Journal of Environmental Psychology 94 (2024) 102245

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.elsevier.com/locate/jep

Mental gravity: Modelling the embodied self on the physical environment

Lachlan Kent

Royal Melbourne Institute of Technology, Melbourne, Australia

ARTICLE INFO

Handling Editor: L. McCunn

Keywords:
Gravity
Cognition
Salience network
Default mode network
Self

ABSTRACT

The theory of mental gravity posits that phenomenological, cognitive, and affective states of an embodied self are structured according to the experience of physical gravity (i.e., internal gravity model). The theory draws a behavioral analogy between external (physical), internal (mental), and relational (socio-emotional) environments to argue that physical gravity serves as a mental template to express socio-emotional aspects of the self-world relationship. The theory is based on the principle of cognitive gravitropism, whereby being "up" and "aligned" to the gravitational field confers survival, adaptive, emotional, and social value. The theory explains how mental gravity manifests in cognition and behavior, emotion and personality, large-scale brain networks, and the phenomenology of selfhood. On a surface level, the template for mental gravity derives from an embodied simulation of gravity's physiological effects. At a deeper level, the theory describes the underlying neural, cognitive, and phenomenological processes driving the mental simulation of physical gravity. Neuroanatomy of mental gravity focuses on the vestibular, salience, default mode, and central executive networks. On the basis of default mode activity, the self is viewed as the brain's autobiographical "centre of mental gravity". The self interacts with the socio-emotional environment from this reference frame, communicating feelings associated with the self-world relationship by simulating the effects of physical gravity through affect, behavior, and language. A continuum of mental gravity states is hypothesised to range from positive "up" and "down" states like ecstasy and mindfulness to negative "up" and "down" states like anxiety and depression, respectively.

1. Introduction

This review will outline the theory of mental gravity (MG) – the psychological counterpart to physical gravity. Mental gravity derives from interactions with the external environment (i.e., the outer world) but applies to interactions within the internal environment (i.e., the inner self) and expressions within the socio-emotional environment (i.e., the boundary between inner and outer worlds). The MG theory explains how physical gravity is internalised through the operation of the internal gravity model to help construct an embodied sense of self. Then, by abstracting this gravity model to the narrative sense of self, the MG theory explains how internal mental states are re-externalised via the relational social-emotional environment in behavioral, linguistic, and affective expressions of positive or negative value. The argument is summarised in Fig. 1, illustrating how gravity is applied to non-physical information derived from purely internal sources. The primary internal source is one's autobiographical memory contents which, just as the body revolves around a physical centre of gravity, revolve around a narrative centre of gravity – namely, the self. The MG theory draws parallels between physical and mental states as expressed through a continuum of positive (happy and calm) and negative (anxious and depressed) socio-emotional states in terms of their verticality – namely, their position within or alignment to gravity.

The following sections will therefore explain each of these principles of the MG theory in turn, beginning with evolutionary adaptation and maladaptation to gravity's ubiquitous biological effects and the importance of verticality for physical and mental wellbeing (Section 2). This includes cognitive adaptation in the form of an internal gravity model (Section 3) and how such a model frames perceived adaptive value and motivates gravity-like behaviors. Neurocognitive mechanisms are suggested to account for this connection between physical/biological gravity and mental/cognitive gravity (Section 4), focusing on the anterior insular cortex as responsible for simulating gravity, and the default mode network as the "source" of mental gravity. A continuum of MG states is then proposed (Section 5) to illustrate how internal states are re-externalised through the socio-emotional environment as expressions of positive and negative verticality (adaptive) value. General implications and limitations are then discussed (Section 6) including possible avenues of empirical research to test the theory through relevant themes and hypotheses.

E-mail address: lachlan.kent@rmit.edu.au.

https://doi.org/10.1016/j.jenvp.2024.102245
Received 28 May 2023; Received in revised form 9 January 2024; Accepted 11 January 2024
Available online 13 January 2024

2. The biological connection between physical and mental gravity

This section details how the external and internal worlds/environments of complex organisms are biologically connected thanks to evolutionary and developmental adaptation to gravity. It begins by defining gravity and how it affects basic and high-order perception and cognition, then goes on to detail what verticality means in the context of biological survival, how adaptation and maladaptation to gravity manifest in physiological and psychological functioning, and how these adaptations underpin the MG theory.

