight. The evidence reports, which are publicly available, are categorized into five broad categories: (1) behavioral health and performance; (2) human health countermeasures (with a focus on bone metabolism and orthopedics, nutrition, immunology, and cardiac and pulmonary physiology); (3) radiation; (4) human factors issues; and (5) exploration medical capabilities. The reports are revised on an ongoing basis to incorporate new scientific information. In conducting this study, an IOM ad hoc committee will build on the 2008 IOM report *Review of NASA's Human Research Program Evidence Books*. That report provided an assessment of the process used for developing the evidence reports and provided an initial review of the evidence reports that had been completed at that time.

Each year, NASA staff will identify a set of evidence reports for committee review. Over the course of the study all evidence reports will be reviewed. The committee will hold an annual scientific workshop to receive input on the evidence reports it is reviewing that year and an update on the recent literature. The committee will issue an annual letter report that addresses the following questions relevant to each evidence report:

1. Does the evidence report provide sufficient evidence, as well as sufficient risk context, that the risk is of concern for long-term space missions?
2. Does the evidence report make the case for the research gaps presented?
3. Are there any additional gaps in knowledge or areas of fundamental research that should be considered to enhance the basic understanding of this specific risk?
4. Does the evidence report address relevant interactions among risks?
5. Is input from additional disciplines needed?
6. Is the breadth of the cited literature sufficient?
7. What is the overall readability and quality?
8. Is the expertise of the authors sufficient to fully cover the scope of the given risk?
9. Has the evidence report addressed previous recommendations made by the IOM in the 2008 letter report?

urged NASA to "require authors to use categories of evidence in future versions of the evidence books, while recognizing that experience with the explicit categorization of evidence may be refined over time, particularly regarding the categories used" (IOM, 2008, p. 12). Nevertheless, NASA still only encourages authors "to label evidence according to the 'NASA Categories of Evidence'" (NASA, 2013a).[3] Authors of NASA evidence reports should be encouraged to adhere to standard guidelines for systematic reviews (Huguet et al., 2013; IOM, 2011; Lefebvre et al., 2013; Wallace et al., 2013).

Furthermore, as noted in the 2013 IOM letter report, substantial variability exists in the formatting, internal consistency, and completeness of the references among individual evidence reports, making it difficult to compare cited evidence for related human health risks. For improved quality and consistency and to aid in future systematic assessments of NASA's evidence reports, the committee again encourages NASA to select a preferred citation format for all evidence reports and to require all writing teams to use that format.

In addition to analyzing the content of individual letter reports, the committee also gathered evidence from existing literature and relevant experts in the field. The committee held two conference call meetings and one in-person meeting, with the latter held in conjunction with a public workshop (see Appendix A). At the workshop, the committee invited individuals with expertise related to at least one of the seven evidence reports to analyze NASA's evidence reports and engage in discussions with the committee, focusing on the following questions:

- How well is the risk understood?
- What, if any, are the major sources of disagreement in the literature pertaining to this risk?
- What are the main gaps in knowledge or fundamental research about the risk?
- What is known about interactions between the risk and other risks identified in NASA's evidence reports?

This report follows the format of the 2013 IOM letter report, which includes the committee's responses to each of the questions listed in its

[3]NASA has identified three categories of evidence that could be included in each evidence report, including data from controlled experiments, observational studies, and expert opinion (NASA, 2013a).

statement of task for each of the seven evidence reports. Although no formal recommendations are included in this report, the committee's observations are intended to inform and improve NASA's ongoing efforts to update the content of individual evidence reports.

THE NASA HUMAN RESEARCH ROADMAP

The evidence reports reviewed in this IOM report are part of a larger roadmap process developed and under implementation by NASA's Human Research Program (HRP). The goals of the HRP are to "provide human health and performance countermeasures, knowledge, technologies, and tools to enable safe, reliable, and productive human space exploration" (NASA, 2014e). As outlined in Figure 1, the evidence reports are the first part of the roadmap, which is followed by clarifying the risks, specifying the research gaps to address those risks, implementing research tasks, and obtaining deliverables. These steps are then assessed to ascertain progress in preventing or mitigating the risk to astronaut health. NASA updates its progress on risk reduction for four design reference missions: (1) 12-month mission on the International Space Station (ISS); (2) lunar (outpost) mission; (3) deep space journey mission (e.g., near earth asteroid); and (4) planetary mission (e.g., Mars) by identifying the extent to which there is evidence that the plans for that mission will meet existing crew health standards or that countermeasures exist to control the risk (NASA, 2013c).

RISK OF ADVERSE HEALTH EFFECTS DUE TO ALTERATIONS IN HOST-MICROORGANISM INTERACTIONS

Astronauts who spend long periods of time in isolated, confined spaceflight environments with minimal clinical care capability are at increased risk from infectious disease (Guéguinou et al., 2009). The extreme environment of spaceflight presents multiple stressors that alone, or in combination, have the potential to alter the outcome of microbial responses and host-microorganism interactions that maintain the balance between cellular homeostasis and disease. This is an important consideration because members of the crew will interact with microbial flora

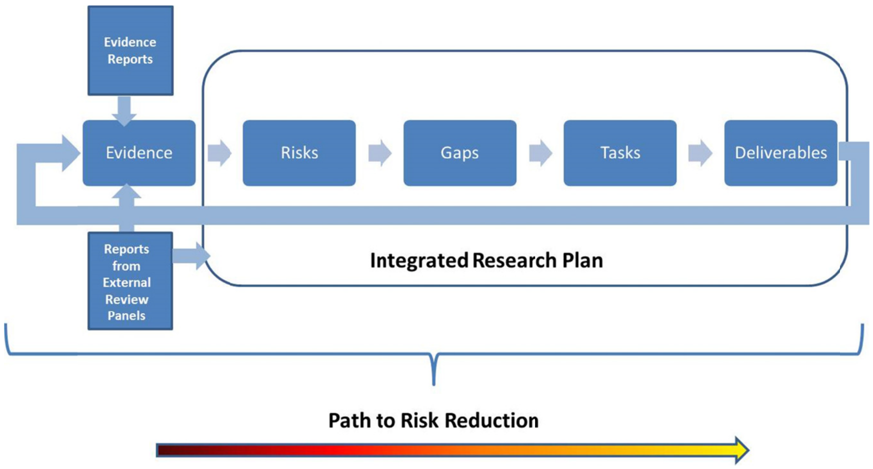

FIGURE 1 NASA's human research roadmap.
SOURCE: Adapted from NASA, 2014e.

(bacteria, viruses, fungi, etc.) from their own bodies, other crewmembers, their food, and the environment. Some of these interactions could compromise the health of the crew and threaten mission success. Despite pre-flight quarantines of crews to mitigate infectious disease risks, stringent microbial monitoring of food and crew environments, selection of healthy astronaut candidates, and use of clean rooms to prepare materials destined for delivery to astronauts, infectious diseases have occurred on numerous Shuttle and ISS missions (Guéguinou et al., 2009; Mermel, 2013).

Although spaceflight-associated alterations in the immune system have been reported for years in humans and animals, only recently has evidence emerged of spaceflight-induced changes in microbial responses pertinent to infectious disease, including alterations in virulence, stress resistance, antibiotic sensitivity, gene expression, metabolism, and host-microbe interactions (pathogens and commensals) (Cohrs, 2008; Crabbé et al., 2011, 2013; Foster et al., 2014; Guéguinou et al., 2009; Kim et al., 2013; McLean et al., 2001; Mehta and Pierson, 2007; Mehta et al., 2014; Nickerson et al., 2004; Ott et al., 2012; Pierson et al., 2005, 2007; Wilson et al., 2007, 2008). Little knowledge exists about the mechanisms underlying spaceflight-induced changes in microbial responses and host-microbe interactions. Because these changes may potentiate the infection process, knowledge about them is critical to accurately predict in-flight infectious disease risks for long duration missions. The evidence report, *Risk of Adverse Health Effects Due to Alterations in Host-Microorganism Interactions* (Chatterjee et al., 2012) (referenced in this report as the Host-Microorganism Report), characterizes these risks.

Does the Evidence Report Provide Sufficient Evidence, as Well as Sufficient Risk Context, That the Risk Is of Concern for Long-Term Space Missions?

The evidence report clearly describes the importance of the potential long-term impacts of spaceflight-induced microbial changes on astronaut health and performance. Because this is a newly identified risk, the committee understands that there is an insufficient mechanistic understanding of induced microbial responses (pathogen and commensal) during spaceflight and spaceflight analogs and of host-microorganism interactions that are relevant to infectious disease. The evidence report was written in 2012 and should be updated with recent findings from a broader collection of relevant spaceflight and spaceflight analog publications, many of which were published after the report was written and are referred to below in the section on additional literature.

Does the Evidence Report Make the Case for the Research Gaps Presented?

This evidence report generally identifies and provides good context and broad support for the research gaps presented and for the existence of high priority knowledge gaps. More research on the underlying mechanisms and the causality of the observed effects of spaceflight and spaceflight-analog culture on microbial responses and host-microorganism interactions on crew health is needed. The committee identified several additional gaps in the section below.

The committee noted that the knowledge gaps identified in this evidence report need to be updated to reflect the latest gaps (AEH 12-15) listed on the Human Research Roadmap summary website (see Box 2) (NASA, 2014f). These updated gaps, which are shown below, largely focus on the modeling of microbial risk and the evaluation of several key

BOX 2
Additional Research Gaps Identified in the Human Research Roadmap

AEH 12: Determine if spaceflight induces changes in diversity, concentration, and/or characteristics of medically significant microorganisms associated with the crew and environment aboard the International Space Station that could affect crew health.

AEH 13: Determine which medically significant microorganisms display changes in the dose-response profiles in response to the spaceflight environment that could affect crew health.

AEH 14: Determine how physical stimuli specific to the spaceflight environment, such as microgravity, induce unique changes in the dose-response profiles of expected medically significant microorganisms.

AEH 15: Current microbial standards identifying microbial risk limits need to be updated and microbial requirements need to be developed to include new technologies and future mission scenarios.

SOURCE: NASA, 2014f.

components of this risk, such as crew exposure, crew susceptibility, microbial concentration, and microbial characteristics (including genus-species identification).

For the individual research gaps identified in the Host-Microorganism Report, the committee has provided the following assessments.

AEH 7: What changes are occurring to microorganisms during human exploration of space that could affect crew health?

The committee agrees that this gap has clear operational relevance. Although distinct microbial responses relevant to infectious disease have been reported during spaceflight (and spaceflight analog culture in the Rotating Wall Vessel bioreactor), limited knowledge exists about the mechanisms initiating microbial responses. Likewise, inadequate data exist about operational experience with illness, which does not always comport with current evidence about microbial virulence, pathogenesis-related host responses, and the causality for infectious disease during spaceflight. As additional studies become available, the evidence report should incorporate new evidence about a mechanistic understanding of observed changes, which can be used to inform future experimental designs.

AEH 8: What changes are occurring to host susceptibility during human exploration of space that could affect crew health?

The committee agrees that inadequate data exist about the clinical relevance of observed spaceflight- and spaceflight-analog induced alterations in crew immunity, especially in the context of whether these alterations may contribute to the development of infectious disease in spaceflight. Limited reporting of infectious disease events, concerns about patient privacy, and a lack of access to crew health records present barriers to assess and correlate risks associated with human susceptibility to infectious disease during spaceflight. For example, there is no mandatory reporting of infectious diseases by the crew during spaceflight, which can result in underreporting of adverse events. More evidence on incidence of inflight infectious disease beyond postflight medical debriefs of adverse events is needed.

AEH 9: What changes are occurring to specific host-microorganism interactions during human exploration of space that could affect crew health?

The evidence report needs to reference mechanistic studies to address this area. For example, reported alterations in urine phosphate secretion in the crew are important (Whitson et al., 1997) given the association between phosphate levels and both alterations in microbial virulence during spaceflight and pathogenesis-related stress responses during spaceflight analog cultures (Castro et al., 2011; Crabbé et al., 2008, 2011, 2013; Foster et al., 2014; Kim et al., 2013; Nickerson et al., 2000; Ott et al., 2012; Wilson et al., 2002a,b, 2007). Collectively, evidence of spaceflight-induced alterations in microbial virulence, pathogenesis-related characteristics, evolutionarily-conserved spaceflight response mechanisms, potential microbiome shifts, and immune function suggest that spaceflight could have a negative impact on crew health (Crabbé et al., 2011, 2013; Crucian and Sams, 2009; Crucian et al., 2013, 2014a; Guéguinou et al., 2009; Ilyin, 2005;. Kim et al., 2013; Lapchine et al., 1986; McLean et al., 2001; Mehta et al., 2014; Mermel, 2013; Tixador et al., 1985; Wilson et al., 2007, 2008).

AEH 10: What changes are occurring to the efficiency of current countermeasures?

Previous reports of increased microbial resistance to antibiotics have been noted (Lapchine et al., 1986; Tixador et al., 1985), but the underlying mechanism(s) for this effect is unknown. Thus this is a fundamentally important research gap with clear operational relevance, as outlined in the evidence report. Since antibiotics are the major countermeasure against infectious diseases in flight, understanding the underlying causes of observed alterations in microbial resistance to antibiotics and other therapeutics or disinfectants during spaceflight is an important research gap. The impact of microbiota composition on antimicrobial efficacy deserves more attention in the evidence report.

