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Opinion

Life on Mars: neuroplasticity in the first Martians

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Every human brain ever studied has developed under the same terrestrial gravitational constant, 9.8 m/s^2. As Mars exploration and eventual habitation become increasingly plausible, a key neuroscientific question emerges: what happens to a brain that never experiences Earth's gravity? In the absence of a dedicated gravity receptor, the brain infers gravity by integrating vestibular, proprioceptive, visual, and somatosensory signals with prior experience. In this opinion article, we review evidence that this internal model of gravity functions as a foundational prior. We examine how altered gravity environments reveal both the flexibility and the limits of this internal model of gravity, highlighting sensory prediction errors as drivers of recalibration. We also discuss underlying neural plasticity mechanisms, including cerebellar circuits, cortical networks, and neuromodulatory systems, and consider their implications for sustaining human life beyond Earth.

Significance

As Mars habitation becomes a realistic prospect, understanding brain development under reduced gravity is essential. While research on altered gravity has largely focused on adult adaptation, far less is known about neurodevelopment in such environments. We argue that the key question is how neuroplasticity shapes the developing brain when a stable, Earth-like gravitational reference is absent, as would be the case for the first generation born and raised on Mars.

Gravity: a foundational prior forged by life on Earth

What would it mean not merely to travel to another planet, but to begin life there—to grow, learn, move, and develop from birth under a gravitational environment radically different from the one we know on Earth? Current plans for crewed missions to Mars focus on enabling astronauts to survive for extended periods in a gravitational environment that is approximately 38% of Earth's gravity [1,2]. These efforts have produced important insights into the physiological challenges of spaceflight, including muscle atrophy, bone demineralization, and cardiovascular adaptations [3]. Yet the long-term success of human exploration beyond Earth will depend not only on engineering solutions but also on understanding how the human brain adapts to altered gravity environments [4–8].

Gravity is among the most stable environmental features on Earth, with organisms evolving under a constant gravitational acceleration of approximately 9.8 m/s^2 (1*g*). This consistency has profoundly shaped the organization of the nervous system. Humans rely on gravity to maintain posture, coordinate movement, predict object trajectories, and orient themselves in space [9,10]. Even everyday actions depend on the brain's ability to anticipate how gravity will influence them.

Importantly, the nervous system has no dedicated receptor for gravity. Instead, the brain constructs an internal representation by integrating inputs from multiple sensory systems. Vestibular signals provide information about head orientation relative to the gravitational vector, while visual, proprioceptive, and somatosensory cues contribute complementary information about body position, movement, and contact forces, respectively [11,12]. Through lifelong interaction with the environment, these signals are combined with prior knowledge to generate predictions about how gravity will affect both the body and external objects [9,11]. This '**internal model of gravity**' (see Glossary) enables efficient interaction with the terrestrial environment by anticipating the physical consequences of action [9].

However, because this model is calibrated through extensive experience under Earth's gravity, it can be challenged when gravitational conditions change [13,14]. Astronauts entering **microgravity** often experience spatial disorientation, postural instability, and motion sickness—

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symptoms that reflect a nervous system confronted with unfamiliar sensory inputs [15]. The brain does not encounter weightlessness as a blank slate; rather, it carries a lifetime of gravity-based expectations that are systematically violated in space.

The prospect of human settlement on Mars brings this question into sharp focus: can the brain form and calibrate an internal model of gravity without ever experiencing Earth's? Because no direct data exist on humans conceived, born, or raised in reduced gravity, this question must currently be approached indirectly by integrating insights from sensorimotor neuroscience, motor learning, spaceflight physiology, developmental science, and animal research.

In this opinion article, we examine how the human brain constructs predictive models of gravity and how these models adapt when gravitational conditions change. We first review the multisensory mechanisms that underpin the internal model of gravity, along with evidence supporting its role in perception and action. We then consider how mismatches between predicted and actual sensory input—sensory prediction errors—drive **recalibration** in altered gravity environments. Next, we explore the neural plasticity mechanisms that support this adaptation, focusing on cerebellar circuits, cortical networks, and neuromodulatory systems. Finally, we discuss the implications of these processes for the development of human life beyond Earth—an understanding that will be essential as humanity extends its presence into space (Figure 1).