2.1. Gravity as a construct for general scientific use

Gravity is a natural fact of life on Earth. Adapting to the gravitational environment has intrinsic survival value, where the tendency to fall and feel heavy is factored into everything living organisms do. Humans have very firm perceptual and motor expectations about how objects will behave under conditions of gravity, including our own body (Jörges & López-Moliner, 2017). These strong expectations in turn promote a tendency to adopt certain behavioral strategies to suit the body's alignment to the gravitational field. For instance, standing upright motivates novel "explore" behaviors over repetitive "exploit" behaviors (Gallagher et al., 2019).

This observation is neither surprising nor counterintuitive – the bipedal human body is designed to move more freely when standing. This is consistent with related ideas of embodied cognition (Lakoff, 2012) and the development of an intuitive physics of how our body functions in a gravitational environment (Kubricht et al., 2017). As a universal force acting on embodied selves, gravity shapes our basic view of the world, our place in it, and relation to it. It is a principal mediator of a person's two-way relationship with the physical environment. The deeper questions are: To what extent does our gravity-based relationship with the physical world determine our relationship with ourselves (i.e., the internal world) and each other (i.e., the socio-emotional world)? How fundamentally do the cognitive effects of gravity underpin higher-order processes of emotion, consciousness, selfhood, and well-being? To what extent does gravity have a more general, systematic, and explanatory role with broad importance for psychology?