AEH 14: Determine how physical stimuli specific to the spaceflight environment, such as microgravity, induce unique changes in the dose-response profiles of expected medically significant microorganisms.

Although long-term effects will be difficult to study, the committee feels that this gap should specify that both short and long-term effects of spaceflight on dose-response profiles of significant microorganisms will be studied.

Are There Any Additional Gaps in Knowledge or Areas of Fundamental Research That Should Be Considered to Enhance the Basic Understanding of This Specific Risk?

The gaps noted in the Host-Microorganism Report cover a wide range of topic areas. However, the committee identified additional significant research gaps that were not adequately addressed and remain to be explored.

The committee acknowledges that its focus is normally on evaluating research gaps related to identified health risks, rather than on research gaps related to the countermeasures applied to reduce those risks. However, for both changes in host immunity and changes in microbiota (bacteria, viruses, fungi, etc.), countermeasures induce perturbations whose effects on dynamic living systems are not sufficiently understood. Unlike countermeasures applied to well understood physical problems (e.g., *g* loads, atmospheric gases), the countermeasures applied to microorganisms and to humans may induce dynamic responses and pressures on microbial evolution that affect the long-term usefulness of those interventions. Research about the mechanisms underlying observed changes in microbial responses and host-microbe interactions and research about the impact of spaceflight on related mitigation strategies that deserve additional consideration include the following:

- *Impact of infection either prior to or during spaceflight*: All evidence of changes in virulence is from models infected post-flight (although the upcoming Micro-5 experiment on SpaceX-5 will address this gap in real time) (NASA, 2014m).
- *Microbial risk assessment and clinical relevance*: Development of quantitative and predictive models of risk assessment is important and is needed to supplement data from spaceflight and spaceflight analog biological experiments for cause and effect relationships. These data are essential to investigate the clinical significance of observed changes in microorganisms and host-microbe interactions.
- *Impact of mission design and length*: Improved understanding is needed regarding how mission design (including mission duration, food source, and life support systems) would influence the effects of the observed changes in microorganisms and their interactions with the host. Further evidence is needed on the effect of long-term spaceflight on heritable changes in microorganisms associated with virulence and pathogenesis-related characteristics and clinical relevance. Moreover, both short and long duration spaceflight and ground-based spaceflight analog studies are needed to understand both transient and heritable changes in microbes and host-microbial interactions, as well as microbial growth characteristics, and alterations in microbiome composition.
- *Evaluation of virulence changes*: Information on virulence changes in additional pathogens, alone or in the context of mixed microbial co-cultures, would greatly improve understanding of the impact of spaceflight on crew health risk.
- *Partial/fractional gravity studies*: Research on the effects of partial/fractional gravity (such as gravity encountered on the moon, Mars, and other planets) is needed to supplement microgravity studies and to improve understanding about how microorganisms are affected by gravity (or environmental conditions created by a

lack of gravity) (Hemmersbach and Häder, 1999; Hemmersbach et al., 2001).

- *Genotypic, molecular genetic, and phenotypic responses*: Further understanding of this risk will require a fuller characterization of the effects of spaceflight and spaceflight analog environments on genotypic, molecular genetic, and phenotypic responses of microbial pathogens and commensal microbiota. This includes use of omics-based approaches, such as genomics/epigenetics, transcriptomics, proteomics, and metabolomics. Evidence from omics studies that generate large data sets should be focused on hypothesis-driven goals that facilitate the practical interpretation and integration of these data into a comprehensive and mechanistic understanding of cellular/molecular responses.
- *Effect of changes in gene expression*: To fully understand the mechanisms associated with spaceflight (and analog-spaceflight) changes in microorganisms, studies are needed to investigate the effect of spaceflight-induced changes in gene expression on stress resistance (including antibiotics and disinfectants), metabolism, pathogenesis, and virulence characteristics (of human, animal, and plant pathogens and commensals).
- *Host tissue microenvironment*: More information is needed on how potential spaceflight alterations of the host tissue microenvironment could change host-microbe interactions and commensal composition and thus affect host immunity and infection potential.
- *Risk of infection by fungi or by reactivation of latent viruses*: These risks are underrepresented in this evidence report. Latent viral reactivation during spaceflight, including the clinically relevant Varicella-zoster virus, has been repeatedly documented, including one report of a crew member diagnosis prior to flight (Guéguinou et al., 2009; Mehta et al., 2014).
- *Effect of sex/gender on infectious disease risks*: Because males and females differ in the intensity, prevalence, and pathogenesis of microbial infections, further information is needed on the effect of sex/gender on infectious disease risk in flight. Sex hormones influence microbiota composition, microbial virulence, and immune responses.
- *Cellular, mucosal, and humoral immunity*: While ongoing experiments on the ISS are starting to address targeted aspects of research on cellular, mucosal, and humoral immunity, this is no

more than a foundation for all of the knowledge needed to understand this risk. Studies in this area, including studies on the role of microbiome composition on this immunity, are also encouraged.

- *Effect of physical and biological causative factors and their interconnections*: There is potential for both physical and biological stimuli to initiate spaceflight- (and analog-) induced responses in microorganisms and host-microbe interactions. A better mechanistic understanding of both physical (e.g., fluid shear, mass diffusion, aeration, radiation) and biological (cellular, molecular, and biochemical) causative factors of spaceflight-induced alterations in microbial responses and host-microbe interactions that could negatively affect or benefit crew health is recommended.

Furthermore, the evidence report needs to include evidence about issues regarding the standardization in experimental methods and tools (e.g., strains used, culture media, sample processing and handling, environmental conditions, time of culture in spaceflight, different organisms used, different hosts used for infection studies) in spaceflight and spaceflight analog studies so that accurate comparisons and reliable conclusions can be made.

Does the Evidence Report Address Relevant Interactions Among Risks?

This evidence report discusses health risks that have the potential to interact with risks discussed in a number of other evidence reports, including (1) *Risk of Crew Adverse Health Event Due to Altered Immune Response* (Crucian et al., 2009); (2) *Risk of Incompatible Vehicle/Habitat Design* (Whitmore et al., 2013); (3) *Risk of Radiation Carcinogenesis* (Cucinotta and Durante, 2009); and (4) *Risk of Therapeutic Failure Due to Ineffectiveness of Medication* (Wotring et al., 2011). While a clear link was made to the Altered Immune Response Report, links between these other reports were not immediately evident.

More attention should be paid to these interactions. For example, the microbial degradation and deterioration of spacecraft and spacecraft systems (including life support systems) is of concern, especially when coupled with the knowledge that spaceflight has been shown to profoundly alter microbial metabolism, antimicrobial resistance, and microbial community composition. Accordingly, the broader risk posed by microorganisms to crew health extends to the impact of microbes and interspecies microbial communication on the crew habitat/environment and spacecraft and systems integrity. Likewise, multiple reports have provided evidence for an association between altered intestinal microbiome composition and a wide range of diseases and disorders, including infectious disease, cancer, autoimmune diseases, inflammatory bowel disorders, diabetes, antisepsis, and asthma. Moreover, there is an obvious reciprocal relationship between the microbiota and medication, in which microbiota composition modifies the effects of medication and how medication affects microbiota.

What Is the Overall Readability and Quality?

Parts of this report were well written, but the writing is uneven and the consistency and organization could be improved. One way to improve the report's quality and ease of review would be to standardize the format of the evidence reports.

Is the Breadth of the Cited Literature Sufficient?

The evidence report presented peer-reviewed publications with references in a consistent format. However, some meeting abstracts and bulletins were also cited, and that information was not easily accessible. Findings from a wider breadth of relevant microbial spaceflight and spaceflight analog publications should be included in the next iteration of the evidence report, many of which were published after the report was written in 2012. The committee is pleased to see rapid literature growth on this topic since the time of the report. Examples of pertinent literature for inclusion in the report include Baatout et al., 2012; Cohrs et al., 2008; Crabbé et al., 2013; Crucian et al., 2008; Foster et al., 2013, 2014; Goncharova et al., 1981; Grant et al., 2014; Hemmersbach and Häder, 1999; Hemmersbach et al., 2001; Horneck et al., 2010; Kim et al., 2013; Kish et al., 2002; Mardanov et al., 2013; McLean et al., 2001; Mehta and Pierson, 2007; Mehta et al., 2014; Mermel, 2013; Ott et al., 2012; Pacello et al., 2012; Pierson et al., 2005, 2007; Taylor, 1974; Taylor et al., 1975; van Loon et al., 2003; Wilson et al., 2002a,b; and Yi et al., 2014.

Is the Expertise of the Authors Sufficient to Fully Cover the Scope of the Given Risk? Is Input from Additional Disciplines Needed?

As with a review of any broad scientific field, additional perspectives could strengthen this report, despite having been authored, in part, by a renowned expert in the field of spaceflight microbiology. These evidence reports deal with inherently complex systems, and, as such, these systems may be prone to develop "emergent properties" not predictable on the basis of knowledge of individual components, nor by analysis of known interactions. This is most evident with, but not limited to, the microbe-immune system (Milanesi et al., 2009). As such, application of expertise from complex systems science (e.g., Arima et al., 2012; Kalinich and Kasper, 2014; Lakin et al., 2007; Milanesi et al., 2009) might be valuable moving forward. This input may prove especially useful when considering the immunosuppressive effects from a systems approach.

NASA also might consult external multidisciplinary infectious disease experts with specific knowledge in immunology, virology, and medical microbiology (from the clinical and academic settings). This would also provide additional opportunity for synergy of, and interaction between, this evidence report and the Altered Immune Response report.

Has the Evidence Report Addressed Previous Recommendations Made by the IOM in the 2008 Letter Report?

This report was developed in response to the 2008 IOM letter report. Thus, there were no other specific IOM recommendations on this topic.

RISK OF CREW ADVERSE HEALTH EVENT DUE TO ALTERED IMMUNE RESPONSE

The immunosuppressive effects and altered immune responses (with some reported dysfunction) associated with spaceflight are well-documented and of concern, because of the potential increased risks for adverse crew health events, including infectious disease, autoimmune disease, and cancer due to weakened defenses (Guéguinou et al., 2009). The risk that altered immune response will have a negative effect on crew health is amplified with the increased duration of exploration class missions. During such missions, the crew will be exposed to a unique combination of stressors, including reduced gravity, radiation, altered microbial flora, altered nutrition, disrupted circadian rhythms, and isolation and confinement, all of which can affect immune function at the cellular, mucosal, and humoral levels, with downstream implications for disease events. Despite the pre-flight quarantines of crew members aimed at mitigating infectious disease risks, as well as a variety of other stringent microbial monitoring precautions, infectious diseases and other adverse health events (including allergic responses and hypersensitivities) have occurred on numerous Shuttle and ISS missions, and have impacted crew performance (Guéguinou et al., 2009). However, neither the mechanisms responsible for spaceflight-associated immune system alterations nor the relationship between these alterations and clinical disease are well understood. A better mechanistic understanding of the relationship between spaceflight, the immune system, and disease manifestation is needed, which should allow for the development and application of efficacious countermeasures to ensure crew health and mission success. The committee provides the following assessment of the NASA evidence report *Risk of Crew Adverse Health Event Due to Altered Immune Response* (Crucian et al., 2009) (referenced in this report as the "Altered Immune Response Report").

Does the Evidence Report Provide Sufficient Evidence, as Well as Sufficient Risk Context, That the Risk Is of Concern for Long-Term Space Missions?

This evidence report provides a substantial amount of compelling information supporting the potential for long-term negative impacts of spaceflight on immune status, along with the resulting implications for astronaut health and performance. This risk has clear operational relevance and, as discussed below, studies are needed to more fully understand the mechanisms underlying these changes and the relationship between altered immune regulation and clinical disease.

Does the Evidence Report Make the Case for the Research Gaps Presented?

The evidence report generally provides good context, overview, and depth of knowledge and presents data on observed alterations in spaceflight and spaceflight analog immune function that clearly support the need to understand the causal relationship to disease. However, this report is less than critical in its analysis of observed spaceflight and spaceflight analog findings. Furthermore, this is a quickly growing field of research and the next iteration of this evidence report should be updated to reflect the new research gaps (IM1-IM3 and IM6-IM8) identified on the Human Research Roadmap summary website (see Box 3; NASA, 2014g).

BOX 3
Additional Research Gaps Identified in the Human Research Roadmap

IM1: The extent to which spaceflight alters various aspects of human immunity during spaceflight missions up to 6 months.

IM2: It is necessary to define a flight standard related to spaceflight-associated immune system dysregulation.

IM3: Define and validate a terrestrial human analog for spaceflight-associated immune system dysregulation.

IM6: The cumulative effects of chronic immune dysfunction on missions greater than 6 months.

IM7: It is necessary to correlate the observed effects of spaceflight-associated immune system dysregulation with known terrestrial clinical conditions.

IM8: The influence, direct, or synergistic, on the immune system of other physiological changes associated with spaceflight.

SOURCE: NASA, 2014g.

