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Technical Note

Selecting Astronauts for Long-Duration Space Missions: Medical, Psychological, and Skill-Based Criteria for Success

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ABSTRACT

Background: Long-duration space missions introduce complex physiological, psychological, and operational challenges due to microgravity, radiation, isolation, and confined environments. Ensuring astronaut health and mission success requires adaptive, evidence-based, and interna-tionally harmonised selection protocols. **Objective:** This narrative synthesis evaluates current astronaut selection criteria for long-duration missions, critically examining physiological, psychological, and technical domains, identifying limitations of existing frameworks, and highlighting emerging technologies and international considerations. **Methods:** Peer-reviewed literature, agency standards, and technical guidance from NASA, ESA, JAXA, Roscosmos, and commercial entities were reviewed. Key physiological stressors, behav-ioural competencies, and skill requirements were linked to exclusion and competency criteria, with a focus on actionable recommendations, comparative analysis, and emerging AI- and digital twin–enabled assessment tools. **Results:** Critical selection domains include musculoskeletal and cardiovascular resilience, ves-tibular and immune system integrity, cognitive and emotional stability, leadership and teamwork capabilities, and advanced academic and operational competence. Comparative analysis reveals variability across agencies, highlighting gaps in mission-specific thresholds, duration-based cri-teria, and integration of emerging countermeasures. AI-assisted monitoring and digital twin simulations offer transformative potential for continuous risk assessment and personalised ad-aptation. **Conclusion:** Developing space programs should implement evidence-informed, adaptive selec-tion frameworks that integrate physical, psychological, and technical competencies, harmonised international standards, and emerging technologies. Prospective evaluation, continuous moni-toring, and tiered, mission-specific criteria are essential to optimise safety, performance, and operational success on long-duration missions.

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NOMENCLATURE

JAXA	Japan Aerospace Exploration Agency
SANS	Spaceflight-Associated Neuro-ocular Syndrome
BHP	Behavioural Health and Performance
MD	Doctor of Medicine
CSA	Canadian Space Agency
ESA	European Space Agency
ISS	the International Space Station

1. INTRODUCTION

Long-duration space missions introduce a spectrum of complex challenges arising from extreme environmental conditions, including microgravity, radiation exposure, prolonged isolation, and confinement. Collectively, these stressors impose substantial physiological and psychological demands on astronauts, which can compound over time [1]. The selec-tion of astronauts for space missions needs evidence-based criteria that address the di-verse range of spaceflight-related stressors to guarantee mission safety and maximize crew performance. Recent policy and standards updates from major human-spaceflight programmes emphasise the need for modernised medical, operational, and technolo-gy-driven selection tools. NASA and other programmatic guidance documents have been revised to support the planning of long-duration exploration missions [1, 2].

Historically, astronaut selection prioritised physical health and flight expertise. However, the evolving nature of space exploration, particularly missions to the Moon, Mars, and beyond, necessitates a broader reassessment of selection criteria. Long-duration missions not only test physical endurance but also demand exceptional psychological resilience, interpersonal aptitude, and interdisciplinary skill sets. This trend is further reinforced by the rapid growth of commercial astronaut programmes and international private mis-sions [3,4].

This paper examines the foundational medical, psychological, and skill-based criteria es-sential for astronaut selection in developing space agencies. It emphasises both exclusion thresholds and competency benchmarks grounded in physiological compatibility, behav-ioural adaptability, and academic qualifications. For context, all candidates are assumed to have completed preliminary administrative requirements, such as host-nation citizen-ship verification, background checks, and security clearances

2. METHODS

This manuscript presents a narrative synthesis of peer-reviewed literature, agency stand-ards, and technical guidance on astronaut selection for long-duration space missions. The focus is on identifying convergent themes, knowledge gaps, and actionable recommenda-tions to inform future selection frameworks.