As a basic relation between matter, energy, space and time, gravity is

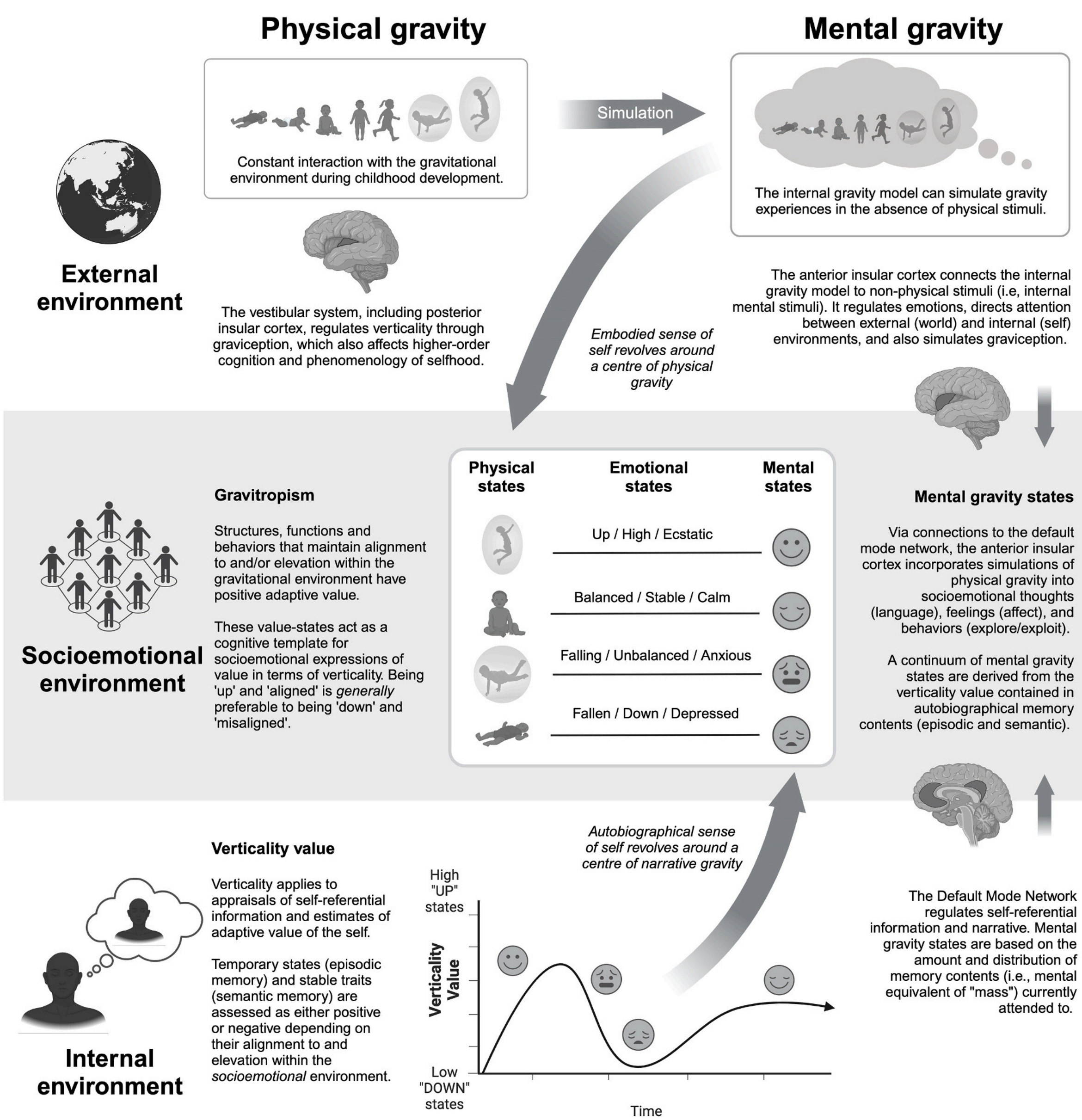

Fig. 1. A visual summary of mental gravity and key concepts, processes, brain regions, and environments.

relevant to many fields of science. Notwithstading its most prominent role in physics as the fundamental law of gravitation (Einstein & Fokker, 1914; Newton, 1687), "gravity models" have been used in economics and other special sciences to describe the size (mass) and movement (energy, space and time) of goods, services, people, or other economic or biological factors (Anderson, 2011; Lewer & Van den Berg, 2008). The central aim of this paper is to investigate whether there is scope for a role for a similar "gravity model" in psychology, or even a formal theory of MG. If so, then what kinds of explanatory models could be put forward by an MG theory? This paper proposes the basic MG principle that language, thought, and experience are conceptually structured according to the experience of physical gravity (i.e., the internal gravity model). The theory draws a behavioral analogy between external (physical), internal (mental), and relational (socio-emotional) environments to argue that physical gravity serves as a mental template for one's internal self and interactions with the social-emotional world.

Before proceeding, though, it is important to make clear what the MG theory categorically is *not*: 1) it is *not* a sociological "law of attraction" that binds people by some spiritual or mental force; 2) it is *not* related to quantum gravity effects in microtubules as per the theory of Orchestrated Objective Reduction in consciousness science (Hameroff et al., 2014); and 3) it is *not* related to the religious notion of a "fallen" human nature in any moral or mythical sense. Instead, the theory connects the perception of gravity to mental phenomena via the notion of verticality.

2.2. Verticality: elevation within, and alignment to the gravitational environment

Just like physical gravity is a universal experience on Earth, a preference for verticality is reflected in fundamental aspects of thought and language. Being "UP" means *intentionally* defying gravity's tendency to make objects fall, something living organisms can only do by coordinating behavior. UP-ness is therefore positive in a very primitive, biological sense. By contrast, being DOWN often connotes a lesser or even negative value (McMullen & Conway, 2002; Pfaltz et al., 2021). However, adapting to the gravitational environment through complex behavior requires more than simply moving UP or DOWN. Complex organisms must also collectively evolve, and individually learn to align and distribute their bodyweight so as to maintain balance and thus stop themselves falling uncontrollably. Upright objects like the human body are more likely to remain UPwhen they are aligned vertically and when their centre of gravity is lower, supported, and stable. Upright objects that are vertically-misaligned, unsupported, or unstable are more likely to fall DOWN, something humans primarily associate with risk of injury or even death (Spiegel, 2022).