The committee emphasizes the need to more fully consider the risks of long-duration spaceflights and to explore the evidence for changes in partial/fractional gravity environments. Current evidence is generally based on a relatively small number of observations, so conclusions from this evidence, including the impact of altered immune systems on NASA short-term missions, should be interpreted very conservatively until more spaceflight data are available. If such data are available, it would be helpful to have data on changes in environmental stress and the link between these changes and immune dysregulation, including data regarding the impact of recent additions to the ISS that might alleviate stress (such as advanced exercise equipment, Internet connectivity, and entertainment options). Furthermore, this report should more fully consider evidence from studies of ground-based analogs of immune dysregulation that simulate the environmental stress levels in space (e.g., the Antarctic winter-over and the Haughton-Mars Project at Devon Island). As noted in the discussion on the host-microbe interactions report, the evidence for this risk is incomplete without the data on the incidence of in-flight disease. A final note of clarification is that the term "microbiome" should be added to Figure 1 (p. 6).

Are There Any Additional Gaps in Knowledge or Areas of Fundamental Research That Should Be Considered to Enhance the Basic Understanding of This Specific Risk?

The committee emphasizes the need for further mechanistic understanding of the observed spaceflight and spaceflight-analog changes in immune function and their clinical relevance to crew health (infectious and non-infectious disease). Issues to be explored to further understand the evidence base of this risk include the impact of spaceflight on acute and chronic inflammatory responses and on antibody production; physical and biological stressors and their impact; and, the extent to which spaceflight-induced changes are a direct effect (gravity-sensing) or indirect effect (e.g., hydrostatic pressure, fluid shear). Statements made in the Immune Evidence Report indicating that immune cells are "gravity sensitive" should be considered for revision, since the statements suggest that there is a direct effect of gravity on cells, while it is possible that these responses may be due solely, or in part, to secondary/indirect effects of microgravity. In the absence of further information on the mechanisms (both in vivo and in vitro), it is difficult to develop mitigation strategies. Additional research gaps that deserve consideration include:

- *Sex/gender differences*: As males and females differ in the intensity, prevalence, and pathogenesis of both infectious diseases, and autoimmune diseases, further understanding of this risk will necessitate more information on sex/gender differences on innate mucosal and adaptive immune function.
- *Microbiome composition*: Given the association between microbiome composition and health status, investigations are needed to understand the impact of spaceflight on the crew microbiome and how that correlates with changes in immune status and disease risk. (An ongoing study to profile the crew intestinal microbiome is an example of the type of research that could serve as a foundation for future experiments [NASA, 2014n]).
- *Knockout immunodeficient models*: Studies using different vertebrate and invertebrate models of immune dysfunction can be useful in determining space radiation effects.
- *Viral reactivations*: Latent viral reactivations (e.g., Epstein-Barr virus and cytomegalovirus) during spaceflight (as measured by increased expression of viral DNA and proteins in crew bodily fluids) have been reported and more needs to be understood about the factors contributing to reactivation and infectious disease and cancer risk.
- *Cellular mechanotransduction studies*: Cellular mechanotransduction studies could provide information on the signaling pathways/events and the spatial localization of signals between cytoplasm and nucleus that may be driving spaceflight and spaceflight-analog responses in immune cells.
- *Wound healing*: Studies focused on the effect of immune dysregulation and microbiota composition in wound healing could be helpful in understanding the risks of crew injuries.
- *Impact of radiation*: The relationship between immunity and radiation and its effect on immune system function is key to further understanding this risk.
- *Tissue microenvironment*: Further information is needed on the effects of spaceflight on the tissue microenvironment and on how resulting changes could alter commensal microbiota composition and thus impact host immunity.

- *Risk assessment models*: It will be important to develop quantitative and predictive spaceflight and spaceflight-analog models of risk assessment to supplement the data obtained from biological experiments. The development of such models could include (1) accessing information from the longitudinal follow-up of astronaut health to monitor potential spaceflight-induced alterations in immune function and adverse health events that may take years to manifest (especially given the small sample size), and (2) understanding the impact of current preventative measures on risk for immune-related disease.

Does the Evidence Report Address Relevant Interactions Among Risks?

This evidence report has relevance to many of the other risks described in NASA's evidence reports, primarily the report on alterations in host-microorganism interactions (Chatterjee et al., 2012), but also reports on the risks regarding the design of the vehicle/habitat (Whitmore et al., 2013), radiation (Cucinotta and Durante, 2009; Cucinotta et al., 2009; Wu et al., 2009), on the effectiveness of medications (Wotring, 2011), on nutrition and the food system (Perchonok et al., 2012; Smith et al., 2009), on exposure to dust and volatiles (James and Kahn-Mayberry, 2009), on sleep loss and circadian desynchronization (Whitmore et al., 2009), on interactions with the central and peripheral nervous systems (Cucinotta et al., 2009), and on the limitations of in-flight medical capabilities (NASA, 2014a). While a clear link was made between this evidence report and the Alterations in Host-Microorganism Interactions report, links between other evidence reports were not immediately evident.

What Is the Overall Readability and Quality?

This evidence report is less than critical in its analysis of spaceflight and spaceflight-analog research findings. Although the report includes information on the negative impact of spaceflight on the functional responses of immune cells isolated from astronaut blood samples (including reduced levels of phagocytosis, antimicrobial oxidative burst, and response to lipopolysaccharides), the location of the evidence is somewhat inconsistent, as some of this information is in the text and some is in the appendix. Integration of the evidence into the context of the HRP gaps would enhance the next iteration of this report.

Is the Breadth of the Cited Literature Sufficient?

The report covers a wealth of information in a rapidly changing field and the next iteration of the evidence report will need to be updated with findings from numerous key publications, including evidence from spaceflight and spaceflight analog studies on the impact of these environments on neuroendocrine/hormone function and its relationship to immune status and infectious disease risk, and evidence on sex-based differences in immune responses and resistance to infection.

The literature presented in this evidence report cites peer-reviewed publications with references in a consistent format. Some meeting abstracts and bulletins were also cited, and that information was not always easily accessible. Key literature on the impact of spaceflight-induced alterations in crew immune function on the ISS has been published since the Immune Evidence Report was written. Examples of pertinent literature that could be added include Aviles et al., 2003a,b, 2004, 2005; Baatout et al., 2012; Belay et al., 2002; Crucian et al., 2014a,b; Kaur et al., 2008; Mermel, 2013; Milanesi et al., 2009; O'Donnell et al., 2009; and Yi et al., 2014.

Is the Expertise of the Authors Sufficient to Fully Cover the Scope of the Given Risk? Is Input from Additional Disciplines Needed?

The authors are highly regarded and are leading experts in spaceflight immunology and have assembled a credible report that provides a general overview of spaceflight and spaceflight analog research findings. It may be beneficial to include an infectious disease expert in subsequent versions of this evidence report to assist in the interpretation of findings on host-microbe interactions relevant to immune system function and to help align current evidence regarding spaceflight-induced alterations in microbial responses and immune function with disease causality. As noted in the section about the Host-Microorganism report, it may be useful to include a content expert in systems biology and/or complex systems science in future revisions.

As noted in the Host-Microorganism report, it may be prudent to also include external multidisciplinary infectious disease experts with specific knowledge in immunology, virology, and medical microbiology. This would provide additional opportunity for synergy of, and interaction between, this evidence report and the Host-Microorganism report, with the added benefit of better standardization of the format and content of these reports. Because of the extensive interaction between this report and the other disciplines discussed above in the section on interactions, it may also be prudent to solicit input from other discipline experts, as well.

Has the Evidence Report Addressed Previous Recommendations Made by the IOM in the 2008 Letter Report?

One of the recommendations made in the 2008 Letter Report was to carry out studies that would help explain the lack of correlation between observed changes in immune function and clinically evident disease in the crew. This remains a major gap in knowledge in the current evidence report.

RISK OF INADEQUATE DESIGN OF HUMAN AND AUTOMATION/ROBOTIC INTEGRATION

The committee examined the evidence report *Risk of Inadequate Design of Human and Automation/Robotic Integration* (Marquez et al., 2013) and provides the following review. In the evidence report, four contributing factors to the risk of human and automation/robotic integration HARI are examined: (1) the assignment of human and automation responses; (2) perceptions of equipment; (3) design for automation; and (4) human-robotic coordination.

The first of these contributing factors addresses task allocation among humans and their tools, focusing on levels of automation and appropriate task allocation among humans and automation. Considered within this factor is the process of analysis required to determine task allocation within a well-defined automation environment. This risk domain is well documented in the report. The second factor addresses the very important issue of human perceptions of equipment and particularly of automation. This factor considers human understanding of the capabilities and limitations of equipment, the impact this has on trust, and the risk created through incorrect calibration of trust.

Among other important issues, the third contributing factor for risk considers inherent transparency in the design of highly complex systems. Important to note is that complete system visibility for any reasonably complex system may not be practical, possible, or even very useful. This is likely to be increasingly so in highly capable future systems. This risk area was appropriately addressed through reference to analysis of accidents caused by confusion about operational modes in highly automated flight systems. The fourth contributing factor—human/robot coordination—is the least well understood, presents the most opportunities, and contributes substantial and little understood risk. NASA has employed robotics for some time and the risks are relatively well known for existing modes of employment, direct control (robotic arms), or open loop (robot executes predetermined instructions from the ground). An emerging mode of operation, human-automation collaboration, is probably necessary for successful long duration exploration. This human-automation collaboration will have significant impact on the better-understood yet still critical risk areas, particularly automation perception and trust (Hancock et al., 2013).

Does the Evidence Report Provide Sufficient Evidence, as Well as Sufficient Risk Context, That the Risk Is of Concern for Long-Term Space Missions?

The evidence report identifies and provides sufficient evidence for the relatively abstract risks cited, particularly for the three areas in which significant relevant experience is available. For the less well-defined risk involving the emerging issue of human-robot collaboration, the report correctly identifies the overall risk inherent in increasing reliance of human-robot collaboration. Given the rapid advances in this domain and the rapidly growing experience and literature base, future evidence reports will be able to more clearly define the specific risk issues. Particularly relevant for this purpose is recent ground robot research specifically addressing issues in collaboration between humans and robot systems (Ososky et al., 2013; Philips et al., 2011; Wiltshire et al., 2013).

Does the Evidence Report Make the Case for the Research Gaps Presented?

The evidence report makes the case, and correctly identifies the research gaps, for the four contributing factors that were discussed: assignment of human and automation resources, perceptions of equipment, design for automation, and human/robotic coordination. Given the rapid evolution of the field of robotics and automation and the significant time before NASA systems will be defined, it will be very important to take maximum advantage of non-NASA developments before committing limited resources that may be redundant. Because the gaps are necessarily high level at this stage of development of human-robot collaboration, this is not a limitation of the current evidence report and the issue has been appropriately recognized.

Unlike other evidence reports (such as the Altered Immune Response and Host Microorganism reports reviewed above), this report did not explicitly address the research gaps listed on NASA's Human Research Program's Roadmap website (see Box 4; NASA, 2014j). However, because most of the research gaps overlap with the topics discussed in the evidence report, the committee believes that these research gaps are adequately covered. Future iterations of this evidence report should more explicitly address the stated research gaps.

BOX 4
Additional Research Gaps Identified in the Human Research Roadmap: Human and Automation/Robotic Integration

- SHFE-HARI-01: We need to evaluate, develop, and validate methods and guidelines for identifying human-automation/robot task information needs, function allocation, and team composition for future long duration, long distance space missions.
- SHFE-HARI-02: We need to develop design guidelines for effective human-automation-robotic systems in operational environments that may include distributed, non-colocated adaptive mixed-agent teams with variable transmission latencies.
- SHFE-HARI-03: We do not know how to quantify overall human-automation-robotic system performance to inform and evaluate system designs to ensure safe and efficient space mission operations.
- SHFE-HARI-04: What are the effects of the delays typical of different mission regimes on teleoperations and how do we mitigate these effects?

- SHFE-HARI-05: We need to identify and scope the critical human-automation/robotic mission activities and tasks that are required for future long duration, long distance space missions.

SOURCE: NASA, 2014j.

Are There Any Additional Gaps in Knowledge or Areas of Fundamental Research That Should Be Considered to Enhance the Basic Understanding of This Specific Risk?

The automation discussion in the report assumes that tasks are largely separable and that the primary decision is how to allocate responsibility between humans and automation. This has been the historical approach and has been adequate for missions and automation tasks in the past. This report does not address functions that will require active collaboration and cooperation among automation, robots, and humans. For long duration space missions, greater flexibility in the distribution of responsibilities between humans and automation may be necessary, due to limits on the number of crewmembers and delays in communication with ground control personnel on Earth. The concept of active interaction and collaboration among humans, robots, and automation of all kinds should be addressed. Issues of human-automation communication, situational awareness, and trust are likely to engender additional HARI risk consideration.

Similarly, the report's discussion of situational awareness and automation transparency addresses some of the issues, but does not consider emerging automation that may have some level of capability that could be considered cognitive. These may mitigate some risks, while creating others. In particular the concept of social robots, naturalistic interaction with automation, and modeling human-comprehensible cognitive decision-making needs to be considered. These technologies are currently in early stages and represent a significant departure from traditional NASA approaches, but hold the promise of significantly increasing human-system performance.

Specifically, the role of levels of autonomy in influencing the nature of human-robot interaction must be examined in the context of long duration space missions. Beer and colleagues (2014) have investigated robot autonomy within the context of human-robot integration and propose a taxonomy for categorizing levels of robot autonomy and evaluating the effects of robot autonomy on human-robot integration, including variables such as acceptance, situational awareness, and reliability. With the increasing use of automation and robotics in manufacturing, the role of human-robot interaction and integration in manufacturing is being studied extensively; the findings from this domain will be valuable in the context of long duration space missions with high levels of stress and complexity of interactions. For instance, Hu and colleagues (2013) have investigated the importance of safety-based human-robot collaboration in the assembly of power protectors.