The review encompasses publications from 2006 to 2025, including empirical studies, op-erational reports, and technical reviews that address crew selection and performance in extended missions. Agency documents from the National Aeronautics and Space Admin-istration (NASA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), and Russian space agency (Roscosmos), together with publicly accessible tech-nical standards, were also examined to integrate institutional perspectives and operation-al criteria.

Inclusion criteria comprised policy documents, peer-reviewed empirical studies, system-atic and narrative reviews, and technical standards relevant to astronaut selection and crew health for missions beyond low Earth orbit. Exclusion criteria included non-English publications without available translations and isolated case reports not linked to broader evidence bases.

Given its narrative synthesis design, the analysis prioritised thematic integration and policy relevance over quantitative meta-analysis. Limitations include dependence on secondary data sources, heterogeneity in reporting quality, and the absence of direct ex-perimental studies involving human participants

3. ENVIRONMENTAL AND PHYSIOLOGICAL STRESSORS IN SPACEFLIGHT

Human spaceflight exposes astronauts to extreme environmental stressors that challenge the limits of physiology and underpin stringent medical standards for selection and recer-tification. Microgravity and radiation exposure induce multisystem changes that cannot be fully replicated on Earth. These stressors form the foundation of a risk-based selection paradigm, prioritising candidates with exceptional resilience, physiological adaptability, and no underlying vulnerabilities that could be exacerbated during flight [1, 2]. Selection therefore favours applicants whose baseline assessments demonstrate low inherent med-ical risk and clear capacity for physiological adaptation.

Microgravity induces profound musculoskeletal and cardiovascular adaptations [5,6]. Prolonged unloading of weight-bearing bones accelerates osteoclastic activity, producing reductions in bone mineral density and an increased fracture risk, particularly in the lumbar spine and lower limbs [5,7]. Antigravity muscles atrophy, reducing functional strength and endurance, while cardiovascular deconditioning impairs orthostatic toler-ance on return to Earth or during exposure to partial-gravity environments such as Mars [6]. Fluid shifts toward the head produce facial oedema and visual impairment through elevated intracranial pressure and optic disc swelling, collectively described as Space-flight-Associated Neuro-ocular Syndrome (SANS) [8]. Given these predictable physiologi-cal effects, selection protocols explicitly exclude or defer candidates with clinically signif-icant bone, joint, or cardiovascular pathology and incorporate objective musculoskeletal and cardiovascular screening (for example, bone-mineral density measurement, function-al strength testing, and orthostatic/cardiopulmonary exercise assessment) to quantify and mitigate risk [1,2].

Ionising radiation represents a second major determinant of astronaut health. Outside Earth's magnetosphere, astronauts are exposed to galactic cosmic rays and episodic solar particle events that increase lifetime cancer risk, induce DNA strand breaks, and can im-pair haematopoietic function [9]. Consequently, agencies enforce dose limits and com-monly exclude individuals with prior radiation therapy or haematological disorders [10]. Mitigation strategies span passive shielding, research into active magnetic shielding, and pharmacological approaches such as radioprotective antioxidants and DNA-repair mod-ulators [11]. Operational selection practices, therefore, require detailed radiation-exposure histories, haematological screening, and cumulative dose management when determining mission eligibility and long-term career planning

Beyond bone, muscle, cardiovascular systems and cancer risk, spaceflight affects vestibu-lar, immune, and gastrointestinal function. The vestibular system undergoes adaptive re-calibration in microgravity, producing space motion sickness early in flight and postural instability on return [12]. Immune alterations include reduced T-cell responsiveness and reactivation of latent viruses, consistent with functional immunosuppression, while gas-trointestinal changes, including reduced motility, shifts in gut microbiota, and altered nu-trient absorption, increase the risk of digestive disturbances and renal calculi [13-15,16]. Collectively, these effects support exclusion of candidates with recurrent nephrolithiasis, autoimmune disease, or compromised immune function.