The brain encodes a predictive model of terrestrial gravity

Successful interaction with the physical world depends on the brain's ability to anticipate how forces shape action, with gravity playing a central role. Humans rely on gravitational expectations to guide behavior; for instance, catching a ball requires predicting its curved trajectory. Rather than passively responding to sensory input, the brain continuously generates predictions about actions and environmental events, comparing them with incoming signals to detect and correct errors [16]. Unlike other properties such as light or sound, gravity is not sensed by a dedicated receptor but inferred by integrating information from multiple sensory modalities [17].

The **vestibular system** (Figure 2) provides the most direct information about gravity. The vestibular otoliths contain small calcium carbonate crystals (otoconia) that rest on sensory hair cells. When the head moves relative to the gravitational vector, the inertia of these crystals deflects the hair cells, generating neural signals that allow the brain to estimate head orientation relative to gravity [12,13]. The brain integrates vestibular signals with visual, proprioceptive, and somatosensory inputs [17]. Visual cues provide references for spatial orientation and motion, including the vertical structure of the environment and the trajectories of moving objects. Somatosensory signals from cutaneous receptors provide information about pressure distribution across the body, particularly at the feet and along supporting surfaces. Proprioceptive signals from muscles and joints convey information about limb position and muscle tension, allowing the brain to estimate posture and body configuration relative to the gravitational axis. The brain combines these sensory signals with experience-dependent priors in a probabilistic, Bayesian-like manner [9,17]. Because gravity is constant across development and evolution, it forms a particularly **strong prior**, leading the nervous system to assume downward acceleration under Earth's gravity unless contradicted by evidence [14,15,18].

Behavioral research supports the existence of a gravity prior. Observers can accurately extrapolate occluded object trajectories, intercept falling targets, and estimate impact timing [10]. This influence extends beyond perception and action, with recent studies showing effects on higher-level cognition, including reasoning about physical events [19,20]. Gravitational dynamics are, therefore, embedded within the brain's predictive computations. Neuroimaging evidence suggests that these computations rely on distributed neural circuits involving the cerebellum

Glossary

Blastocyst: refers to the early stage of embryo development, occurring 5–6 days after conception.

Brain-derived neurotrophic factor (BDNF): operates in synergy with dopamine signaling to enhance neural plasticity, allowing motor adaptation to an environmental perturbation.

Dopamine: a neurotransmitter involved in the regulation of brain neuroplasticity, supporting adaptation. Dopamine neurons report a reward prediction error, mediating reinforcement learning and motivation.

Internal model of gravity: the brain anticipates and validates the consequences of gravity by comparing the sensory input from the vestibular, proprioceptive, somatosensory, and visual systems with that predicted by its internal model.

Microgravity: refers to the near-weightlessness condition in an orbiting vehicle, such as the ISS.

Ontogenetic: the developmental history of an organism across its lifespan.

Recalibration: dynamic reweighting of inputs from different modalities. Microgravity is suggested to cause down-weighting of vestibular input (as the vestibular information becomes less reliable) and up-weighting of other sensory inputs (e.g., somatosensory and vision).

Sensorimotor adaptation: also known as sensory error-based learning, is the process of learning aimed at reducing sensory prediction errors caused by a perturbation. It is characterized by the incremental reduction of sensory prediction errors and a gradual improvement toward pre-perturbation performance. Related paradigms include visuomotor and force field adaptation tasks, where the relationship between expected and actual sensory input is altered.

Strong prior: in a Bayesian framework of cognition, gravity is not merely an environmental constant but a 'strong prior', deeply ingrained through evolutionary and lifelong experience with gravity.