For us bipedal humans, the tendency to stay upright therefore has intrinsic value that is present, for example, in our aesthetic preferences for vertically-aligned objects in art (Gallagher & Ferrè, 2018), and vertical features of geometric shapes or spaces that symbolise sacredness, dominance, and attractiveness (Costa & Bonetti, 2016). Disbalance or misalignment can also mean negative consequences for mental life. People experiencing severely negative mental states like depression and anxiety often have problems with spinal alignment, posture, dizziness, and balance (Canales et al., 2017; Dehcheshmeh et al., 2023; Feldman et al., 2020). Embodied cognition implies a bidirectional relationship between mental states and the bodily experience of those mental states via emotion, intention, and action (Lakoff, 2012). The MG theory proposes that verticality influences emotion, thought, and language because it has shaped biological adaptation to the environment over evolutionary timescales.

2.3. Biological adaptation to the gravitational environment

Unlike air pressure, temperature, chemical composition, solar radiation, and other physical factors present in the biological environment, gravity has been constant throughout the evolution of all life on Earth. It has always been precisely 1-g (g = gravitational force equivalent to that experienced on the surface of the Earth) because the Earth has not appreciably changed mass for billions of years. Aquatic and terrestrial life experience gravity differently because air is buoyant underwater (i.e., floatation is tantamount to antigravity), but both have nevertheless adapted by evolving specific structures to overcome bodyweight and the tendency to fall – air-sacs to float, wings to fly, skeletal structures to stand, roots for stability, trunks to grow tall, and so on (Adamopoulos et al., 2021). The degree to which humans are adapted to the 1-g environment is especially pronounced now that we can escape gravity's influence entirely. The absence of gravity during space missions can adversely affect metabolism (Albi et al., 2017), digestion (Yang et al., 2020), immunity (Hauschild et al., 2014), cellular function (Najrana & Sanchez-Esteban, 2016; Wnorowski et al., 2019), and a whole host of other processes evolved to function optimally with the assistance/resistance of gravity.

On a more mundane level, gravity affects everything humans do day-to-day. We spend two-thirds of our lives upright, and developmental milestones typify mastery over the gravitational environment – standing, walking, jumping, riding a bicycle, and so on. When we are well-adapted biologically, developmentally, and situationally to the constant 1-g force operating on our bodies, we tend to experience physical health and wellbeing. When we are ill-suited to deal with gravity, we tend to suffer physical ill-health and pain instead of health and wellbeing. Common forms of maladaptation, mismanagement or intolerance to 1-g gravity include back pain, vertigo/dizziness, and even heart failure (Spiegel, 2022). In low-gravity environments, astronauts also often experience "space adaptation syndrome" and problems with sensorimotor function, intracranial pressure, motion sickness, and other potentially-debilitating symptoms (Kornilova & Kozlovskaya, 2003; Matsnev et al., 1983; Yang et al., 2020; Young et al., 1984).

One physiological aspect of gravity dysregulation or maladaptation that has received attention recently is digestion. Spiegel (2022) hypothesised that Irritable Bowel Sydnrome (IBS), which affects approximately 10% of the adult population, results from subtle forms of gravity intolerance. He argues that the many and varied signs and symptoms of IBScan be attributed to a failure of the body to manage vertical g-forces exerted on the gut and its support structures, resulting in hypersensitivity to other g-forces, hypervigilance to prevent excessive g-forces, and even gravity exhaustion. Such gravity intolerance causes altered stool transit and stasis, altered microbiome, abdominal pain, cramping, bloating, constipation and diarrhea. Hypersensitivity and hypervigilance can also cause related problems and co-morbidities such as musculoskeletal tension, chronic pain, migraine headache, sleep disturbances, dizziness, fibromyalgia, and visceral anxiety (Camilleri, 2009; Spiegel, 2022; Whitehead et al., 2002).