Technological advances are reshaping risk assessment and management by enabling dy-namic, in-flight monitoring and adaptive countermeasures. Wearable biosensors and con-tinuous telemetry permit real-time tracking of vital signs, muscle activity, and cardiovas-cular parameters during training and flight, and artificial intelligence algorithms can de-tect early deviations in physiological trends to support predictive health management in austere environments [17-19]. These innovations are shifting practice from a static pre-selection model toward continuous risk assessment and iterative countermeasure de-velopment

4. PSYCHOLOGICAL AND BEHAVIOURAL ADAPTATION

Psychological resilience and behavioural stability are as critical to astronaut success as physiological robustness. The cognitive, emotional, and interpersonal demands of space-flight, characterised by isolation, confinement, sensory monotony, and high operational stakes, necessitate rigorous psychological screening and ongoing monitoring. Cognitive performance degradation, often labelled "space fog," has been observed during extended missions and is attributed to circadian disruption, sleep deprivation, and neuroimmune modulation; such impairments compromise attention, decision-making, and situational awareness, creating direct operational risks [20, 21]. Consequently, the selection process needs to include tests that determine how well candidates handle stress and eliminate candidates who show signs of unacceptable operational risks.

The most common psychological problems in space exploration stem from disrupted sleep patterns and irregular circadian rhythms. For example, astronauts aboard the Inter-national Space Station (ISS) experience 16 sunrise–sunset cycles every 24 hours, disrupt-ing endogenous melatonin production and circadian alignment [22]. Resultant insomnia, fatigue, and mood dysregulation can impair cognitive efficiency and teamwork [20-22]. The implementation of dynamic LED lighting systems and personalised melatonin treatment has demonstrated some effectiveness in fixing sleep patterns and maintaining circadian rhythms [21]. Still, susceptibility to circadian disruption should be considered during selection, including an evaluation of sleep history, prior shift-work tol-erance, and response to sleep deprivation as part of candidate appraisal.

Personality profiling is another cornerstone of selection. Space agencies often use psy-chometric frameworks, such as the Five-Factor Model, to identify traits predictive of team cohesion, leadership, and adaptability [23,24]. High conscientiousness, agreeableness, and emotional stability consistently correlate with superior performance under stress, whereas high neuroticism or low agreeableness is associated with conflict, poor commu-nication, and reduced mission success [23,24]. Psychiatric contraindications to selection should then include psychotic disorders, major depression, anxiety disorders, and sub-stance dependence. Evaluation methods, including combined structured interviews, psy-chometric batteries, and simulated operational tasks, may identify and prioritise profiles predictive of resilience and adaptive performance.

The psychological dynamics between crew members become essential when working in multinational crews. Cross-cultural communication competence, tolerance of ambiguity, and conflict resolution skills are increasingly emphasised to manage the psychological complexity of long-duration missions [24]. These behavioural competencies are integrated into NASA's Behavioural Health and Performance (BHP) model, which informs both se-lection and in-flight psychological support [25]. Selection panels should therefore incor-porate group exercises and cross-cultural simulations to observe teamwork and conflict management under simulated stress, using performance in these tasks to inform crew composition and candidate ranking

Emerging artificial-intelligence-based monitoring tools present new options for early de-tection of stress, fatigue and mood changes during flight. The use of passive analytics through speech-processing algorithms and facial-expression analysis enables unobtrusive affective state tracking, but they introduce ethical challenges around privacy, consent and data governance [26]. While such tools augment in-flight detection of behavioural risk, se-lection and acceptance decisions must be supported by transparent governance frame-works and informed-consent procedures so that they remain ethically sound

5. COMPETENCY AND QUALIFICATION STANDARDS

Beyond medical and psychological thresholds, astronaut selection emphasises advanced technical competence and multidisciplinary academic achievement. NASA requires ap-plicants to hold at least a master's degree in a science, technology, engineering, or math-ematics (STEM) discipline, or a Doctor of Medicine (MD), accompanied by a minimum of three years of progressively responsible professional experience [27]. The selection process for future astronauts needs to prove their ability to conduct scientific research and solve problems while adapting to mission requirements because these skills are essential for independent deep-space operations. Therefore, it is recommended to adopt the Doctor of Philosophy (PhD) as the new baseline educational standard for mission-critical astronaut roles. Doctoral training provides deeper expertise in hypothesis-driven research and ad-vanced experimental design. It also develops independent problem-solving and rigorous data analysis skills. In addition, PhD graduates gain experience leading complex, multi-disciplinary projects. These capabilities are directly transferable to autonomous scientific and technical operations in deep-space environments.