Vestibular system: within the inner ear, comprises the semicircular canals that sense the rotational acceleration of the head in three-dimensional space and the otolith organs that sense the linear acceleration, including the orientation of the head relative to gravity.

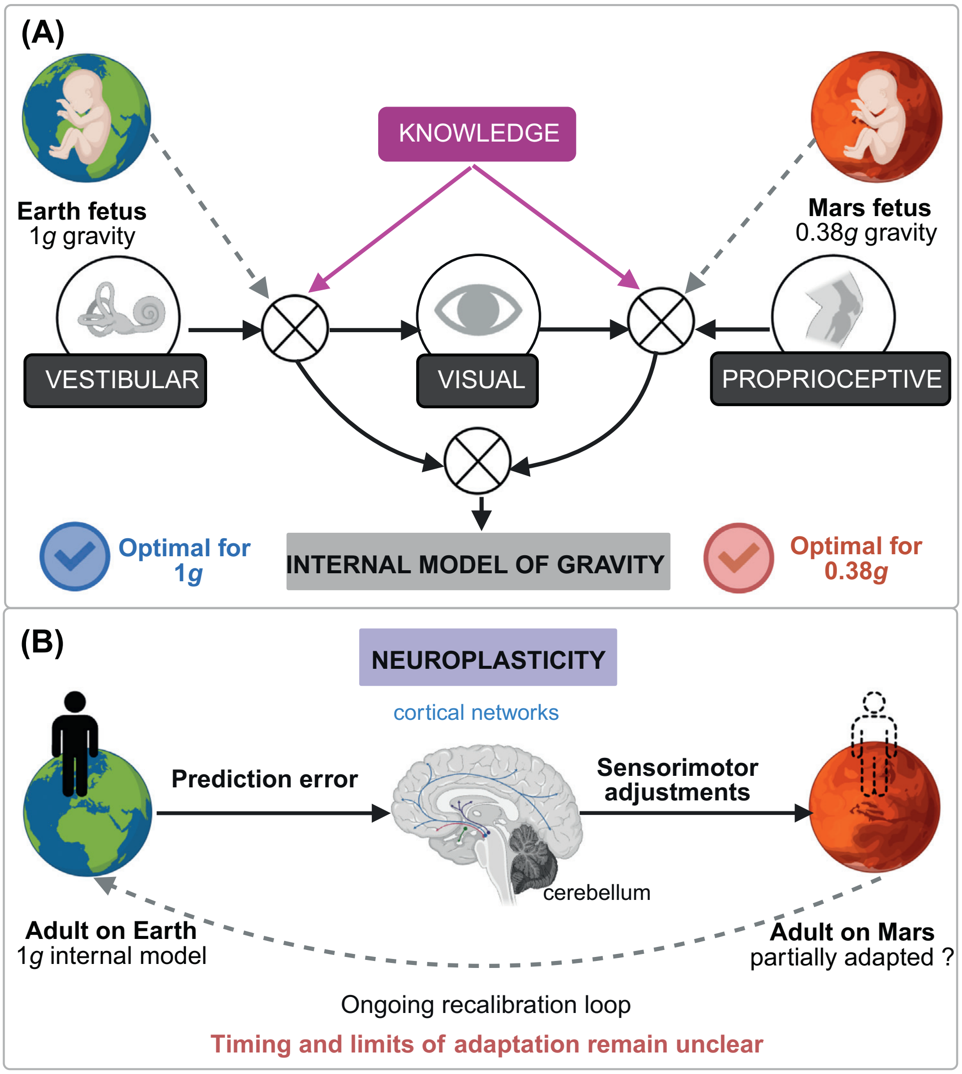

Figure 1. The adaptability of the internal model of gravity. (A) The nervous system builds a predictive internal model of gravity through multisensory integration (vestibular, visual, and proprioceptive), shaped by lifelong experience and prior knowledge. Critically, this model is tuned to whichever gravitational environment the critical developmental period occurs in—yielding a fully functional model whether development takes place on Earth (1*g*) or on Mars (0.38*g*). (B) Although the 1*g* internal model is strongly shaped by terrestrial development, it retains some flexibility. When an adult travels between gravitational environments, prediction errors drive sensorimotor adaptation supported by neuroplasticity within cerebellar and cortical networks. Unlike developmental calibration—which reliably produces an optimal model for the native gravity—adult recalibration is not guaranteed to be complete, and its timing and limits remain unclear. This figure was created using BioRender (http://biorender.com/).

