Man has always explored, exploited, colonised and controlled his environment by expanding his field of activity. From the very first hominids, technological progress has exposed our species to extreme situations and hostile environments. Previously, the great explorers and navigators, conquerors of the impossible, travelled incredible distances across the seas and oceans. Land that was undeveloped and unexplored by civilization thereby ‘disappeared’, and land borders fell away.

But although mankind’s expansion into Space seems irreversible, it is still a major challenge for humans because of the significant gap between man’s evolutionary history and the environment in which he will have to survive for months or even years. Gravity has shaped the plant and animal world over millions of years, and we spend much of our lives resisting it.

In the context of spaceflight, this situation becomes evident after just 15 days of microgravity, when major changes are seen in the cardiovascular, skeletal, muscular and nervous systems, to mention only the most important. Even at the cellular level, microgravity causes changes in gene expression and alterations in cell response and morphology.

The scientific communities working on Life Sciences in the microgravity environment can call on a number of different existing space- and ground-based facilities to conduct their experiments.

The International Space Station (ISS) is the primary experimentation platform for these disciplines (Fig. 1). Others, including recoverable capsules, sounding rockets, balloons, parabolic flights and ground simulation equipment, are put to use within national, European or international frameworks.

Bioastronautics research has applications in routine medicine that are increasingly being recognised, particularly to address the physiopathology of metabolic risks associated with the population’s shift to a more sedentary lifestyle.
This has now become a real public health issue, since physical inactivity has been ranked the second cause of death in industrialised countries. The prolonged bed-rest model (Fig. 2) used in space medicine offers a unique way of reproducing severe long-term inactivity and testing the effects of physical inactivity on healthy subjects who will recuperate.

Under these unique conditions, the harmful mechanisms of inactivity leading to disease can be studied. These studies are not of course confined to metabolism, but also investigate the bones (osteoporosis), muscles (sarcopenia) and cardiovascular system (orthostatic intolerance). All the body’s physiological functions are addressed by space medicine. It is undoubtedly one of the few remaining disciplines in which expertise in integrative physiology has been maintained. This integrative approach is obviously enhanced by recent developments in molecular biology and new analytical technologies such as the «omics».

More specifically, the topics covered in space physiology deal mainly with functions whose adaptation causes problems for astronauts’ wellbeing and performance (Fig. 3). These include the musculoskeletal and cardiovascular systems, immunology (this is one of the research priorities for planetary exploration because ever since spaceflight began, a higher frequency of infections - in flight or after returning to Earth - has been observed; only recently have data been available to examine the mechanisms), nutritional and energy sciences, animal gravitational biology, radiation biology, psychology and lastly neurosciences and development, which are the subject of an article in this report to COSPAR.

The development issues relate to central problems of evolutionary biology. The article presented by Dr Jamon in this report will review our knowledge of the role of gravity in development, whereas the one presented by Dr McIntyre will look at control of visual-motor coordination in humans.
Life Sciences in Space

The adaptation of posturo-motor control in mature and developing mammals exposed to hypergravity

In the perspective of exploration and colonization of far space, human being will be durably exposed to gravity levels lower than Earth gravity. This is a considerable challenge for the organisms that evolved under the constant drive of Earth gravity. The potential consequences of these new life environments can be viewed in the motor and postural output that is driven by the musculo-skeletal and the vestibular systems, both nearly dependent on the gravity vector. Durable reduction of the gravity level cannot be reproduced on Earth. Instead, artificial increase of gravity by chronic centrifugation is used assuming that biological responses exhibit alteration of cognitive and vegetative functions. These responses do not fit the hypothesis of a continuum in the adaptation to gravity.

The effect of hypergravity on posturo-motor control was studied in mice centrifuged at different levels of gravity or at different ages. The results showed that the motor control adapts to the gravity level perceived during early motor development. In adult hypergravity improved muscular output until 3g, then perturbed the vestibular response with alteration of cognitive and vegetative functions. These responses do not fit the hypothesis of a continuum in the adaptation to gravity.

To get a comprehensive view of the effects of hypergravity on the control of posture and movement, experiments were carried out on mature or immature mice, C57BL/6j, exposed to different levels of gravity in a large diameter centrifuge designed by the CNES [2]. Two months old mice were centrifuged during 21 days at gravity levels of 2, 3 or 4g to check for continuity in the response to gravity. The gain of body mass during the centrifugation was inversely proportional to gravity (Fig. 1a), but the various tests performed after centrifugation did not fit the continuity principle. The muscular performance increased until 3g, but higher level of gravity was detrimental (Fig. 1b, 1c). This change was mirrored in the structures of muscles and bones, but did not affect the posture and motricity. The mice centrifuged at 3 and 4g, but not 2g, showed a different vestibular response (Fig. 1d). They also showed an impaired spatial learning and an increased anxiety (Fig. 1e) [4], that were probably related to the altered vestibular response. Indeed, the vestibular system influence spatial learning by acting on the head direction cells that code for the directional heading with respect to the environment [3], and the stress level through a modulation of the sympathetic responses by vestibulo-thalamic connexions [5].