The selection process for pilots includes extra operational criteria that guide their assess-ment. Requirements such as minimum Pilot-in-Command hours, experience in high-performance aircraft, or graduation from an accredited test-pilot programme estab-lish an objective baseline for manual flight proficiency and airmanship. Where appropri-ate, agencies may recognise equivalent achievement, such as doctoral-level technical ex-pertise that can substitute for flight hours [27]. As the methods of evaluating equivalency are not universal across agencies, selection should still rely on practical evaluation through simulator assessment and aeronautical proficiency testing to confirm candidate capability under emergency and degraded-automation scenarios.

As human spaceflight moves toward longer missions and greater autonomy, selection criteria are changing to include new mission-relevant skills. Competencies such as robot-ics operation, human–AI interaction, systems thinking, biomedical self-care, and in-mission data analysis are increasingly valued. As a result, selection processes should now include task-based evaluations, targeted training programs, and evidence of multidisciplinary practice to assess a candidate's ability to perform these roles inde-pendently. NASA's Artemis program and commercial entities such as Axiom Space now emphasise multidisciplinary skill integration, enabling astronauts to conduct research, repair complex hardware, and manage onboard medical events [28,29]. The implemen-tation of a PhD as the standard qualification enhances these advantages because candi-dates already demonstrate advanced research methods and independent study experience, which minimises the need for additional training during science-based missions.

Commercial human spaceflight introduces further complexity. While governmental agen-cies prioritise scientific and operational criteria, commercial providers may adjust stand-ards for mission objectives ranging from tourism to lunar construction. Some private pro-grammes adopt reduced medical thresholds supplemented by enhanced onboard moni-toring or shorter mission duration [30]. This expansion of civilian participation under-scores the need for harmonised medical and competency baselines to safeguard safety without constraining innovation.

6. INTERNATIONAL STANDARDS AND HARMONISATION

The selection frameworks for astronauts between different agencies show distinct differ-ences regarding their level of transparency and their organisational structure and assess-ment boundaries. NASA makes its selection criteria accessible to the public through de-tailed medical and psychological standards, which outline absolute exclusion criteria and specific waiver conditions [1,2]. The European Space Agency (ESA) uses a similar evalu-ation system that focuses on behavioural competencies while conducting step-by-step as-sessments during training phases [31]. In contrast, JAXA and Roscosmos maintain more confidential medical frameworks, reflecting differing national risk tolerances, operational philosophies, and selection priorities that influence who ultimately qualifies for mission assignment.

These inconsistencies can hinder international collaboration and interoperability, partic-ularly for joint missions or commercial–government partnerships. For example, waiver criteria for minor medical anomalies may differ between agencies, creating barriers to cross-qualification and limiting the pool of otherwise suitable astronaut candidates. Ad-ditionally, current selection frameworks fail to differentiate between short-duration and deep-space missions because they use identical evaluation criteria even though these mis-sions require distinct operational and physiological requirements. This uniformity can inadvertently exclude highly capable candidates who might meet the requirements for low-Earth orbit operations but not for Mars-class missions, reducing overall selection flexibility.

A harmonised global framework could improve transparency, comparability, and fairness in astronaut selection. The International Space Station (ISS) Multilateral Crew Operations Panel serves as an existing model for standardising operational procedures and crew cer-tification because it brings together all five international partners: NASA, Roscosmos, JAXA, ESA, and the Canadian Space Agency (CSA) [31,32]. Extending this cooperative model to astronaut selection criteria would create equal selection opportunities because it would unify medical, psychological, and academic requirements between agencies to produce equivalent selection results. The ability to transfer crew members between agen-cies becomes possible when such coordination exists because it allows for crew changes during missions.