and parietal regions implicated in sensorimotor prediction [11]. Together, these systems integrate sensory signals with prior knowledge to construct a dynamic representation of gravity. On Earth, this internal model operates seamlessly, supporting stable posture, coordinated movement, and accurate prediction of object behavior in daily life. Beyond Earth, however, in environments such as microgravity or reduced gravity, this same model can become a source of systematic error, as predictions tuned to 1*g* no longer match incoming sensory signals. Because the model is

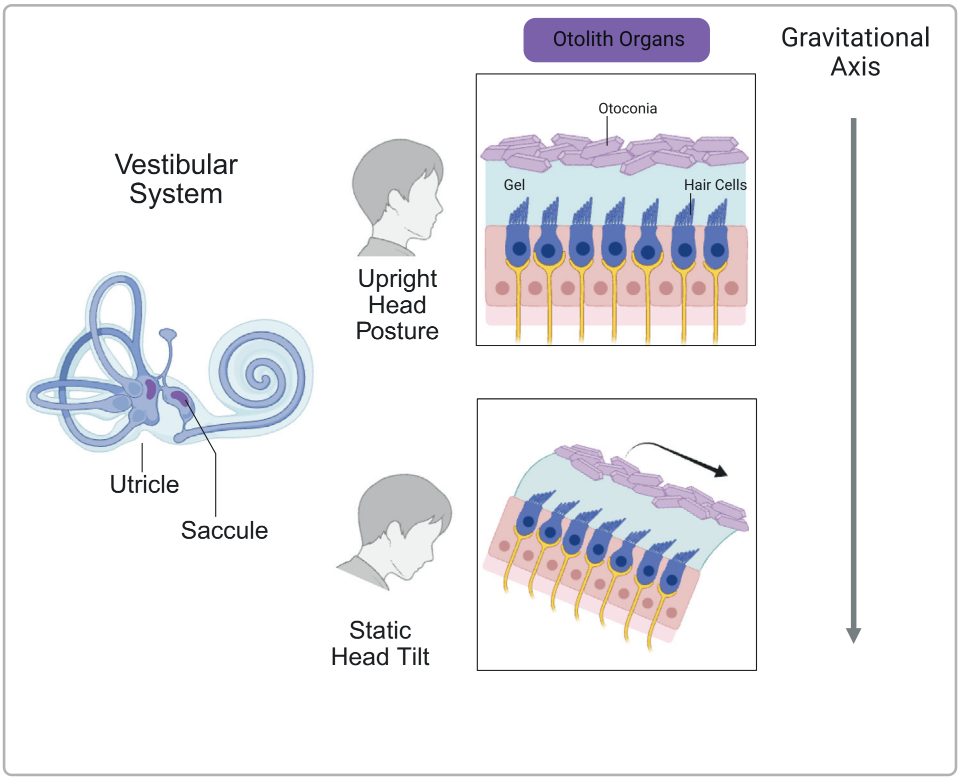

Figure 2. The vestibular system. The vestibular system consists of three semicircular canals, which detect angular acceleration, and two otolith organs (utricle and saccule), which detect linear acceleration (i.e., gravity and translational movements). The surfaces of the utricular and saccular maculae are covered by the otolithic membrane, consisting of fibers embedded in a gel with a superficial layer of stone-like crystals, the otoconia. Linear accelerations or gravity produce displacements of the otoconia, bending the cilia of the hair cells. This figure was created using BioRender (http://biorender.com/).

calibrated through lifelong experience under Earth's gravity, it must be updated when individuals transition to non-terrestrial environments.