Does the Evidence Report Address Relevant Interactions Among Risks?

The evidence report explicitly identifies interactions between the risks it discusses and the risks covered in the evidence reports on human-computer interaction, critical task design, and training; it also explicitly discusses the need for examining these sets of risks in concert (Barshi, 2012; Holden et al., 2013; Sándor et al., 2013). There is significant overlap between this report and the report on human-computer interaction, but that overlap appears to be coordinated and managed well, at least for situations that come up at present. In discussing missions in the far future, it will likely be more difficult to justify, the distinction made between these two reports. Consideration should be given to how best to ultimately merge or manage the cross-cutting issues between these taxonomic divisions.

What Is the Overall Readability and Quality?

The readability of the report is good and the report appears to cover the important issues in identifying the risks with the exception of the areas previously noted.

Is the Breadth of the Cited Literature Sufficient?

The breadth of literature cited is quite thorough, especially for the more conventional aspects of HARI. The report quite correctly identified a number of issues associated with human robot teaming and human-automation collaboration; however, the report could benefit from citing more recent publications that address issues of shared mental models between robots and humans, trust and confidence, human perception of robot action, and human-robot teaming. Furthermore, the report needs to explore the challenges and research gaps that are being seen in automation and robotic integration in fields such as manufacturing, distribution, and vehicle and human factors design, etc. Examples of additional literature include Arif et al., 2014; Cabibihan et al., 2012; DeSteno et al., 2012; Fiore et al., 2013; Hancock et al., 2011a,b, 2013; Hu et al., 2013; Kahn et al., 2012; Lebiere et al., 2013; Lobato et al., 2013; Ososky et al., 2012, 2013; Phillips et al., 2011; Saulnier et al., 2011; Syrdal et al., 2010; Van Doesum et al., 2013; Vinciarelli et al., 2012; and Wiltshire and Fiore, 2014.

Much of the literature on robot teaming, social and cognitive robotics, and naturalistic interaction is recent and in journals that focus more on human factors than robotics (e.g., Cabibihan et al., 2012; Fiore et al., 2013; Lebiere et al., 2013; Leite et al., 2013; and Syrdal et al., 2010).

Is the Expertise of the Authors Sufficient to Fully Cover the Scope of the Given Risk? Is Input from Additional Disciplines Needed?

Author expertise is sufficient for the scope of the risks that were cited. Consideration should be given to adding some non-NASA authors involved in robotics research, in order to provide a broader perspective on expected HARI developments applicable to NASA. Not directly addressed is the issue of team performance, in particular human-automation collaboration that is likely to be required for missions traveling beyond the moon. The U.S. Army, in particular, has been actively exploring the concept of human-robot collaboration (Hill, 2014). A review of their efforts and of the composition of the research teams involved might be useful in considering possible additions to research team membership.

Has the Evidence Report Addressed Previous Recommendations Made by the IOM in the 2008 Letter Report?

The structure of the documents has changed significantly. In the 2008 report, the groupings of issues related to human factors were clustered in Chapter 23 of a single evidence book, *Lack of Human-Centered Design*, which addressed three risks related to human factors: inadequate information, poor human factor design, and poor task design. There were no previous recommendations relevant to the specific topics on HARI.

RISK OF INADEQUATE HUMAN-COMPUTER INTERACTION

Human-computer interaction (HCI) is at the core of a safe and successful space mission. The ultimate consequence of inadequate HCI could include the loss of one or more human lives on the mission. While the term "computer" in "human-computer interaction" is historical, it is appropriate to evaluate the risk in a broader context to also include human interaction with embedded systems thereby encompassing both classic "computing" devices and non-traditional and emerging technologies, devices, and interfaces such as joysticks, voice, and gesture associated with information processing on space missions. An embedded system is defined as a device with a microprocessor or microcontroller that by itself is not intended to be a general-purpose computer (Wolf, 2012). The committee examined the evidence report *Risk of Inadequate Human-Computer Interaction* (Holden et al., 2013) and provides its assessment below.

Does the Evidence Report Provide Sufficient Evidence, as Well as Sufficient Risk Context, That the Risk Is of Concern for Long-Term Space Missions?

The report presents the key characteristics of long-term space missions, including, among others, the absence of the safety net of ground control, the long duration of the missions, the varying levels of alertness of mission personnel, and limited resources, and it provides sufficient evidence for the risks that inadequate HCI poses to mission success when carried out under those unique and extreme conditions. The report also recognizes the key limitation that the evidence is drawn from "post-spaceflight crew comments, and from other safety-critical domains like ground-based power plants, and aviation" (Holden et al., 2013, p. 3). The closing sentence of the report succinctly captures how critical this risk is: "Without these improvements, errors due to inadequate HCI will continue to pose a risk to mission success" (Holden et al., 2013, p. 36).

Does the Evidence Report Make the Case for the Research Gaps Presented?

The report uses the framework of the eight core contributing factors associated with the risk of inadequate HCI (derived from the Human Factors Analysis and Classification System) and it makes an excellent case for the identified research gaps. It recognizes that future work "must focus on identifying the contributing risk factors, evaluating their contributions to the overall risk, and developing appropriate mitigations" (Holden et al., 2013, p. 3). Moreover, it identifies the importance of the rapid emergence of touch-based interfaces, which will pose additional risks in operations carried out under extreme conditions, especially when the users wear pressurized gloves during (extravehicular activity) and are also subjected to vibration. The evidence report recognizes how critical the risks associated with inadequate HCI are and also acknowledges the absence of a structured process associated with human-centered design.

The evidence report acknowledges the research gaps in the HRP Roadmap (see Box 5; NASA, 2014k), and the next iteration could explore those in greater depth.

BOX 5
Additional Research Gaps Identified in the Human Research Roadmap: Human-Computer Interaction

- SHFE-HCI-01: What are the effects of vibration and acceleration on crew task performance and how can those effects be mitigated?
- SHFE-HCI-02: We need to understand what aspects of cognitive function and fine motor skills change during long-duration missions and how these changes affect task performance.
- SHFE-HCI-03: We need HCI guidelines (e.g., display configuration, screen-navigation) to mitigate the performance decrements identified in SHFE-HCI-08 due to the spaceflight environment.
- SHFE-HCI-04: We need to understand how emerging multimodal and adaptive display and control technologies are best applied to the design of HCI for proposed long-duration DRM (Design Reference Missions) operations.
- SHFE-HCI-05: We need verifiable requirements that specify standard measurement techniques and metrics for evaluating the quality of user interfaces with specific attention to the usability and evolvability of an interface.
- SHFE-HCI-06: We need guidelines to ensure crewmembers receive all of the information required to accomplish necessary tasks in a timely fashion, even when operating autonomously.
- SHFE-HCI-07 (SM11): Can crewmember spatiomotor abilities be more accurately predicted and countermeasures and training techniques developed to mitigate spatial disorientation during spaceflight?
- SHFE-HCI-08: We need to define the acceptable level of risk for HCI performance relative to terrestrial baselines.

SOURCE: NASA, 2014k.

Are There Any Additional Gaps in Knowledge or Areas of Fundamental Research That Should Be Considered to Enhance the Basic Understanding of This Specific Risk?

While the evidence report draws upon findings and experiences in a wide array of related application domains, the risk of inadequate HCI can be better understood and mitigated by exploring research and lessons from emerging domains that involve human-device interactions that are comparable to those of space missions. Such interactions include high-stress environments in which the time for processing and responding to large amounts of information is very short, available solutions or feedback are limited, the risk of failure due to improper processing of information is high, and the trust that humans have in these devices is critical (Moreno et al., 2013; Xie et al., 2014). These include

- immersive environments such as those found in gaming (Lalor et al., 2005; Nahrstedt et al., 2011);
- augmented reality (Seo and Lee, 2013);
- firefighting (Rosengren et al., 2014);
- high-speed racing (Grand Prix, NASCAR) (Lee, 2004);
- war games (e.g., situational awareness-based effective responses) (Bainbridge, 2010);
- health care (e.g., checklists in surgery, organ transplants) (Gawande, 2013; Pronovost and Vohr, 2010);
- expedition-type work, e.g., NEEMO (NASA Extreme Environment Mission Operations) (NASA, 2014d), Antarctica expeditions; and
- long-duration submarine trips (Kimhi et al., 2011).

Touch-based interfaces are significantly transforming human-device interactions in everyday life so much so that a young child given a paper book is dismayed that the contents do not change when the page is "swiped." The impact of the rapid proliferation of touch-based interfaces on the cognitive perceptions and responses of mission personnel who have to simultaneously deal with physical/mechanical devices during the mission must be studied in order to mitigate the risks associated with dealing with different modes of human-device interaction. An example of such a study is the one being conducted by Honeywell for the Federal Aviation Administration that is investigating the efficiency of touchscreen devices vis-à-vis pilot workload, accuracy, and fatigue when operating in turbulent environments (Bellamy, 2013). Montuschi and colleagues (2014) discuss recent developments in human-computer interaction in the context of emerging natural user interfaces such as gesture, body poses, speech, and gaze.

Methodologically, the systems engineering concepts of failure-modes and effects analysis (McDermott et al., 2008) may provide answers for many of the critical questions (including the lack of standards for space missions) raised in the closing paragraph of the discussion on

"Contributing Factor 2, Informational Resources/Support" which address the critical issue of the numerous "unknown unknowns" associated with long-term space missions (Holden et al., 2013, p. 16).

Does the Evidence Report Address Relevant Interactions Among Risks?

The report makes an excellent case for a systems or integrated approach to addressing the interactions among the risks associated with HCI, HARI, critical task design, and training. It specifically recognizes the relative importance of efficiency, effectiveness and complexity associated with the various interactions.

What Is the Overall Readability and Quality?

The report is authored well from the points of view of readability and quality.

Is the Breadth of the Cited Literature Sufficient?

The breadth of the cited literature is sufficient from a classical HCI perspective. As noted above, the report could benefit from citing more recent research on HCI issues in the area of gaming (see, for example, Tedjokusumo et al., 2010) and other high-stress domains such as fire-fighting and car racing (e.g., Grand Prix, NASCAR), where the human-device interaction is critical to the successful execution of the task.

Is the Expertise of the Authors Sufficient to Fully Cover the Scope of the Given Risk? Is Input from Additional Disciplines Needed?

Yes. However, the authorship could be expanded to bring in the newer perspectives and understandings associated with emerging technologies in human-device interaction.

Has the Evidence Report Addressed Previous Recommendations Made by the IOM in the 2008 Letter Report?

Yes. The report uses the “quality-of-evidence” criteria specified in Recommendation No. 1 of the 2008 report (IOM, 2008, p. 11) in assessing the risk of inadequate HCI. It also recognizes the inadequacy of evidence at levels I and II. The report addresses the need to discuss the issue of “too much information” on performance (IOM, 2008, p. 83) by discussing the importance of information granularity in enhancing HCI. Further, the report addresses the cross-cutting issues of manual controls, displays, fatigue and spatial disorientation (see IOM, 2008, p. 82) in detail through the specific sections highlighting each of these issues using the framework of “core contributing factors” in the context of HCI.

RISK OF INCOMPATIBLE VEHICLE/HABITAT DESIGN

All human space travel necessarily involves a vehicle, and the interaction between the vehicle and the occupants (crew, researchers, or tourists) inevitably raises the possibility of incompatible vehicle/habitat designs. The full discussion of such interactions necessarily involves such topics as human-computer interaction, manual control, decision aids and on-board training, as well as ergometric issues such as fit and function. The evidence report *Risk of Incompatible Vehicle/Habitat Design* (Whitmore et al., 2013) covers a wide range of topics, and the authors were face with the challenge of deciding where to focus the discussion and how to integrate the discussion with the other evidence reports on human factors (Holden et al., 2013; Marquez et al., 2013), as well as other closely related evidence reports such as those on risk of injury from dynamic loads (Caldwell et al., 2012) and extra-vehicular activities (EVAs) (including suit systems) (Gernhardt et al., 2009). Issues discussed in this evidence report include: anthropometry, motor skills coordination, visual environments, vibration and G-forces, noise, seating, visibility, and vehicle volume and layout. Because this evidence report focuses on the habitat, it would have been helpful to point the reader to other NASA work and standards relevant to the space habitat and human health, such as the *Human Integration Design Handbook* (NASA, 2014b) and the NASA standards on human factors, habitability, and environmental health (NASA, 2011).

Does the Evidence Report Provide Sufficient Evidence, as Well as Sufficient Risk Context, That the Risk Is of Concern for Long-Term Space Missions?

This evidence report provides a number of descriptions of anecdotal reports and examples from experiences on the Shuttle, ISS, and Constellation programs. These examples provide the reader with the starting points for understanding the context, but more could be done to identify and analyze the key research gaps that are identified by those accounts. In several places, the report offers broad generalizations that could be followed up by specifics on the research gaps. An example is the discussion on repetitive stress/strain injuries on page 7, which could benefit from more specifics on what relevant research has been done in this area (including the substantial literature beyond space-specific research) and the specific gaps that remain to be filled. The committee recognizes that many areas of research are covered in this evidence report, and that priorities will need to be determined regarding where to focus efforts to identify research gaps.