The coordination of medical and psychological standards would create shared databases that contain medical incident reports, waiver decisions, and selection statistics. The com-bined evaluation process for multinational crews becomes more efficient through integra-tion, while evidence-based selection decisions improve because of aggregated data analy-sis for risk assessment and candidate-mission compatibility optimisation. A single standardised system would also enable scientists to conduct extended research about as-tronaut wellness and performance, which would help develop better models for under-standing risk tolerance and treatment effectiveness. Ultimately, a standardised process enables agencies to select candidates based on their demonstrated abilities and mission readiness instead of administrative rules, which leads to fairer astronaut recruitment and scientific progress.

7. FUTURE DIRECTIONS AND ETHICAL CONSIDERATIONS

Astronaut selection is shifting toward an integrated, data-driven and ethically informed model; however, further research is required. The combination of wearable biosensing technology with genomic profiling and AI-assisted evaluation systems provides real-time monitoring of physical and mental performance, but creates ethical challenges regarding consent and privacy protection and surveillance duration that require strong ethical over-sight for selection policies.

The selection process needs to follow a multi-tier structure, which presents clear require-ments for minimum medical standards, psychological evaluations, and competency tests while adding specialised modules for extended spaceflight and deep space exploration.

Research priorities need to focus on long-term studies that combine physical and mental health markers with molecular indicators through biobanking, bed-rest, and mission an-alogue trials to establish new ethical guidelines for selection data utilisation. The research findings should develop improved selection criteria through the identification of specific characteristics that enhance space stress tolerance in simulated environments [33].

The protection of genetic information from discrimination and unfair exclusion requires three essential elements: clear consent procedures, independent monitoring, and stand-ardised risk disclosure practices. The selection process needs to establish both fairness and inclusion by recognising various areas of expertise, including robotics, planetary sci-ence, and healthcare innovation, to enhance team problem-solving abilities and innova-tion while making diversity a quantifiable selection goal [34].

A global consortium of agencies and private partners could create standardised proce-dures for medical information exchange and ethical oversight systems exploration through physical and psychological and ethical training. The coordinated approach would eliminate unnecessary work while creating equal opportunities for space access and maintaining clear decision-making processes between contributing nations

8. CONCLUSION

The selection process for astronauts on long-duration missions needs to shift away from static exclusion lists toward an adaptive system that uses evidence to connect candidate assessment to mission requirements and available countermeasures and acceptable risk levels. The selection process for deep space missions requires thorough physiological evaluations, strong psychological assessments, and clear competency assessments sup-ported by real-time flight monitoring and adaptive countermeasures to handle changing risk factors. The adoption of advanced research training at a doctoral level for science lead positions will enhance onboard problem-solving abilities, independent research capabili-ties, and decrease the requirement for mission-specific skill development. Similatainoiusly, the deployment of wearable biosensing technology with AI analytics for early detection of physiological and behavioural changes requires proper governance frameworks, consent protocols, and data protection systems to prevent surveillance violations and maintain ethical standards.

Harmonisation of medical, psychological and competency standards across national and commercial programmes will facilitate equitable access to missions, simplify cross quali-fication between agencies and enable aggregated learning from larger, pooled datasets. A coordinated international framework based on operational multilateral organisations should establish standardised waiver procedures, collective incident tracking systems, and support research to optimise risk assessment and selection criteria. Research priori-ties, therefore, include longitudinal analogue and mission-linked studies that combine clinical, cognitive and molecular markers. The implementation process needs to protect safety requirements through an inclusive system that embraces diverse expertise and uses transparent evaluation methods that prevent discriminatory information usage. The com-bination of these measures enables the development of selection systems that combine scientific validity with operational effectiveness and ethical compliance to enhance crew readiness for space exploration beyond Earth's orbit.

CONFLICTS OF INTERESTS

No conflict of interest has been expressed by the authors.

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