When gravity changes: sensorimotor adaptation in space

Astronauts entering microgravity often experience disturbances in posture, locomotion, force generation, and spatial orientation [15,21]. These difficulties arise because incoming sensory signals no longer match predictions generated by the brain's internal model of gravity [22,23]. In microgravity, the otolith organs are no longer continuously detecting Earth's gravitational pull [13]. As a result, vestibular signals become ambiguous, requiring the nervous system to reinterpret the relationship between sensory input and environmental dynamics. This mismatch gives rise to sensory prediction errors, that is, discrepancies between expected and actual sensory feedback [24]. Such errors are central to **sensorimotor adaptation** [25,26]: when the brain detects a persistent mismatch, it updates its internal model to reduce future errors [27–29].

Evidence from human spaceflight shows that astronauts progressively recalibrate their sensorimotor systems in response to these errors. The Apollo missions provide a particularly striking example. Upon first stepping onto the lunar surface, astronauts—whose motor systems were calibrated under Earth's gravity—encountered a radically different gravitational environment

(0.16*g*). Early movements were often hesitant and inefficient, with frequent misjudgments of momentum and occasional falls. However, within a short period, behavior changed markedly: movements became smoother and more economical, and astronauts adopted a characteristic bounding gait better suited to lunar gravity. These observations capture the nervous system actively recalibrating its expectations of how the body moves under altered gravitational conditions [15].

More broadly, during the early stages of space missions, astronauts typically exhibit impaired locomotion and reduced postural stability. These effects tend to diminish over time as 'adaptation' occurs [22,30], particularly when partial gravitational cues are available, as in lunar or Martian gravity [31–33]. Converging evidence from ground-based analogs supports the same pattern: a 4-month isolation study conducted in a simulated space-station environment demonstrated comparable adaptation in locomotion under simulated lunar (1.625 m/s^2; 0.16*g*) and Martian (3.721 m/s^2; 0.38*g*) gravity [34].

Prior experience also plays a role in this process. Astronauts with previous spaceflight exposure often adapt more rapidly on subsequent missions [35,36], a phenomenon known as 'savings', suggesting that earlier sensorimotor learning can be retrieved to accelerate recalibration. Further evidence of gravity-dependent updating comes from postflight aftereffects. Upon return to Earth, astronauts commonly exhibit transient impairments in balance and locomotion, indicating that the internal model of gravity has been recalibrated during flight and must readjust to terrestrial gravity [23,37].

Although these findings demonstrate that the brain can adapt to altered gravitational environments, the time course and limits of this recalibration remain poorly understood [38–40]. From a computational perspective, the relatively slow adaptation may reflect the strength of prior expectations about gravity [41]. Because the nervous system is shaped by a lifetime of exposure to Earth's gravitational field, updating this strongly weighted prior likely requires prolonged and consistent sensory evidence.

Neural mechanisms supporting adaptation to non-terrestrial gravity

Sensorimotor adaptation depends on plastic changes within distributed neural circuits that update predictions about the sensory consequences of actions [42]. Converging evidence from behavioral experiments, lesion studies, and neurophysiological investigations indicates that the cerebellum plays a central role in this process [25,43,44]. The cerebellum is thought to implement forward internal models that predict the sensory outcomes of motor commands. When discrepancies arise between predicted and actual sensory feedback, cerebellar circuits compute error signals that drive adaptive changes in motor output. Patients with cerebellar damage exhibit profound impairments in sensorimotor adaptation, highlighting the importance of this structure in error-based learning [26]. animal studies provide evidence that sensorimotor adaptation involves the updating of a cerebellum-based internal model [22,27,28]. Recent findings show that motor adaptation to altered gravity follows temporal dynamics similar to those observed during adaptation to external perturbations, further supporting the hypothesis that the cerebellum plays a central role in both forms of adaptation [45].