Does the Evidence Report Make the Case for the Research Gaps Presented?

The report identifies a number of research gaps but, as noted above, the case would have been stronger if a deliberate effort had been made to tie each of the gaps to specific human health and safety risks. Updated versions of this report should explicitly include those listed in the Human Research Roadmap Summary (see Box 6; NASA, 2014h), under the "Gaps" section to enable more efficient cross checks across NASA documents.

While all the information presented made sense individually, it did not necessarily provide a comprehensive framework encompassing habitat design and habitability factors. Without such an overarching vantage point, the list of covered topics appears randomly selected and incomplete. A short paragraph at the beginning of the evidence report might be helpful to summarize how this report fits within the bigger picture of space habitat design concerns and to explain more clearly what is addressed and what is not.

BOX 6
Additional Research Gaps Identified in the Human Research Roadmap: Risk of Incompatible Vehicle/Habitat Design

- SHFE-HAB-03: We need to understand how new aspects of the natural and induced environment (e.g., vehicle/habitat architecture, acoustics, vibration, lighting) may impact performance, and need to be accommodated in internal vehicle/habitat design.
- SHFE-HAB-05: We need to understand what aspects of human physical capabilities and limitations (e.g., body size and shape, range of gross movement) change for predetermined mission attributes, and need to be accommodated in internal vehicle/habitat design.
- SHFE-HAB-07: We need design guidelines for acceptable net habitable volume and internal vehicle/habitat design configurations for predetermined mission attributes
- SHFE-HAB-08: We need to refine the definition of the Risk of Incompatible Vehicle/Habitat Design including mission attribute list, and define the acceptable level of risk due to inadequate internal vehicle/habitat design.
- SHFE-HAB-09: We need to identify technologies, tools, and methods for data collection, modeling, and analysis that are appropriate for design and assessment of vehicles/habitats (e.g., net habitable volume, layout, and usage) for predetermined mission attributes, and for refinement and validation of level of acceptable risk.

SOURCE: NASA, 2014h.

The evidence report places considerable emphasis on anthropometry and on noise, without explicit discussion of the consequences of inadequate design in these areas; these limitations of the report are discussed below. The other research gaps (e.g., visual environment, vehicle volume and layout) are adequately addressed in this evidence review, although, as noted above, these are each broad areas of research with many unknowns for long duration space flights.

Anthropometric and Biomechanical Limitations

The evidence report makes the case that appropriate anthropometric consideration is critical when designing the crew habitat and stations, in order to avoid injuries and potentially fatalities. More could be noted about the research gaps relevant to characterizing the space crew members and their accommodation and interaction with various equipment and workstation configurations. The report cites the study by Scheuring and colleagues (2009) that examined musculoskeletal injuries that have occurred over the course of the U.S. space program and provides the relevant, although limited, causality information that is available on the types of activities or design that might be risk factors for injuries. Further identification of the sites and nature of those musculoskeletal injuries will be particularly important for informing ongoing research. It will also be important to apply multivariate analysis in order to deal with types of anthropometric crew variability such as long limb/short torso or long torso/short limb individuals. Most of the work described in the evidence report uses univariate analysis.

The text in the evidence report on the NASA report on neutral body posture (Mount et al., 2003) demonstrates that anthropometric fluctuations in a long-term space environment can reduce task capability and increase the risk of injury. The authors suggest that the list of injuries does not represent all types of hazardous scenarios and the mission health and safety monitoring systems could be improved so as to more systematically prompt operators to log injuries and near-miss events. The limits of digital human modeling are also described and point to an ongoing research gap.

Additional areas in which there are research gaps include

- Suit effects, including mobility for surface EVAs and energy expenditure;
- Vehicle effects and biomechanics as related to gravitational and non-gravitational environments;
- Neutral body posture and the impact of anthropometric considerations including skeletal build and fat-to-muscle ratio and their impacts on posture; and
- Restraints (beyond foot holds and hand holds) and their utilization.

Noise

The evidence report makes the case that noise is a spaceflight-related health risk but there may be other literature that should be considered in the report. The design limit of 67 A-weighted decibels (dBA) is conservative in terms of long-term damage. However, it should be recognized that even at this noise level the crew may need to use earplugs or headphones, which would interfere with normal aural communication. The literature supports a limit of 70 to 75 dBA, depending on spectra. At these levels, temporary threshold shift is not incurred, and recovery from prior temporary threshold shifts will occur (Ward et al., 1976).

Are There Any Additional Gaps in Knowledge or Areas of Fundamental Research That Should Be Considered to Enhance the Basic Understanding of This Specific Risk?

As this evidence report covers a broad range of both basic and applied research, a number of research gaps could be considered but other than those noted in the section above, no specific issues were identified by the committee.

Does the Evidence Report Address Relevant Interactions Among Risks?

Although human system integration with the habitat/vehicle is discussed throughout the report, there could be further efforts to address the relevant interactions among the various risks described in this evidence report and also among the risks described in other evidence reports.

Interactions among risks that are not described include

- Interactions where changes in human health (such as changes in muscle strength and bone stability caused by vibration and G-forces, as well as and visual acuity)could occur on long-duration flights and affect the crew's interactions with the vehicle and habitat;
- Interactions of acceleration and vibration (see, e.g., Griffin, 2001); and
- Interactions that could affect behavioral health and performance (such as lighting issues related to fatigue and circadian rhythms).

The section on anthropometry discusses a number of interactions of fluctuating human body dimensions with suit design, fit, and seating/restraints/equipment (along with other vehicle and habitat design issues).

What Is the Overall Readability and Quality?

The executive summary and risk overview are succinct and provide a well-written summary of the evidence. The body of the evidence report could have been greatly strengthened by paying greater attention to synthesizing and analyzing the individual experiences and examples so that specific risks could be identified more clearly. For example, in the section on restraints, an analysis of the examples could have included the key design features that could potentially cause injury or health risks, rather than making the general statements that "restraints that are overly complex, difficult, or time-consuming to set up or get in/out of, will not be used by the crew" (Whitmore et al., 2013, p. 26).

Throughout the report there is a need for increased attention to health risks and how the various design features affect crew health, rather than paying attention to more general operations issues. Broad descriptions, such as introduction of the Extravehicular Mobility Units (p. 11), the issues with the closure mechanisms on rack doors (p. 13), the lighting analysis (pp. 17-18), and the introduction of the equipment section (p. 26) could be shortened and edited to focus on health risks. The descriptions of ISS issues regarding accessibility and stowage (p. 31) and other issues are important, but need to be tied to health and safety risks. However, the gaps need to be focused on future spacecraft and further exploration missions, rather than on the specific design issues of ISS or of Constellation.

Furthermore, the report would have been enhanced by professional editing as well as careful consideration of which figures and photographs were needed to make the point regarding risks. The organization and readability of the report could also have been strengthened by using a single template for all of the risk factor sections, so as to provide a consistent style and format between factor descriptions.

Is the Breadth of the Cited Literature Sufficient?

Given the breadth of research covered by this evidence report, the authors had to be selective about what literature was cited. However, in many places throughout the report the literature that is cited relies too heavily on NASA studies and needs to be expanded into the broader literature. This is particularly true for areas where the risks have strong terrestrial analogs such as noise, anthropometry, and visibility. For example, the current literature on short- and long-term noise effects on cognition could be cited (e.g., Szalma and Hancock, 2011). The evidence report notes that most of the information comes from observations and case studies and summaries of subjective experience data from spaceflights and training. Efforts to provide more research-based examples, where available, are encouraged.

Is the Expertise of the Authors Sufficient to Fully Cover the Scope of the Given Risk? Is Input from Additional Disciplines Needed?

As with all reports that are written by authors working for a single federal agency, the report could benefit from the involvement of independent, multidisciplinary researchers, engineers, and clinicians. For example, input from the biomechanics discipline, particularly on the subjects of impact, vibration tolerance, and sustained acceleration is needed, and those sections could be augmented by accessing the vast expertise of the defense laboratories, especially at Wright-Patterson Air Force Base and Fort Rucker. The coverage of the noise problem is limited and dated.

Has the Evidence Report Addressed Previous Recommendations Made by the IOM in the 2008 Letter Report?

In the 2008 report, the groupings of issues related to human factors were clustered in an evidence book *Lack of Human-Centered Design*, Chapter 23, which addressed three risks related to human factors: inadequate information, poor human factor design, and poor task design. There were no previous recommendations relevant to the specific topics on vehicle and habitat design.

RISK OF INADEQUATE CRITICAL TASK DESIGN

Astronauts are frequently confronted with inadequately designed mission tasks, task flows, schedules, and procedures. The risks associated with these problems are compounded by time and communication delays and, therefore, could be serious challenges on longer expeditions to asteroids and the planets. NASA's evidence report on this topic, *Risk of Inadequate Critical Task Design* (Sándor et al., 2013), recognizes the need to develop a better understanding of relevant human capabilities and limitations for performing tasks and how these factors might affect workload and degrade performance on long-duration missions. The evidence report also acknowledges the need to understand the effect that other factors might have on human-system performance and suggests automation as a subject of particular concern. The committee's responses to the key review questions are summarized below.

Does the Evidence Report Provide Sufficient Evidence, as Well as Sufficient Risk Context, That the Risk Is of Concern for Long-Term Space Missions?

The evidence book makes an excellent case for developing a better understanding of the work that is and will be performed by astronauts, but there are important omissions. Among the most salient omissions of the evidence report is the recognition of the enormous responsibilities that ground personnel face in preparing realistic schedules, accurate procedures, and optimum presentation of information to guide task performance in space.

The report discusses inadequate task design in general terms and, to illustrate potential consequences, uses examples drawn almost exclusively from aviation. It cites evidence from the ISS crew comments database to support the claim that poorly prepared and erroneous procedures are a persistent problem for ISS crew. No concrete examples are provided, although many are available from recent studies (e.g., Stuster, 2010) and others have been provided anecdotally by former ISS crew members. For example, a former ISS commander described to the committee several problems with procedures, including inconsistencies in format, inconsistencies in nomenclature used for equipment and materials, and having to jump from one set of procedures to another in order to perform a task (Lopez-Alegria, 2014).

The evidence report defines the risk of inadequate task design in somewhat ambiguous terms as concerned with tasks, schedules, and procedures, with most tasks performed using human-computer interfaces. The executive summary correctly describes three contributing factors to the risk: (1) operational tempo and workload, (2) procedural guidance, and (3) technical/procedural knowledge. Unfortunately, the emphasis is consistently on the astronaut's ability to accommodate to the procedures and schedules, rather than on the developers and schedulers performing their jobs appropriately. In addition, the report focuses on cognitive elements (or effects?) of task performance and only occasionally acknowledges the possibility of physical limitations and risks. Identifying gaps as either physical or psychological/cognitive, while recognizing that interactions are almost certain to occur, might improve the focus of the evidence book. Alternatively, excluding motor tasks that do not include a high cognitive component (e.g., physical exertion during EVA) might be appropriate. With the exception of the June 1997 Mir incident, there is no review of mission risk related to operational tempo or workload for spaceflight.

The Human Factors Analysis and Classification System (HFACS) differentiates between errors (unintentional behaviors) and violations (willful disregard of the rules and regulations) (Shappell and Wiegmann, 2000). In terms of this HFACS distinction, the evidence report discusses only errors, with no review of violations. A summary of unsafe acts using the HFACS would be useful. In particular:

- What are the incidence rates of errors versus violations?
- When violations occur, why did crewmembers execute a decision contrary to flight rules?

Does the Evidence Report Make the Case for the Research Gaps Presented?

The evidence report provides justification for all of the research gaps identified. However, the data provided are almost exclusively summative, based on crew report. Thus, a large gap exists in formative evaluation which would identify when tasks are too stressful for crew members. The evidence report correctly points out that delays between training and knowledge utilization will cause an increase in workload as crew members attempt to access required knowledge. Automation is both an aid and a potential crutch, especially when knowledge and understanding of automated systems become compromised.

Updated versions of this report should use sub-headings for categories of research gaps, including those listed in the Human Research Roadmap Summary (see Box 7) under the “Gaps” section, to enable more efficient cross checks across NASA documents.

Are There Any Additional Gaps in Knowledge or Areas of Fundamental Research That Should Be Considered to Enhance the Basic Understanding of This Specific Risk?

The role that task analyses should play in the human-centered design process is described thoroughly in the evidence report. However, the report fails to include, in its list of research gaps, a discussion of the need for task analyses of the work to be performed on expedition-class missions. The absence of task analyses for ISS operations and for future long-duration expeditions represents a major oversight which could be corrected easily and soon. A July 2014 NASA research announcement includes a study of the general abilities required for planetary expeditions, which almost certainly will begin with a systematic analysis of expedition tasks; an analysis of the work to be performed on those expeditions is the first step in the Human Factors Method, and will be necessary to identify the skills and abilities required to perform the work

BOX 7
Additional Research Gaps Identified in the Human Research Roadmap: Critical Task Design

- SHFE-TASK-01: How can workload measures and tools be developed to unobtrusively monitor and trend workload throughout the mission design and verification cycle in a consistent manner?
- SHFE-TASK-02: What model-based HF Tools can assist with the design and evaluations of spacecraft systems and task procedures?
- SHFE-TASK-03: How can a capability for semi-autonomous planning and dynamic replanning of crew schedules be developed?