Relevant for present purposes, Spiegel (2022) connects physical and mental health via a shared mechanism – the gut's "g-force accelerometer" – where gut-brain feedback loops interpret visceral sensations based on the (mis)perception of gravity. Like the MG theory outlined in the remainder of this paper, the author relates the visceral, embodied feeling of anxiety to the fear induced by sub- or supra-optimal g-forces experienced when falling or accelerating in an uncontrolled way. Abdominal butterflies, for example, can be viewed as a psychosomatic experience of nervousness or anxiety derived from the "real" physiological experience of an abrupt deviation from 1-g, which humans are biologically programmed to interpret as a fear-inducing loss of bodily control akin to falling:

> It is possible that as *Homo sapiens* evolved a larger and more complex brain capable of processing both physical and psychosocial threats, we co-opted our g-force accelerometer to alert for any serious threat rather than evolve a new program. Because "down" is neurobiologically bad, it is efficient that our time-tested down alarm would step in for any potentially unsafe threat, even those that do not involve literal g-forces … Viewed through the lens of the gravity hypothesis, visceral anxiety may result from hypervigilant surveillance of g-force events—in

essence, a neurovisceral fear of falling … [This] can lead to vital exhaustion, a form of mental gravity where IBS sufferers can no longer tolerate the biopsychosocial toll of ineffective load management, as if they need to succumb to gravity. (p. 1944).

Anxiety and depression are the most common mental health conditions worldwide (Steel et al., 2014), and also common comorbidities of IBS. The MG theory generalises Spiegel's (2022) physiological gravity hypothesis to argue that mental health and wellbeing, including conditions like anxiety and depression (Kent, 2023), are also governed by the co-opted, gut-brain gravity alert system. Mental gravity is the process by which "non-literal g-forces" are derived from the internal mental environment, conceptualised in thought and language, and ultimately physically re-enacted through cognitive, affective, and behavioral manifestations in the social-emotional environment. The MG theory creates an isomorphism between physical and socio-emotional environments, meaning same ("iso") body or shape ("morphism"). The physical self-world relation is mirrored in the mental self-world relation, in other words. Humans demonstrate thriving with positive manifestations of gravity adaptation, regulation, and management. But the MG theory also connects these socio-emotional expression of mental health to their counterpart expressions of mental ill-health as manifestations of falling in anxiety and having fallen in depression (see Section 5 below on the MG continuum).

2.4. Formulating the MG theory

Table 1 summarises key isomorphisms between physical and mental gravity that underpin the MG theory. It defines key MG concepts of verticality, elevation, alignment, stability, centre of gravity, and uprightness as isomorphic properties of the embodied mind that derive from the co-opted regulatory system that evolved to maintain verticality, elevation, alignment, stability, centre of gravity, and uprightness of the physical body. It also defines the key concept of "falling" in MG which, as with the IBS gravity hypothesis above (Spiegel, 2022), is associated with perceived risk of injury. The continuum of MG states (as detailed in Section 5) is as varied as the range of physical states a body can occupy to regulate verticality, ranging from positive states of elevation and alignment through to negative states of non-elevation and misalignment. Between these extremes, intermediate states represent varying degrees of adaptational-regulatory success and, importantly, changes in elevation and alignment. Some changes can be positive if they are adaptive, mitigate risk, or regulate self-world relations. Other changes can be negative if they are maladaptive, exacerbate risk, or dysregulate self-world relations. Falling in anxiety is the prototypically negative gravitational event arising from a dysregulated, uncontrolled loss of elevation and/or alignment. Being depressed is the negative socio-emotional state associated with having fallen mentally.

This section has sought to establish a biological connection between physical and mental gravity. The next section elaborates on the origins of MG in the embodied mind, beginning with the internal gravity model and extending into domains of cognitive tropism (i.e., the intrinsic drive to maintain verticality), value (positive or negative), and behavior.

3. Mental gravity stems from the internal gravity model

This section discusses how the capacity to perceive gravity is linked to higher-order functions of cognition and behavior, including language that expresses value in terms of verticality. It begins by giving a brief overview of the graviceptive system and the principle of cognitive gravitropism as derived from biological gravitropism (i.e., the evolutionary capacity and impulse to maintain verticality). The section concludes by proposing a general principle of verticality that is evident in affective, linguistic and behavioral expressions of positive and negative value.

Table 1
Principles underpinning the mental gravity (MG) theory.