Early stages of adaptation often involve additional brain regions associated with cognitive control [46,47]. Functional imaging studies have reported increased activity in prefrontal areas and the presupplementary motor area when individuals first encounter sensorimotor perturbations [48]. These regions likely support the development of explicit strategies to compensate for unexpected changes in the environment. As adaptation progresses and performance stabilizes, neural activity shifts toward sensorimotor regions, including the posterior parietal cortex and primary motor cortex [49,50]. These areas are believed to contribute to the consolidation and long-term storage of updated sensorimotor representations.

Plasticity underlying these behavioral changes operates across multiple levels of neural organization, from synaptic modifications within local circuits to large-scale reconfiguration of functional brain networks [51,52]. Measures of cerebellar brain inhibition, a physiological marker of the inhibitory influence exerted by the cerebellum on the primary motor cortex, often decrease during sensorimotor adaptation tasks [53]. The magnitude of this reduction correlates with behavioral improvements, suggesting that adaptive learning is accompanied by changes in cerebellar excitability and cerebello-cortical connectivity [54]. Such findings support the idea that adaptation involves dynamic adjustments in the balance of activity across distributed motor networks [55]. Neuromodulatory systems further influence these plasticity mechanisms. **Dopamine**, in particular, plays a central role in shaping motor learning by signaling reward prediction errors and modulating synaptic plasticity within cortico-basal ganglia circuits. Genetic studies have shown that individual differences in dopaminergic transmission can influence adaptation performance, with polymorphisms affecting dopamine availability predicting variability in learning rates and retention [56]. Similarly, **brain-derived neurotrophic factor (BDNF)** contributes to synaptic strengthening and long-term potentiation, supporting the consolidation and retention of newly acquired motor behaviors [57]. This is particularly relevant in altered gravity, where recalibrated sensorimotor mappings must be stabilized beyond the initial exposure if performance is to remain reliable over time or upon re-exposure. Consistent with this role, the val66met polymorphism in the *BDNF* gene has been associated with alterations in short-term cortical plasticity and reduced rates of adaptation to environmental perturbation during learning in humans [57,58].

These neuromodulatory influences help regulate the efficiency and persistence of sensorimotor learning. Accordingly, data from spaceflight indicate divergent effects on key regulators of neural plasticity, with evidence suggesting reduced dopamine levels alongside relatively preserved BDNF levels [59,60]. However, findings from spaceflight remain limited, and further research is required to clarify the underlying mechanisms and refine countermeasures targeting the dopamine system.

Although most of this evidence comes from terrestrial laboratory studies, research conducted in spaceflight and spaceflight analog environments suggests that similar plasticity mechanisms support adaptation to non-terrestrial gravitational conditions, even though the findings need to be cautiously interpreted due to inherent methodological difficulties associated with space neuroimaging research [40,61,62]. Neuroimaging studies conducted before and after long-duration missions provide emerging evidence for structural and functional changes associated with space adaptation [63]. For example, magnetic resonance imaging studies have reported alterations in functional connectivity within networks involving the cerebellum, parietal cortex, and sensorimotor areas following extended missions aboard the International Space Station (ISS) [64]. These changes are thought to reflect the reorganization of neural circuits responsible for integrating vestibular and somatosensory information. Structural brain imaging studies also indicate that spaceflight can induce changes in white matter microstructure and cerebrospinal fluid distribution, particularly in regions involved in vestibular processing and motor control, suggesting that prolonged exposure to microgravity may drive structural remodeling within neural circuits supporting sensorimotor integration [65]. That is, adaptation to altered gravity involves dynamic reorganization of distributed sensorimotor networks [36]. The cerebellum appears to play a central role in updating predictive models in response to sensory prediction errors, while cortical and neuromodulatory systems contribute to strategic compensation, consolidation, and long-term retention. Understanding how these mechanisms interact will be essential for developing strategies to enhance human adaptability to non-terrestrial gravitational environments.

