

# *Neuroeconomics in Orbit: Insights into Astronaut Decision-Making via Prospect Theory and Space-Induced Neurophysiological Changes.*

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## **ABSTRACT**

The success of a space exploration mission heavily depends on the astronaut's ability to make rational decisions under conditions of risk and uncertainty. Importantly, astronauts' brains undergo significant neurophysiological changes. This makes understanding the brain areas and neuromodulatory systems involved in risky decision-making critical for the safety of space travel. Prospect theory, developed by Daniel Kahneman and Amos Tversky, is a high level theory which explains economical decisions of people under risk and uncertainty. More specifically, its components, including the value function, weighting function, and prospect representation, provide a framework for understanding how individuals evaluate options and make choices in high-stress environments. Conducting experiments in space is challenging if not impossible. To overcome this, I will analyze existing literature to (i) examine the involvement of specific brain regions in each component of the value, weighting function, and prospect representation, (ii) investigate neurophysiological alterations in these brain regions during space travel, (iii) demonstrate how alterations in brain function influence astronaut behavior during decision-making.

## **INTRODUCTION**

While decision-making under risk is inherently stressful, high-stakes environments such as spaceflight amplify the stress to an exponentially higher degree — and they often require swift yet accurate decisions, where the cost of error is extraordinarily high. Impaired decision-making by astronauts in space can potentially lead to catastrophic failures, jeopardizing lives and multi-billion-dollar investments; however, there is a scarce amount of documented accidents, possibly related to space agencies which, along with providing rigorous psychological training, seek a balance between raising awareness and maintaining privacy [1]. For example, several former astronauts, such as Scott Kelly and Mike Massimino, have

discussed the challenges they faced in their books, which are not always captured in real-time mission reports. Additionally, Bryan Burrough's book, "Dragonfly: NASA And The Crisis Aboard Mir," details critical incidents on the Russian space station Mir, including fires, collisions, and the psychological stress experienced by astronauts and cosmonauts. These accounts highlight the complexities of space missions that may not be fully documented in official reports. Still, unsuccessful incidents on spacecraft that are documented are primarily attributed to the objectively poor decisions of the team as a whole, rather than to the inaccurate decision-making of an individual astronaut. This is because missions are considered as highly collaborative efforts, with decisions made collectively by the crew and mission control. However, as we enter the era of long-distance and long-term space travel, space agencies are likely to grant astronauts more autonomy in decision-making [2], [3] — this change is anticipated due to the challenges in maintaining constant monitoring that arise from communication difficulties [4], [5]. Thus, the proficiency of astronauts in autonomously making risky decisions while navigating a wide array of challenges — such as spacecraft maintenance, navigation, adapting to unexpected environmental conditions, efficient resource management, medical emergency response, and dealing with isolation — especially under stress, is crucial.

The ability to make successful decisions under risk and stress is examined in the field of Neuroeconomics, which connects behavior in economic choices to neuroscience, often more specifically to behavioral neuroscience, computational neuroscience, and neurophysiology. One of the most important theories developed since the emergence of the field was Prospect theory, which revolutionized the way we think about choices under risk. In 1979 Daniel Kahneman and Amos Tversky challenged the prevailing Expected Utility Theory by introducing Prospect Theory, and delineating its three pivotal components — the value function, the weighting function, and

prospect representation—to offer a comprehensive model for predicting human behavior in economic choices [6].

Firstly, the value function in Prospect Theory demonstrates how individuals perceive outcomes in terms of gains and losses relative to a reference point, rather than in terms of absolute outcomes. It posits a concave curve for gains, indicating diminishing sensitivity to increasing gains, and a convex curve for losses, suggesting increasing sensitivity to escalating losses. This reflects the principle of loss aversion, illustrating the human tendency to experience losses more intensely than equivalent gains. Secondly, the weighting function provides insight into the assessment of risks, and the biases behind it. Specifically, it highlights the relationship between objective probabilities and how those probabilities are subjectively interpreted. Based on this function, people tend to underweight high probabilities and overweight low probabilities. Lastly, prospect representation introduces two new concepts: framing effect and editing operations. The perception of choices can be systematically altered by their description, affecting whether outcomes are viewed as losses or gains from a particular reference point, called the status quo. This framing effect alters decision-making; for example, medical treatment options may be perceived differently when described in terms of survival rates versus mortality rates[7]. During editing operations, decision-makers often mentally change and simplify the presentation of their choices by (i) combining similar outcomes, (ii) segregating sure outcomes, (iii) canceling out common elements between options, (iv) rounding off numbers for simplicity, and (v) immediately dismissing options that are clearly inferior.