SOURCE: NASA, 2014i.

(NASA, 2014c). As knowledge is gained from this work, it can be incorporated in future revisions of the evidence report.

The report would benefit from the addition of information about the type of job aids that have been provided to ISS crew and about the crew's response to the various formats: longer videos of full procedures, hyperlinks to shorter videos showing specific tasks, paper copy, online only, or other formats.

Another gap is the need for research to identify the optimum procedure format for different types of tasks. It is understandable that this was overlooked because there have been no task analyses conducted to identify categories of similar tasks. It should be noted that one of the fundamental products of a properly conducted task analysis is the identification of a job incumbent's information requirements at each step in the work to be performed. Knowledge of information requirements is directly relevant to the design of appropriate job aids.

The report should also address the effects of time and scheduling as they relate to the risk of critical task design. A persistent scheduling problem aboard the ISS is the failure to allocate sufficient time to prepare for tasks, assemble materials, and stow equipment properly after task completion. The on-orbit constraints result in crew members running behind schedule almost continuously, which is the single greatest contributor to stress identified by participants in a study of confidential astronaut journals (Stuster, 2010). Involving crew members in developing schedules and a review of new procedures by former ISS crew members are two options that could be explored. Further gaps remain regarding the effect of delayed communications with the ground on task performance during interplanetary expeditions; more needs to be learned about how to write procedures to support autonomous operations.

The list of research gaps is generally thoughtful, and the discussion of human-in-the-loop evaluations being particularly appropriate, especially because spacecraft design will continue to evolve and include greater automation. A few additional gaps to be considered include

- Trainability as an aspect of task design: The evidence report acknowledges task design. Perhaps, a reciprocal gap should be addressed.
- Acknowledgement of cognitive changes suggests that the concept known as "universal design" might be worthy of studying for applicability to spacecraft procedures.
- Function allocation, the second step in the Human Factors Method, would logically follow the carrying out of the task analysis proposed above. Determining which tasks are appropriately performed by humans, and which are more appropriately performed by computers or robots, is a rational process that must be informed by an understanding of task requirements, human capabilities and limitations, and operational conditions (mostly constraints). Although the general rule is to automate when pos-

sible, a contra-intuitive approach might be warranted on long duration space expeditions where meaningful work might be in short supply. Roald Amundsen said that boredom is the worst enemy of the polar explorer, and most expedition leaders during the heroic era made sure that there would be plenty of tasks to keep the crew engaged (Stuster, 2011).

- Meaningfulness of work: The evidence report refers to "nuisance operations" as tasks to be avoided, but work that is considered to be trivial, repetitive, or a nuisance under normal conditions might prove to be rewarding on long-duration expeditions. For example, Fridtjof Nansen's engineer disassembled and reassembled the Fram's steam engine three times while locked in the ice during the Norwegian Polar Expedition of 1893-1896; it was a repetitive but meaningful task that kept the engineer and his assistant fully engaged (Stuster, 2011).
- Crew autonomy and guided input: The evidence report states that, "automated support for these planning tasks should allow crewmembers to manage daily tasks and ensure that these tasks are performed appropriately when ground support is unavailable" (Sándor et al., 2013 p. 8). Long-duration missions beyond low Earth orbit will likely require significantly more crew autonomy and "guided" input (e.g., guided by expert systems on board). Input from the human factors engineers who are contributing to the design of self-driving automobiles may provide additional input into this discussion.
- Physical workload: The evidence report emphasizes cognitive workload, which is appropriate. However, physical workload also should be addressed, especially for planetary expeditions that will presumably involve surface operations and will be accompanied by muscle atrophy and perhaps other negative environmental effects, such as vision degradation.
- Automated job aids to correct operator errors: Research on task design should include consideration of automated procedures which might be developed that would have the capability of detecting errors and suggesting mitigating actions, in the same manner that a global positioning system (GPS)-guided trip computer can detect a wrong turn and then provide turning directions to regain the route.

- Design approaches: Automated defibrillators (or other similarly designed devices), which are now available in almost all public places and designed to be used by anyone without prior training, might offer a model for the design of procedures to be followed under emergency conditions.
- Workload measurement techniques: Self-reports of workload may be unreliable so more objective measures are needed.

Does the Evidence Report Address Relevant Interactions Among Risks?

Links are provided in this evidence report to the NASA evidence reports on inadequate human-computer interaction (Holden et al., 2013), training deficiencies (Barshi, 2012), sleep loss and circadian rhythm (Whitmore et al., 2009), and behavioral conditions and psychiatric disorders (Slack et al., 2009). Additional relevant interactions include vision impairment (Alexander et al., 2012) and those related to physical deconditioning. Also, problem solving in an autonomous environment will be required on future expeditions and should be studied.

What Is the Overall Readability and Quality?

The evidence report starts off with excellent justifications for applying the HFACS to the design of procedures and equipment. The style becomes uneven beginning around page 12 and occasionally lapses into jargon-filled sentences that are difficult to follow. Clarification of the jargon would be helpful. The committee recognizes that this is a technical subject. Overall the report is well-written.

Is the Breadth of the Cited Literature Sufficient?

Many references are old, which is not necessarily a negative, but there are recent studies that could be cited concerning problems with procedures and schedules on the ISS and about analogous conditions (e.g., medical procedures). Also, several of the references could not be found; references should be accessible and should be cited in a format that allows the reader to easily locate and read them (e.g., URL followed by "accessed on" date).

Is the Expertise of the Authors Sufficient to Fully Cover the Scope of the Given Risk? Is Input from Additional Disciplines Needed?

The expertise of the authors is sufficient, although additional perspectives are always valuable. Additional areas of expertise could include task design for health care and input on the importance of effective hand-off procedures. Videography or graphic design expertise is also relevant, especially after the research has been conducted to identify the optimum presentation modes, or formats, for displaying procedures.

Has the Evidence Report Addressed Previous Recommendations Made by the IOM in the 2008 Letter Report

In the 2008 IOM report, the discussion regarding task design was part of the review of a broad chapter, Chapter 23 in *Lack of Human-Centered Design*, that addressed three risks: inadequate information, poor human factor design, and poor task design. The 2008 report recommended:

- the use of more recent examples of task design problems, which appears to still be an issue;
- further discussion on the "gaps associated with determining the impact on efficiency of an error-reducing task design" (IOM, 2008, p.85);
- discussion of relevant interactions, including how "the design of tasks that necessitate EVA must consider the physical and other limitations created by the EVA suit" (IOM, 2008, p. 85).

Further discussion of each topic listed in the 2008 report is needed.

RISK OF PERFORMANCE ERRORS DUE TO TRAINING DEFICIENCIES

Astronauts spend much of their time in the astronaut corps training for future missions. For example, 3 years are devoted to nearly constant preparation prior to each 6-month expedition to the ISS. Astronauts become training experts, or, at least, expert critics of the training that they receive. Nearly all astronauts comment anecdotally about the relief they experience when their training ends and their launch day finally arrives, and most consider the high-tempo of ISS operations to be easy compared to their training schedules. Training for ISS expeditions is intended to prepare astronauts for all the tasks they are likely to perform during their stay on the ISS as well as for many emergency tasks they hope will not occur. The relatively brief durations of ISS expeditions make this comprehensive approach to training possible. However, future long-duration expeditions to asteroids and the planets might require different training strategies to minimize the risks associated with performance errors resulting from training deficiencies. The committee reviewed the evidence report *Risk of Performance Errors Due to Training Deficiencies* (Barshi, 2012) and summarizes its response to the key questions below.

Does the Evidence Report Provide Sufficient Evidence, as Well as Sufficient Risk Context, That the Risk Is of Concern for Long-Term Space Missions?

This evidence report discusses inadequate training in general terms and cites evidence from the ISS crew comments database to support the claim that training for ISS missions is long and stressful, and often provides inadequate preparation. No concrete examples were provided, but the 2010 report documenting the Journals Flight Experiment includes several examples in which astronauts claim that the training they received only slightly resembled the task they were required to perform on orbit and that they were required to familiarize themselves with tasks during off-duty time just prior to performing them (Stuster, 2010). That is, evidence suggests that, among other problems, training can be misaligned and missing, despite crew members having devoted 3 years to preparing for a 6-month expedition. The report recognizes the additional risks that could result from inadequate training for long-duration expeditions and from communication lag times that will constrain customary support options.

The evidence report makes a reasonable case for the risk context and its importance for complex tasks that require high levels of situational awareness. The committee expected that the report would have included examples from previous spaceflight experience, but the evidence presented in the review draws largely from analog environments, especially military and commercial aviation. A relatively large database of accidents that have been documented in actual spaceflight conditions exists and could provide more directly relevant insights. For example, Zimmerman (1998) outlines several cases in the development of space stations, and Shayler (2000) does a commendable job of reviewing accidents in the U.S. and Soviet space programs. The National Research Council report *Preparing for the High Frontier: The Role and Training of NASA Astronauts in the Post-Space Shuttle Era* also offers useful information (NRC, 2011). The situations surrounding STS-37 (landing winds) and STS-87 (Spartan satellite grapple) included notable anomalies and the problems that emerged in the Spartan experience, in particular, were largely attributed to inadequate training. The evidence report needs additional examples taken directly from the field of space flight to illustrate the risks of inadequate training.

Does the Evidence Report Make the Case for the Research Gaps Presented?

Justification is provided for the three research gaps that are identified:

- Lack of modeling and simulation platforms that can be leveraged for training on emerging technology;
- Inadequate or unavailable training programs; and
- Inconsistencies with training, individual attributes and mission demands.

The statements concerning gaps are vague and incomplete. The case made for task training is reasonably compelling, but the cases for the research gaps are less clear. In particular, an interplanetary space expedition will require launching a crew and then probably transferring that crew to another space vehicle before they depart on the outbound transit to their destination. Information support from ground controllers will be an important part of task performance during the early phase of the outbound transit, but at some point communication lags will become too long for immediate feedback from ground controllers rendering real-time voice and text communication impossible. What will be the algorithm to switch from direct interaction to autonomous crew capability? At what point in the transit will this be considered? This condition does not exist in spaceflight currently, but could be simulated on the ISS and is an unexplored gap for which a research platform already exists. Also, one example is provided in the report to make a strong case for understanding the utility of "just-in-time" training, especially when experimental schedules do not necessarily align with crew rotation schedules.

In addition to expanding the research gap section, in general, authors of updated report versions should consider structuring the section around categories of research gaps, including those listed in the Human Research Roadmap Summary (see Box 8), as suggested throughout this letter report.

BOX 8
Additional Research Gaps Identified in the Human Research Roadmap: Performance Errors Due to Training Deficiencies

- SHFE-TRAIN-01: We do not know which validated objective measures of operator proficiency and of training effectiveness should be used for future long-duration exploration missions. (Previously: How can we develop objective training measures to determine operator proficiency during and after ground training?)
- SHFE-TRAIN-02: We need to identify effective methods and tools that can be used to train for long-duration, long-distance space missions. (Previously: How do we develop training methods and tools for space medical application if time is minimal?)
- SHFE-TRAIN-03: We need to develop guidelines for effective onboard training systems that provide training traditionally assumed for pre-flight. (Previously: How can onboard training systems be designed to address just in time [JIT] and recurrent training needs for nominal and off nominal scenarios?)
- SHFE-TRAIN-04: We do not know the types of skills and knowledge that can be retained and generalized across tasks for a given mission to maximize crew performance.

SOURCE: NASA, 2014l.

Are There Any Additional Gaps in Knowledge or Areas of Fundamental Research That Should Be Considered to Enhance the Basic Understanding of This Specific Risk?

Various types of training are discussed in the evidence report, including pre-mission training, refresher training, and just-in-time training (by which the author meant contingency training under emergency conditions). However, in general, the discussions of training are abstract, that is, without reference to actual tasks or specific knowledge, skills, and abilities that might be required for mission success—or to survive an emergency. Like the companion report on inadequate critical task design (i.e., procedures) (Sándor et al., 2013), this review of training risks fails to include, in its list of research gaps, the need for task analyses of the work to be performed on expedition-class missions. The absence of task analyses for ISS operations and for future long-duration expeditions handicaps understanding of associated risks and limits discussion to vague and unanchored generalities. What skills and knowledge will be necessary for successful performance on a 6 – month asteroid mission or a 3 – year mission to Mars? In considering such missions, the first step is to identify the tasks that will be performed and the specific and general abilities that will be required of the crew. One of the products of a properly conducted task analysis is identification of the abilities needed to perform the work successfully. Knowing what abilities are needed leads directly to the design and delivery of appropriate training. On page 11 the report states, "Research is required to develop appropriate generalizable, skill-based training," but this research requirement was not included in the list of gaps presented.

As mentioned above in the review of the evidence report on critical task design, NASA's recent research announcement (July 2014) includes a study on the general abilities required for planetary expeditions (NASA, 2014c). NASA issued a similar research announcement in 2013 related to "novel adaptive and context-sensitive refresher training and/or just-in-time training methods and tools for autonomous crews performing tasks such as robotic or maintenance activities" (NASA, 2013b). The resulting research will likely feed into future iterations of this evidence report by identifying the work to be performed on these expeditions and the accompanying needs for training in specific skills and abilities. One issue that should be examined is increasing the efficiency of training.