Development in altered gravity

For the mature astronaut, altered gravity is a perturbation imposed on an already calibrated organism. For the fetus, infant, and child, by contrast, gravity is part of the teaching signal from which calibration itself emerges. The vestibular apparatus begins developing early in gestation; vestibular receptors are functional before birth, and the central circuits that integrate vestibular, visual, proprioceptive, and somatosensory cues continue to mature through infancy, childhood, and into adolescence [66,67]. In that sense, gravity is not merely a background force that the brain compensates for; it is one of the regularities through which the developing nervous system learns what counts as upright, effortful, stable, and predictable.

This framing changes the meaning of the altered-gravity literature. The strongest lesson from animal developmental studies is not simply that changing gravity perturbs development, but that timing matters. In rodents, prenatal spaceflight and other altered-gravity exposures can delay righting responses, modify the branching of graviceptive vestibular afferents, and produce lasting effects that depend on when, during development, the perturbation occurs; more broadly, the available evidence points to sensitive periods spanning the peripheral vestibular organs, vestibular nuclei, cerebellar development, and postural-motor output [67–70]. These studies are fragmentary, species-bound, and confounded by maternal physiology, stress, and mission constraints; therefore, they do not justify deterministic claims about human outcomes. However, they do justify a stronger conceptual point: Mars would not merely require recalibrating a terrestrial prior; it could alter the conditions under which that prior is first built.

Mars matters especially because it is not microgravity but partial gravity. A child raised at 0.38*g* would still receive chronic graviceptive and mechanical input, but it would be weaker than the signal under which terrestrial human development evolved. As discussed, adult studies of lunar- and Martian-like unloading already show that partial gravity changes gait mechanics, ground reaction forces, gait transitions, and the dynamics of everyday functional tasks such as standing up, walking, obstacle negotiation, and fall recovery [1,15,71]. Developmentally, this suggests not a uniform delay but a redistribution of constraints. Some actions may become mechanically easier because body weight is lower; at the same time, weaker loading of muscles, joints, plantar surfaces, and otolith-linked postural reflexes may reduce the fidelity of the very signals used to tune balance, gaze stabilization, and body orientation. The likely outcome is therefore not 'slower Earth development in light gravity', but a different solution to the problem of becoming a stable, mobile body.

This is where the vestibular literature becomes especially important. In children on Earth, severe vestibular impairment is associated with delayed acquisition of head control, sitting, standing, and independent walking, as well as with downstream consequences for gaze stability, reading, and broader spatial-cognitive development [66,72–75]. Mars would not remove vestibular input in the way bilateral vestibular loss does, but partial gravity may still shift the weighting of sensory evidence during exactly the years when the brain is learning which cues deserve trust. A concrete prediction, therefore, is not global impairment but altered sensory weighting: children raised in Martian gravity may come to rely more heavily on visual and somatosensory cues when estimating verticality and stabilizing posture, especially under conditions of sensory conflict. Such a phenotype could be adaptive on Mars and yet prove costly during transitions to Earth, where the same internal model would suddenly be wrong in systematic ways.

The implications may extend well beyond balance and locomotion. Developmental science has repeatedly shown that motor milestones are not isolated outputs of maturation; they reorganize what infants can perceive, explore, manipulate, and learn. Posture provides the base for looking and reaching; self-locomotion changes visual input, social access, and opportunities for exploration. Earlier sitting and walking predict later gains in spatial language, spatial cognition, and vocabulary, in part through their effects on exploratory behavior [76–79]. Recent altered-gravity work in adults goes further, suggesting that the capacity to recalibrate movement under non-terrestrial gravity covaries with the ability to update abstract physical reasoning under the same altered rules [80]. Taken together, these findings argue that gravity-related priors are unlikely to be confined to posture and action. They may help scaffold how developing minds learn the statistical structure of physical events—what falls, how fast, what counts as support, and how bodies move through space.