The exposition to hypergravity induced a totally different profile of responses in immature mice [6]. For instance, mice centrifuged at 2g from the conception to the age of 1 month (P30) (i.e. when the motor development is completed), then tested at the age of two months, showed a lower muscular force (Fig. 2c), a postural change, with more extended hindlimbs and more flexed forelimbs (Fig. 2a), and they walked with smaller and faster strides than controls (Fig. 2e, 2f).
They showed also reduced otholitic sensitivity, but their vestibular performance was not impaired. These changes suggested that gravity level supported during specific periods of the development definitely shaped the adult motor pattern. To test this hypothesis mice were centrifuged either from conception to P10, or from P10 to P30. The first period encompassed the main part of the development of the vestibular system, and the latter the acquisition of locomotion, even though the full developmental process of these functions overlapped. The change in the motor pattern was observed in mice centrifuged from P10, but not before, thus the motor characteristics were driven by the gravity supported during the acquisition of locomotion. On the other hand the postural change was found in all groups suggesting that earlier centrifugation sufficed to modify the postural arrangement. In addition, the mice centrifuged during part of their development showed other changes probably due to the incoherence of the gravity level perceived during the vestibular and motor development. Fore instance, the mice centrifuged from P10 showed impaired vestibular reactions (Fig. 2d), that suggested a conflict between the gravity level perceived during vestibular development and later developing associated structures, probably the vestibulo-cerebellar connections. On the other hand, the mice centrifuged until P10 showed a higher metabolic rate (Fig. 2b).

The present studies showed that postural and motor control is tuned with reference to the gravity level supported during the development of the related functions, while it remains relatively stable in adults subjected to altered gravity. Nevertheless, the increased constraint supported under hypergravity first acts as endurance training on the musculo-skeletal system, then both musculo-skeletal and vestibular system are affected, with side effects on secondarily related functions. The threshold is about 3g in mice, but varies with the species and body size. These results do not fit continuity in the response to gravity change. Even though mirror effects were previously observed between micro- and hypergravity environments, the exposition to minigravity should be investigated further, and particularly the existence of threshold in the response of the organism should be evaluated.

References

How the brain adapts to the unusual conditions of weightlessness has attracted considerable attention by neurophysiologists ever since humans have embarked on orbital spaceflight and beyond. Early studies concentrated on the role of the otolith organs of the inner ear and the control of posture, due to the obvious link between these two systems. To stand upright, one must maintain the body’s center-of-gravity over a limited base of support (the feet). Sensory information about the direction of gravity, provided by the otoliths, serves to maintain this critical vertical configuration of body segments on the ground.

Neural circuits link voluntary movements of the upper limbs to compensatory activity in postural muscles of the trunk, hips and ankles in anticipation of the destabilizing effects that changing limb configuration has on the center-of-gravity and dynamic stability. During spaceflight, however, the absence of gravity removes the threat of falling. It is therefore surprising to see these same neural responses in astronauts when they first arrive on orbit [1].

The continued presence of these synergies between muscles of limb and trunk in 0g, with only a gradual adaptation to weightlessness, attests to the relatively hard-wired tuning of neural circuits to the constraints imposed by a normal gravitational field. Still, careful analysis of movement dynamics in weightlessness reveals the capacity of the nervous system to adapt and control separately postural equilibrium and goal-directed movements, providing insight into how the CNS simplifies the highly complex problem of controlling movements of the body [2].

Spaceflight has thus provided a valuable tool for understanding basic mechanisms of postural control in humans, a process that obviously depends critically on knowing the direction of gravity’s effects on the body. More recent studies have revealed, however, more subtle influences of gravitational sensation on other, more cognitive aspects of human behavior. Consider the task of intercepting a moving object. Fundamental theory suggests that the brain uses simple ‘first-order’ approximations, equivalent to calculating distance divided by velocity, to estimate future positions of the target, effectively ignoring acceleration because the eye does not directly provide such higher-order information.

Studies on the ground suggest, however, that the brain specifically anticipates gravitational acceleration, allowing one to precisely synchronize interceptive movements, such as a tennis swing, to the arrival of a falling object. When astronauts caught balls projected downward aboard the space shuttle, they produced systematic shifts in the timing of muscular responses, thus demonstrating that the nervous system indeed anticipates the effects of gravity on flying objects even when gravity is not there [3].

**Abstract**

**Lors d’un vol spatial, le cerveau humain doit gérer des informations sensorimotorices qu’il n’a jamais rencontrées auparavant sur Terre. Étudier la capacité des astronautes à s’adapter à l’impesanteur est donc primordial pour assurer la sécurité des vols habités vers la Lune et au delà. En même temps, ces études nous renseignent sur le traitement de l’information gravitaire par le système nerveux en conditions terrestres. L’exploration de l’espace veut, donc, aussi dire l’exploration du cerveau humain.**

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It is likely that sensory cues such as lighting, presumed to come from above, the clearly identified floor, walls and ceiling of the orbiting module and the normal upright posture of astronauts within this environment creates a cognitive up/down context that replaces the reference usually provided by gravity, causing the nervous system to predict that a moving target will accelerate in the ‘downward’ direction (Fig. 1). Nevertheless, human subjects show a reversal in the relative timing of interceptive responses to upward or downward moving targets during very brief (20 s) exposure to 0g (Fig. 2a) [4].

These reversals can be linked to the expected discharge patterns of otolith sensory organs during the frequent gravity transitions experience during parabolic flight (Fig. 2b), thus demonstrating a somewhat astonishing effect of vestibular sensation on processes of eye-hand coordination (Fig. 2c).

Spaceflight has thus provided a fascinating window into the workings of the human brain. Future studies using sophisticated techniques such as multi-electrode electroencephalography (EEG) [5] promise to provide further insight into how the human brain processes sensory information about gravity and how it adapts its perceptual mechanisms and sensorimotor processes to the unique conditions of weightlessness.

References