This study is organized around the hypothesis posited by Trepel et al., which pinpointed the brain regions associated with the subcomponents of Prospect Theory.

The brain areas that we are going to explore (NAcc, dACC, VMPFC) have shown sensitivity to space-related conditions, including microgravity, radiation, and altered circadian rhythms.

Despite considerable advancements in understanding how specific brain regions are

implicated in decision-making processes, a significant research gap persists at the intersection of neuroeconomics and astronaut neurophysiology. By bridging this gap, we will obtain a deeper understanding of the effects environmental conditions have on cognitive functions, and consequently, on economic choices and risk assessment. Such an interdisciplinary approach will contribute to the optimization of decision-making processes in space and the development of more effective strategies for supporting astronauts' mental and physical well-being during long-duration space expeditions (LDSEs), ultimately enhancing overall mission success.

## ANTICIPATED GAINS

Astronautics, with its inherently social focus, warrants consideration of findings from studies exploring the activation of brain parts towards both self-directed and charity-directed rewards, including social rewards.

### *Nucleus accumbens*

Nucleus accumbens (NAcc) is located within the ventral striatum and is well-recognized established for its significant involvement in appetitive and aversive motivated behavior, specifically reward and loss anticipation. The connection between the ventral tegmental area (VTA) and NAcc is fundamental to understanding reward mechanisms within the brain, e.g. increased activity from VTA was shown to increase dopamine release into the NAcc [8]. While some studies indicate its prevalence mostly in reward anticipation than loss anticipation [9], other studies also demonstrate its activation during loss anticipation. In this section, we will mostly discuss its role in reward anticipation.

As mentioned before, space exploration directly or indirectly pursues socially oriented goals, for example, the development of space technologies which are subsequently implemented on Earth or scientific research studies. As stated by NASA, “the fundamental benefits of space exploration are (i) innovation, (ii) culture and inspiration, and (iii) new means to address global challenges” [10]. Thus, it can be presumed that astronauts may experience a strong sense of social responsibility towards their

colleagues, mentors, young aspiring astronauts, funding agencies and the human kind. In fact, it was stated that the experience of space flight has increased astronauts' sense of interconnectedness with other people [11]. Accordingly, it is critical to explore particularly charitable and social rewards in the context of astronauts' risky decision-making. This is underscored by findings that demonstrate a significant difference in brain response—specifically, the nucleus accumbens (NAcc) exhibits lower activation to charitable rewards than to self-directed rewards [12]. This approach highlights the importance of differentiating rewards an astronaut might face in space.

Interestingly, the reward processing of astronauts extends to their honesty levels. Honesty may manifest in their interactions with crew members, colleagues on Earth, whether it involves social interactions, reporting research results, or sharing milestones achieved. A 2014 research study has investigated the correlation between individuals' NAcc activation during anticipated reward and their demonstrated levels of honesty. Following the assessment of NAcc signals during reward anticipation, participants were provided an opportunity to gain money through inaccurate self-reporting. The findings suggested that individuals with heightened NAcc activation during reward anticipation tend to exhibit lower levels of honesty, possibly attributable to a higher valuation of monetary rewards [13]. This is further reinforced by the observation showing a parallel increase in NAcc activity with the rise in expected gain magnitude [14].

What implication does this trend have in spaceflight? The NAcc activation is influenced by the ventral tegmental area (VTA) sending dopaminergic projections to the NAcc. The activation of both D1- and D2-type receptors is critical for this process [15-], [16], [17]. It has also been specifically shown that variations in risk preference and real-time risky decision-making can be largely attributed to how prior unfavorable outcomes are encoded by D2R-expressing NAcc cells during decision-making [18]. Furthermore, although it has been widely held that reward processing predominantly involves D1 type neurons [19], [20], recent findings indicate that stimulation of both D1- and D2-type neurons can enhance

various types of motivation in mice [21], [22]. Thus, research on dopamine neurons in spaceflight conditions like microgravity may provide important insights into NAcc activation.