We should, therefore, discuss one stage earlier in development: gestation and birth. Here, the evidence base becomes strikingly thin. There have been no human pregnancies in space, and the available mammalian data are sparse, heterogeneous, and difficult to disentangle from radiation, maternal physiology, and other spaceflight stressors [81–83]. The prenatal period cannot be treated as irrelevant to gravity-dependent development: the fetus is not simply 'weightless' because the vestibular system becomes functional before birth and is stimulated indirectly by maternal motion, while maternal cardiovascular and uterine physiology remains gravity-sensitive [67,83]. Intriguingly, two-cell mouse embryos cultured aboard the ISS developed to the **blastocyst** stage with apparently normal early differentiation, suggesting that the earliest stages may be more robust than once assumed [84]. Yet other studies point in the opposite direction, with simulated microgravity impairing sperm navigation, fertilization, and early embryonic development, and rat spaceflight studies documenting altered labor dynamics and neonatal vestibular effects [68,85,86]. The right conclusion is neither complacency nor science fiction. It is that conception, implantation, placentation, gestation, birth, and postnatal development must be treated as separable questions, each with its own gravitational biology.

Seen in this light, altered gravity becomes a uniquely powerful problem for developmental cognitive neuroscience. It tests how deeply a seemingly stable feature of the physical world becomes embedded in the architecture of perception, action, and thought. The most interesting prediction is not that Mars-born children would be globally impaired, nor that they would be effortlessly adapted, but that they would be locally optimal for a different planet. Their motor solutions, sensory weightings, and expectations about object dynamics might be coherent, efficient, and developmentally normal within a 0.38-*g* world, while becoming maladaptive when imported back to Earth. Adult astronaut adaptation already shows that internal models of gravity are plastic; developmental evidence suggests that the period of highest plasticity is also the period of highest **ontogenetic** consequence. If so, the first generation born beyond Earth would not simply teach us about resilience in extreme environments. They would force us to ask a deeper question: how much of what we call human cognition is, in fact, cognition calibrated by one planet?

Concluding remarks

Human exploration of space is entering a new era in which long-duration missions and potential planetary settlements are becoming increasingly plausible. As humanity prepares to expand beyond Earth, understanding how the brain adapts to altered gravitational environments will be essential. The evidence reviewed here suggests that the nervous system constructs a predictive internal model of gravity through multisensory integration and lifelong experience. Although this model is strongly shaped by terrestrial conditions, it remains flexible enough to recalibrate

Outstanding questions

How do different mechanisms interact during adaptation and change over the course of adaptation? How do these multiple processes interact in more complex sensorimotor tasks?

Which spaceflight changes are adaptive, compensatory, or damaging?

Do these compensatory mechanisms come with specific trade-offs? What is the timeline for these mechanisms?

How does neuromodulatory signaling affect plasticity during motor learning in spaceflight-analog environments?

How is space affecting the regulation of brain function in humans?

How will the changing interaction between body and environmental constraints on Mars affect infants' behavior and cognition?

when gravitational environments change. Sensorimotor adaptation, driven by prediction errors and supported by plasticity within cerebellar and cortical networks, allows humans to adjust their behavior in novel environments. However, the limits of this adaptability remain unclear. Future research must address several key questions (see Outstanding questions): how quickly can gravitational predictions be recalibrated, how stable are these changes over time, and how might developmental processes unfold under reduced gravity? Preparing humans for life beyond Earth may therefore require proactive strategies that enhance the adaptability of the sensorimotor system. Ultimately, the challenge of living in extraterrestrial environments is not only a technological problem but also a neuroscientific one. Understanding how the brain learns to navigate new physical realities will play a crucial role in shaping the future of human exploration.

Author contributions

H.G.R., O.O., and E.R.F. jointly developed the conceptualization for this opinion and wrote the manuscript. All authors have read and approved the final manuscript.

Declaration of interests

The authors declare no competing interests.

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