Reviewing other areas in which training is critical for successful task performance (e.g., surgery) might lead to the identification of additional research gaps (see discussion below on the breadth of the cited literature). Some of the work on failure analysis in the medical field is patterned on work in commercial and military aviation, which might prove to be circular, but the manner in which this same body of material has been adapted to the medical environment might provide transferrable insights. Also, the evidence report provides little in terms of specific types of training, frequency of training, and adequacy of refresher experiences for astronauts.

Another area that needs further discussion is the assessment of the skills and experience that astronauts and their trainers bring to a mission and the training for that mission. A former shuttle astronaut and ISS commander who spoke to the committee described NASA's approach to training as being task-focused for shuttle missions and skill-focused for ISS expeditions (Lopez-Alegria, 2014); that is, U.S. ISS crew are expected to be experts in everything, which might be an unreasonable approach and certainly contributes to the training burden about which astronauts complain. Selecting some personnel with specific skills and then providing task-focused training and job aids and other support during task performance might be more effective. Furthermore, the factors that affect crew members' trust in the training and trainer need to be explored. The workshop speaker noted the challenges of receiving training from novice instructors with no spaceflight experience. Competence and spaceflight experience are among the factors that could be examined.

Does the Evidence Report Address Relevant Interactions Among Risks?

The evidence report mentions only "inadequate task design" as a related risk. Beyond task design, the most salient training-related risk is inadequate personnel selection, which involves both the initial criteria for selection and the criteria used to select a specific crew composition. The necessary skill sets and experience are both areas that should be examined. For example, the report mentions on several occasions that rote memorization and training for infrequent task performance is brittle, erodes over time, and is not generalizable. In addition, all members of the crew also must be demonstrably adept at getting along with others in isolation and confinement. Getting along with others is a skill that can be trained, but it might be more effective to select individuals who have a history of exhibiting key traits and abilities — such as perseverance, fidelity, and affability — in addition to specific technical expertise. In other words, many of the risks associated with inadequate training could be mitigated by proper personnel selection.

Other risks that might interact with the risk of inadequate training include those related to human-robotics interaction (Marquez et al., 2013), circadian rhythm (Whitmore et al., 2009), vestibular function (Paloski et al., 2008), and possibly vision (Alexander et al., 2012). The principles of universal design could also be explored in considering the design of tasks and the associated training. A simple example might be the use of scalable fonts in displayed instructions.

What Is the Overall Readability and Quality?

The evidence report is well-written overall and easily readable, but it could be improved with greater specificity.

Is the Breadth of the Cited Literature Sufficient?

The emphasis in the material cited is on aviation-related research, which is relevant and probably unavoidable. However, the committee also notes that many of the references are not easily accessible and that there seems to be a relative dearth of citations to the peer-reviewed literature. A relevant body of literature that could be included is the medical literature concerning failure avoidance, training, and team support. In the past 20 years, the healthcare field has focused on reducing patient care errors and has developed a number of practices and this body of literature could be explored for relevance to spaceflight training (see Box 9).

BOX 9
Examples of Analogous Situations and Training Paradigms

Mentors and trainers: Explanation of procedure execution errors on page 1 of the evidence report seems roughly analogous to the role played by faculty surgeons during surgical training. After medical school, future surgeons enter residency training programs (and subsequently more specialized fellowships), in which they learn the cognitive and physical skills necessary for safe practice. These training programs span 5 or more years of increasing clinical responsibility. In the operating room, each patient presents slightly different anatomy and/or altered physiology, testing the ability of the trainee to apply general principles and reason through the operation. The faculty surgeon, having generally performed at least an order of magnitude more instances of the particular operation than the trainee, brings experience to bear in the modifications needed from the "textbook procedure" to the actual patient (ACGME, 2014; Kauvar et al., 2006). Flight controllers appear to fulfill a similar role. The report rightly emphasizes that as transmission delays increase (with travel beyond low Earth orbit), this "safety net" will be less available. What should be the role of expert systems in filling the gap?

Generalizable training: Surgical training is designed to prepare a surgeon for a lifetime in the operating room. Many of the skills that residents learn are generalizable. For instance, a surgical resident who is facile at performing laparoscopic appendectomies has acquired skills that transfer to performance of laparoscopic cholecystectomy. There are differences in anatomy, indications, and so on, but the required mechanical skills are very similar. In addition, these mechanical skills can be practiced on simulators or in animal models (Boyle et al., 2011; Cristancho et al., 2013, 2014; Smink et al., 2012). What are the equivalent generalizable skills that astronauts must master? To take it one step further, can tasks be designed in a "modular" fashion so that generalizable skills are used as much as possible, with reference to specific variations through expert systems (see, e.g., Healy and Bourne, 2012)? The evidence report alludes to this approach.

Just-in-time training: The evidence report states that, "contributing factors regarding training deficiencies may pertain to organizational process and training programs for spaceflight, such as when training programs are inadequate or unavailable" (Barshi, 2012, p. 2). It seems intuitively clear that emergencies (where there is an urgency to solve the problem) allow little or no time for just-in-time training. This may be where drawing upon "generalizable skills" becomes most important. When there is a little more time, it becomes feasible to have just-in-time training (addressed late in the report), or support from flight controllers who could devise a procedure to "fix" the problem and then provide the checklist or procedural guidance needed.

Situational awareness: Anesthesiologists must maintain situational awareness during the long stable period between induction and emergence. Except during emergency procedures (or when emergencies occur during elective procedures) nothing much happens for a long time. The really good anesthesiologists are constantly aware of what is happening in the operating room and anticipate problems (perhaps sensing a change in the emotional environment, vital signs,or a surgeon's tone of voice). Technology is being developed to enhance situational awareness in the perioperative environment (Lane et al., 2012).

Workarounds as a source of failure: Lack of needed information, supplies, or equipment results in workaround solutions have been identified as a source of failure in the healthcare environment (Tucker et al., 2014).

Team communication: Team communication is an area of intense interest in the operating room environment. "Huddles" — where team members get together at the beginning of the day or before a procedure to discuss what is planned and what is needed to accomplish it, offer one example of such communication (Patterson, 2013). The checklists used to facilitate handoffs at shift change in hospitals offer another example, and (Mullan et al., 2014) preoperative checklists offer a third (Lingard et al., 2008). Increasingly, where possible, checklists are employed to increase safety. These are primarily used in the pre-surgical period (to ensure that the right patient is having the right operation performed on the correct side of his or her body, that antibiotics have been given and other precautions taken, etc.).

Training methods: The evidence report mentions that training for a certain task consisted of three PowerPoint (PPT) slides. Although PPT files can be configured to be effective training tools, NASA should continue to investigate other methods. Head-up displays that provide data while allowing the user to maintain his or her usual view are now commercially available (e.g., Google Glass) and some surgical operations are heavily dependent on modern imaging capabilities. Head-up displays that allow a surgeon to view the operating field and the imaging studies simultaneously will be available soon. The report states, "Again, determining which events can be handled using performance support tools and how such tools can best be designed requires systematic methodologies that do not yet exist" (Barshi, 2012, p.8).

Is the Expertise of the Authors Sufficient to Fully Cover the Scope of the Given Risk? Is Input from Additional Disciplines Needed?

This evidence report has a single author who has extensive research expertise in addressing the cognitive issues involved in the skilled performance of astronauts, pilots, and flight/air traffic controllers. This research focus is appropriate for the risk. However, this evidence report, as with each of the evidence reports on a broad topic, would benefit from additional perspectives. This input, with additional expertise on task analysis and human factors engineering included, should be helpful in identifying the risks of inadequate training for expedition-class missions.

Has the Evidence Report Addressed Previous Recommendations Made by the IOM in the 2008 Letter Report?

In the 2008 IOM report, the discussion regarding training was part of the review of a broad chapter that focused primarily on teams (i.e., Chapter 15 "Performance Errors Due to Poor Team Cohesion and Performance, Inadequate Selection/Team Composition, Inadequate Training, and Poor Psychosocial Adaptation"). The 2008 report states, "The section on training (pp. 12-13) mentions previous studies that show different kinds of training have an impact on 'performance.' But the issues are treated in a very general way. What kind of training? For what kinds of individuals? Conducted by whom? How was performance measured?" (IOM, 2008, p. 66). The questions asked in the 2008 report have been addressed for the most part by pulling out the training issues as a separate evidence report. The 2013 evidence report provides significantly expanded coverage on the risk of inadequate training and highlights the research needed on types of training and measurement of its impact, although, as noted in this review, greater specificity is needed, where feasible.

SUMMARY

This is the second of five letter reports which will review the entire series of NASA's evidence reports on human health risks. This letter report reviewed seven evidence reports and provided the committee's responses to the questions detailed in the statement of task. The evidence reports are quite thorough in their review of the evidence of spaceflight risks, although they vary in format and in the consistency and quality of the writing. In general, the reports would benefit from the perspectives of authors from more diverse fields and from adding authors from outside of NASA staff and contractors.

As noted by the committee, several of the reports need to strike a better balance between using evidence solely from aviation and spaceflight and using evidence from other fields of science and from analog environments. Several of these reports cover broad fields of research, and the committee appreciates the challenges in identifying and summarizing the most salient literature. Similarly, challenges arise in finding the best way to highlight the interactions between risks. The reports do an adequate job of discussing the interactions between those risks that are most directly related (e.g., altered immune response and host-microorganism interactions), but they struggle with establishing the connections and interactions among risks that are related, but a bit more tangential (e.g., altered immune response and inadequate nutrition). Because the space industry is changing so rapidly with increased private-sector commercialization, it will be important for future iterations of the evidence reports to consider the implications of these changes in identifying and addressing spaceflight risks. Further, as noted throughout the report, the evidence reports need to be more explicit in considering the risk implications for long duration spaceflights with more tenuous and delayed connections to ground crew.

The committee greatly appreciates the opportunity to review the evidence reports and applauds NASA's commitment to improving the quality of its reports. The evidence reports provide the basis for the work of NASA's Human Research Program, and the in-depth review that they provide will contribute to improving the health and performance of future astronauts and enhancing future human spaceflights endeavors.

Sincerely,

Carol E. H. Scott-Conner, *Chair*

Daniel R. Masys, *Vice Chair*
Committee to Review NASA's Evidence Reports
on Human Health Risks

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A

Meeting Agendas

First Meeting of the
Committee to Review NASA's Evidence Reports
on Human Health Risks

Telephone Conference

May 5, 2014

OPEN SESSION

3:00 p.m. **Official Charge to the Committee and Discussion of First Letter Report**
Mark Shelhamer, Chief Scientist, Human Research Program, NASA

Discussion of Statement of Task and 2014 Reports with the Committee
Facilitator: Carol Scott-Conner, Committee Chair

3:45 p.m. **Public Session Adjourn**

**Second Meeting of the
Committee to Review NASA's Evidence Reports
on Human Health Risks**

**National Academies Keck Center
500 Fifth Street, NW, Rooms 208 and 206
Washington, DC**

July 17-18, 2014

OPEN SESSION

9:00 a.m. **Welcome**
Carol Scott-Conner, *Committee Chair*

9:15 a.m. **Panel 1: Risk of Inadequate Design of Human and Automation/Robotic Integration and Risk of Inadequate Human-Computer Interaction**
Facilitators: Randall Shumaker and Sundaresan Jayaraman, Committee Members

9:15–10:00 a.m. Presentations
- Susan Hill, Army Research Laboratory
- Robert Hoffman, Florida Institute for Human and Machine Cognition
- James L. Szalma, University of Central Florida

10:00–10:30 a.m. Discussion with the Committee

10:30 a.m. **Break**

10:45 a.m. **Panel 2: Risk of Incompatible Vehicle/Habitat Design**
Facilitator: Larry Young, Committee Member

10:45–11:15 a.m. Presentations
- Andrew Liu, MIT Man Vehicle Lab
- William Albery, Booz Allen Hamilton

11:15–11:45 a.m. Discussion with the Committee

11:45 a.m. **Lunch**

12:45 p.m. **Panel 3: Risk of Adverse Health Effects Due to Alterations in Host Microorganism Interactions and Risk of Crew Adverse Health Event Due to Altered Immune Response**
Facilitator: Cheryl Nickerson, Committee Member

12:45–1:45 p.m. Presentations

- James Wilson, Villanova University
- Hernan Lorenzi, J. Craig Venter Institute
- Alexander Choukèr, Ludwig Maximalians University (*via WebEx*)

1:45–2:15 p.m. Discussion with the Committee

2:15 p.m. **BREAK**

2:30 p.m. **Panel 4: Risk of Inadequate Critical Task Design and Risk of Performance Errors Due to Training Deficiencies**
Facilitator: Jack Stuster, Committee Member

2:30–3:30 p.m. Presentations
- Michael Lopez-Alegria, Commercial Spaceflight Federation
- Scott Shappell, Embry-Riddle Aeronautical University
- Marissa Shuffler, Clemson University
- Warren M. Zapol, Massachusetts General Hospital

3:30–4:00 p.m. Discussion with the Committee

4:00 p.m. **Public Comment**

4:30 p.m. **Closing Remarks**
Dan Masys, Committee Vice Chair

B

Committee Biographical Sketches

Carol E. H. Scott-Conner, M.D., Ph.D., M.B.A. (*Chair*), is a professor in the Department of Surgery, University of Iowa, Iowa City. Dr. Scott-Conner received her undergraduate training in electrical engineering from the Massachusetts Institute of Technology and worked as an engineer before attending medical school at New York University (NYU). In 1976, she received her M.D. from NYU, where she also completed a residency in surgery. After leaving NYU, she joined the faculty at Marshall University and then moved to the University of Mississippi. During her tenure there, she earned a Ph.D. in anatomy from the University of Kentucky and an M.B.A. In 1995, she became professor and head of surgery at the University of Iowa. Dr. Scott-Conner has been active on 22 editorial boards and has written more than 200 original papers, abstracts, reviews, and book chapters. She is certified by the National Board of Medical Examiners and the American Board of Surgery and has a certification of added qualifications in surgical critical care. Dr. Scott-Conner has served on a number of Institute of Medicine (IOM) committees, and she chairs the IOM Standing Committee on Aerospace Medicine and the Medicine of Extreme Environments.