To start, one piece of research indicates that following a week of exposure to microgravity, subjects showed a reduced number of D2 receptors in the striatum compared to those in the control group [23]. Consistent with the findings that increased D2 receptor expression in the NAcc enhances motivation [24], the expectation that decreased D2 receptor expression will decrease motivation is supported by numerous studies.

Additionally, more recent studies have also demonstrated that spaceflight leads to a decrease in D1 receptor expression [25] and a general decrease in the activity of critical genes in the dopamine system [26]. Interestingly, in a mice research study, the infusion of the D1 receptor antagonist into the NAcc led to a reduction in Conditioned Avoidance Responses (CAR) during the training sessions of two-way active avoidance [27]. This implies that in spaceflight conditions, astronauts might exhibit enhanced risk-taking behavior due to difficulties in properly assessing and responding to risks, caused by impaired D1 receptor signaling. This is further supported by the finding that individuals with heightened NAcc activation exhibit higher risk taking behaviour

However, another family of thoughts contradict this reasoning. Through reward prediction error (RPE) signals, dopamine contributes to the modification of value assessments in adaptive behavior, specifically in the reinforcement learning mechanism [28], [29].

In a very recent mice study, it was found that despite the significant impact of rewards on choices and dopamine activity, manipulating dopamine neurons (either by activation or inhibition) at the time of trial outcome did not alter subsequent choices [30]. The researchers concluded that the impact of rewards on decisions may originate from dopamine-independent information regarding the state of the world, rather than from the dopaminergic reward prediction errors (RPEs) generated.

### **Dorsal anterior cingulate cortex (dACC) [Effort based decision making]**

dACC plays a significant role in reward-based decision making [31]; recent studies have also differentiated between dACC activity in foraging choices, which involve changing the default option to another, from traditional economic choices, which typically entail simultaneous evaluation of all available options. This distinction is due to the adaptive nature of foraging behavior, where decisions are often sequential and based on the evaluation of one option at a time. During this type of assessment, activity in dACC was shown to be better explained by choice difficulty than foraging value, i.e. expected reward [32], [33].

Moreover, Shenhav and colleagues showed that dACC's activity does not follow a straightforward path in relation to foraging value. Their findings showed the highest levels of dACC activity when choices between engaging and foraging were equally likely, with a decrease in activity observed when one option significantly outweighed the other [32]. We will apply these findings in discussing the possible changes in astronauts' behaviour during risky decision making with foraging. Moreover, there was found an increased activity of the dACC in the conditions of microgravity [34].

In response to stress, the DMN exhibits increased resting-state functional connectivity to key nodes of the SN (AIC, dorsal ACC [dACC] and amygdala).

Since the HRV HF-component reportedly relates to connectivity between dACC, AIC and amygdala to thalamus and the brainstem, brain oscillatory activity may shift from lower-frequency to higher-frequency bands during adaptation processes. Adaptation to microgravity in Group B1 astronauts may thus be initiated by the SN. Social stress responses reportedly upregulate the DMN functional connectivity towards an alerted default mode, the DMN being intrinsically related to both SN and ECN nodes, mediated by increased activity of the right AIC and dACC.

### **ANTICIPATED LOSSES**

#### **Ventromedial prefrontal cortex (VMPFC)**

Ventromedial prefrontal cortex plays a crucial role in the assessment of loss probabilities, and particularly value calculations. Respectively, excitatory or inhibitory stimulations of that region affect the ability of subjects to anticipate losses and make rational decisions [35].

For example, patients with lesions in the VMPFC consistently demonstrate an inability to make rational decisions, particularly showing a preference for choices that offer immediate rewards despite entailing greater losses [36]. Moreover, it was shown that the anticipatory skin conductance responses (SCRs) of VMPFC patients were much lower than those of the control group [37]. Such lower skin conductance responses were prevalent in people who exhibited risk-seeking behaviour in another research study [38]. From here, it can be stated that people with lesions in the VMPFC area might be prone to exhibit risk-seeking behaviour. Furthermore, studies examining the direct link between VMPFC lesions and heightened risk-seeking behavior in risky decision-making situations often describe this as an "increase in risk appetite" [39], [40].

However, a more straightforward research work directly focused on the effect of spaceflight such as microgravity. It was found that a notable reduction in VMPFC deactivation following a simulated exposure to microgravity implies a diminished capacity for value assessment among participants afterward [41]. Value assessment, or the value calculation process, weighs the potential advantages and disadvantages of a decision, taking into account its subjective value or utility.

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