Daniel R. Masys, M.D. (*Vice-Chair*), is an affiliate professor of biomedical and health informatics at the University of Washington School of Medicine, where he joined the Department of Biomedical Informatics and Medical Education in 2011. Previously, he served as a professor and the chair of the Department of Biomedical Informatics and a professor of medicine at the Vanderbilt University School of Medicine. An honors graduate of Princeton University and the Ohio State University College of

Medicine, he completed postgraduate training in internal medicine, hematology, and medical oncology at the University of California, San Diego (UCSD), and the Naval Regional Medical Center, San Diego. He served as chief of the International Cancer Research Data Bank of the National Cancer Institute, National Institutes of Health, and was director of the Lister Hill National Center for Biomedical Communications, which is a computer research and development division of the National Library of Medicine. He also served as director of Biomedical Informatics at the UCSD School of Medicine, director of the UCSD Human Research Protections Program, and professor of medicine. Dr. Masys is an elected member of the Institute of Medicine (IOM). He is a diplomate of the American Board of Internal Medicine in medicine, hematology, and medical oncology. He is a fellow of the American College of Physicians and fellow and past president of the American College of Medical Informatics. Dr. Masys served as a member of the IOM Committee on Aerospace Medicine and Medicine of Extreme Environments and chaired the 2008 IOM review of NASA's Human Research Program evidence books.

Susan A. Bloomfield, Ph.D., earned her B.S. in biology at Oberlin College (Ohio) and her M.A. in physical education (exercise physiology) at the University of Iowa. After completing a Ph.D. (exercise physiology) at Ohio State University, Dr. Bloomfield joined the faculty in the Department of Health and Kinesiology at Texas A&M University in 1993, where she currently holds the rank of professor and is director of the Bone Biology Laboratory. In addition, she serves as assistant provost in the Texas A&M Office of Graduate and Professional Studies. Her research interests focus on the integrative physiology of bone, with specific reference to adaptations to disuse, microgravity, and caloric deficiency and how the sympathetic nervous system, altered blood flow, and endocrine factors modify those adaptations. Her more recent work has focused on the independent and combined effects of partial weight bearing and simulated space radiation on the integrity of bone and muscle, involving several experiments at Brookhaven National Laboratory. Collaborations with muscle biologists have enabled definition of concurrent changes in muscle-bone pairs with disuse and/or radiation exposure. Her work has been funded by the National Space Biomedical Research Institute (NSBRI), the Department of Defense, and, currently, NASA's Space Biology Program. From 2000 to 2012, Dr. Bloomfield served as the associate lead for the Bone Loss (later, Musculoskeletal Alterations) Team within the NSBRI, and she has served on numerous NASA and European Space Agency review panels during the past 14 years. She is a member of the Texas A&M Department of Nutrition and Food Sciences graduate faculty and is an associate member of the Texas A&M University Health Sciences Center School of Graduate Studies.

Karen S. Cook, Ph.D., is the Ray Lyman Wilbur Professor of Sociology, director of the Institute for Research in the Social Sciences, and vice provost of the Faculty Development and Diversity Office at Stanford University. She conducts research on social interaction, social networks, and trust. She has edited and coedited a number of books in the Russell Sage Foundation Trust Series, including *Trust in Society* (2001); *Trust and Distrust in Organizations: Emerging Perspectives*; *eTrust: Forming Relationships in the Online World*; and *Whom Can We Trust?* She is coauthor of *Cooperation Without Trust?*, and she co-edited *Sociological Perspectives on Social Psychology*. In 1996 she was elected to the American Academy of Arts and Sciences and in 2007 to the National Academy of Sciences. In 2004 she received the Cooley-Mead Award from the American Sociological Association's Social Psychology Section for career contributions to social psychology.

Sundaresan Jayaraman, Ph.D., is the Kolon Professor in the School of Materials Science and Engineering with a joint appointment in the Scheller College of Business at the Georgia Institute of Technology in Atlanta, Georgia. He and his research students have made significant contributions in enterprise architecture and modeling methodologies for information systems; engineering design of intelligent textile structures and processes; and design and development of knowledge-based systems for textiles and apparel. His group's research has resulted in the realization of the world's first Wearable Motherboard™ or Smart Shirt. Dr. Jayaraman is currently engaged in studying the role of management and technology innovation in health care. He received his Ph.D. from North Carolina State University, in 1984, and the M.Tech. and B.Tech. degrees from the University of Madras, India, in 1978 and 1976, respectively. He was involved in the design and development of TK!Solver, the first equation-solving program from Software Arts, Inc. Dr. Jayaraman worked as a product manager at Software Arts, Inc., and at Lotus Development Corporation, before joining Georgia Tech in the fall of 1985. Professor Jayaraman is a recipient of the 1989 Presidential Young Investigator Award from the National Science Foundation for his research in the area of computeraided manufacturing and enterprise architecture. Dr. Jayaraman serves on the National Research Council's National Materials and Manufacturing Board and has previously served on a number of Institute of Medicine (IOM) committees, including the IOM Committee on Personal Protective Equipment in the Workplace.

Cheryl Nickerson, Ph.D., is a professor in the School of Life Sciences, at the Biodesign Institute at Arizona State University in the Center for Infectious Diseases and Vaccinology. Her research focuses on characterizing the effects of biomechanical forces on living cells (microbial and human), how this response is related to normal cellular homeostasis or infectious disease progression, and translation to biomedical and clinical applications. She has developed several innovative model pathogenesis systems to study these processes, including three-dimensional organotypic cell culture models to study host-pathogen interactions, and characterizing pathogen responses to physiological fluid shear forces encountered in the infected host and in the microgravity environment of spaceflight. She is a recipient of the Presidential Early Career Award for Scientists and Engineers and of NASA's Exceptional Scientific Achievement Medal, and she was selected as a NASA astronaut candidate finalist. Her research has flown on numerous NASA Shuttle missions and on the International Space Station, and will fly on upcoming SpaceX missions. She is founding editor-in-chief of the Nature Publishing Group journal, *npj Microgravity*, a new multidisciplinary research journal dedicated to publishing the most important scientific advances in the life sciences, physical sciences, and engineering fields that are facilitated by spaceflight and analogue platforms.

James A. Pawelczyk, Ph.D., is an associate professor of physiology, kinesiology, and medicine at Pennsylvania State University. Dr. Pawelczyk served as a payload specialist on STS-90 Neurolab (April 17 to May 3, 1998); the experiments on-board the space shuttle *Columbia* flight focused on the effects of microgravity on the brain and nervous system. Dr. Pawelczyk is a former member of the NASA Life Sciences Advisory Subcommittee in the Office of Biological and Physical Research, and he served as a member of NASA's ReMaP Task Force in 2002, which was charged with reprioritizing research on the space station. Dr. Pawelczyk's research areas include central neural control of the cardiovascular system and compensatory mechanisms to conditioning and deconditioning. He received his M.S. in physiology from Pennsylvania State University and his Ph.D. in biology (physiology) from the University of North Texas. He chaired the National Research Council (NRC) Decadal Survey on Biological and Physical Sciences in Space: Integrative and Translational Research for the Human System Panel and chaired an Institute of Medicine (IOM) report on NASA's directed research programs in 2012. He has served on several NRC and IOM committees and recently completed rotations on the IOM's Committee on Aerospace Medicine and the Medicine of Extreme Environments and the NRC's Space Studies Board.

Robert L. Satcher, Jr., M.D., Ph.D., is an assistant professor of surgical oncology at MD Anderson Cancer Center. He earned a Ph.D. in chemical engineering from the Massachusetts Institute of Technology in 1993 and an M.D. from Harvard Medical School in 1994. His medical specialties are orthopedics and oncology, and he has done much work in treating bone cancer in adults and children. Selected as an astronaut candidate by NASA in 2004, he completed his training 2 years later. He was aboard the space shuttle *Atlantis* that journeyed to the International Space Station for almost 11 days in November 2009. Classified as a mission specialist, he studied the influence of zero gravity on muscles and bone density as well as the effects of space on the immune system. He also used his surgical training to install an antenna and help repair two robotic arms on the space station. Dr. Satcher is director of the eHealth Research Institute at Texas Medical Center and a member of the User Panel at the National Space and Biomedical Research Institute (NSBRI). He is a frequent reviewer and adviser for medical issues related to spaceflight.

Randall Shumaker, Ph.D., is the director of the University of Central Florida's Institute for Simulation & Training and a former Naval Research Laboratory executive. He is an expert on artificial intelligence and human-robot interactions, including in health, security and military applications. He has also explored the challenges and comfort levels of humans accepting various roles that robots can play in society. Dr. Shumaker's research interests include artificial intelligence, biomorphic computing methods, and advanced techniques for software development. He is a frequent reviewer and adviser for military research programs and has had significant success in transitioning research from academia into government and industry. Dr. Shumaker is the author of more than 60 scientific publications and is a frequent speaker on a variety of technical topics. Previously, he served as superintendent of the Information Technology

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Jack Stuster, Ph.D., is the vice president and principal scientist of Anacapa Sciences, Inc., a human factors and applied behavioral sciences research firm. He received a bachelor's degree in experimental psychology from the University of California, Santa Barbara, and a master's and Ph.D. degrees in anthropology from the same institution. Dr. Stuster is a certified professional ergonomist, specializing in the measurement and enhancement of human performance in extreme environments. He has analyzed the tasks performed by U.S. Navy SEALs, SEAL delivery-vehicle pilots and navigators, explosive ordnance disposal technicians, crews of high-speed hovercraft, maintenance personnel, and military leaders. Dr. Stuster's work for NASA began in 1982 with a systems analysis of space shuttle refurbishing procedures, which has been followed by studies of conditions on Earth that are analogous to those found on space missions. Dr. Stuster has been awarded Fellow status by the Human Factors and Ergonomics Society and the Borneo Research Society. He was a member of the Science Council of NASA's Institute for Advanced Concepts and is now a member of the External Advisory Council of the National Space Biomedical Research Institute. He has also served on several government advisory groups, including the standing committee of the National Academies Board on Army Science and Technology to support the efforts of the Joint Improvised Explosive Device Defeat Organization, for which he received a patriotic Civilian Service Commendation in 2011. He currently serves as the principal investigator of the Journals Flight Experiment and of the development of the Cultural Depot, an information-sharing system for use by special operations personnel.

Gayle E. Woloschak, Ph.D., is a professor in the Department of Radiology at the Feinberg School of Medicine at Northwestern University. Her research interests include studies of the molecular biology of lymphocyte and motor neuron abnormalities in DNA repair–deficient mice, studies of radiation-inducible nanoparticles, and the analysis of molecular mechanisms of oncogenesis in radiation-induced tumors. She received her Ph.D. in medical sciences (microbiology) from the Medical College of Ohio and did postdoctoral training in the departments of immunology and molecular biology at the Mayo Clinic. Dr. Woloschak was a senior molecular biologist and group leader of the Biosciences Division at Argonne National Laboratory, and a senior fellow at the Nanosciences Consortium of Argonne National Laboratory–University of Chicago. She has served as a member on the National Institutes of Health's radiation study section and on the National Research Council's Committee on the Evaluation of Radiation Shielding for Space Exploration, and she has chaired NASA's peer-review radiation biology committee.

Laurence R. Young, Sc.D., is professor of astronautics and professor of health sciences and technology at the Massachusetts Institute of Technology. He was the founding director (1997 - 2001) of the National Space Biomedical Research Institute. Dr. Young is a full member of the International Academy of Astronautics. He received an A.B. from Amherst College; a certificate in applied mathematics from the Sorbonne in Paris, as a French government fellow; and S.B. and S.M. degrees in electrical engineering and an Sc.D. in instrumentation from the Massachusetts Institute of Technology (MIT). He joined the MIT faculty in 1962 and cofounded the Man Vehicle Laboratory, which does research on the visual and vestibular systems, visual-vestibular interaction, flight simulation, space motion sickness, and manual control and displays. In 1991, Dr. Young was selected as a payload specialist for Spacelab Life Sciences 2. He spent 2 years in training at the Johnson Space Center and served as alternate payload specialist during the October 1993 mission. He was chairman of the Harvard–MIT Committee on Biomedical Engineering and Physics and the interdepartmental Ph.D. program in biomedical engineering, and he directs the Harvard–MIT Program in Bioastronautics. Dr. Young is a member of the Institute of Medicine (IOM) and the National Academy of Engineering and has served on many IOM and National Research Council committees, including the IOM Committee on Aerospace Medicine and the Medicine of Extreme Environments.