Physical Gravity	Mental Gravity	Key claims
Positive adaptive and survival value: all life evolved to coordinate complex behavior in a 1-g environment. Organisms survive through physiological structures and behavioral repertoires that regulate bodily verticality.	Evolution co-opted gravity structures and behaviors to regulate verticality of the self in the internal MG environment. The gravitropic mind expresses mental verticality through socio-emotional relations of affect, language, and behavior.	• UP-ness has positive value in physiology (Spiegel, 2022), language, (Hamdi, 2016; Lakoff & Johnson, 2008), aesthetics (Costa & Bonetti, 2016; Gallagher & Ferrè, 2018) and motivation (Gallagher et al., 2019). •Gravitropic cognition underpins embodied and situational representation (Myachykov et al., 2014).
Vertical position and alignment: organisms regulate position within (height) and alignment to (uprightness) the gravitational environment to optimise self-world relations.	Position within (elevation) and alignment to (stability) the MG environment regulates socio-emotional self-world relations. Being high or low can be positive or negative depending on the context.	•Mental gravity arises from simulation of the internal gravity model (McIntyre et al., 2001) •The anterior insular cortex (salience network) mediates simulated graviception (Rousseau et al., 2020).
Centre of gravity: organisms dynamically control the elevation/stability of their body's centre of gravity through coordinated regulation of mass/weight and energy/motion.	The weighting of mental contents and energy-consuming mental processes regulates the centre of MG (i.e., sense of self) and its relation to the socio-emotional environment.	•Self as the centre of narrative gravity (Dennett, 1992) defined by mental mass (autobiographical memory). •Default mode network constitutes the brain's neural centre of gravity (Davey & Harrison, 2018).
Dynamical range: gravity states exist between positive (surviving or thriving) and negative (injury or death) gravitational outcomes along a continuum ranging from vertically elevated/aligned to non-elevated/misaligned.	Embodied minds exhibit a wide range of gravity-like behaviors to regulate vertical elevation and stability in response to internal MG dynamics and relational socio-emotional context.	•Embodied gravity-like behaviors express socio-emotional states of the self-world relation. •Positive states reflect more elevation/stability, negative states reflect less elevation/stability.
Continuum of states: organisms exhibit a spectrum of gravitational states to regulate vertical elevation and stability in response to environmental context and biophysical selection pressures.	A spectrum of MG states exists to reflect positive and negative adaptation, regulation, and tolerance of the socio-emotional environment along a continuum from elevated/aligned to non-elevated/misaligned.	•Positive MG states reflect MG tolerance and wellbeing. •Positive states include HIGH states of elevated joy, love or ecstasy, and BALANCED states of stability or calm, mindfulness, and contentment.
Negative adaptive and survival value: organisms risk physical injury when gravity adaptation-regulation fails (e.g., centre of gravity's uncontrolled loss of elevation/stability when falling).	Embodied minds risk socio-emotional injury when MG adaptation-regulation fails (i.e., centre of MG's uncontrolled loss of elevation/stability when falling).	•Anxiety as the MG-equivalent to the fear of falling felt due to low stability (Spiegel, 2022). •Depression as the MG-equivalent of having fallen to a low elevation (Kent, 2023; McMullen & Conway, 2002).

3.1. Internalising gravity to model the self in the world

To perceive gravity – called graviception – the brain integrates vestibular, visual, proprioceptive, and visceral sensory input to create an "internal gravity model" of the body and the environment (Gallagher et al., 2021). The internal gravity model generates strong and relatively inflexible predictions about perception and action under gravitational constraints (Jörges & López-Moliner, 2017). Basic information about verticality stems from the vestibular system, comprising the vestibular organs in the inner ear, the vestibular nerve projecting to the brainstem and cerebellum, and parieto-insular vestibular cortices. The vestibular system perceives both the downward pull of gravity when the head is stationary (inertial), and acceleration when the head is moving in any direction (non-inertial). Vestibular organs contain calcium crystals that exert force on fine, pressure-sensitive hairs in response to linear and angular acceleration (Angelaki & Cullen, 2008; Day & Fitzpatrick, 2005).

Gravity is a constant, linear, downward acceleration that the brain distinguishes from other non-constant, non-linear accelerations of the head and body in any direction, including downwards (Day & Fitzpatrick, 2005). The vestibular sense organs must therefore recruit high-order cognitive processes to distinguish gravity from other accelerations of the head. Gravity and acceleration both produce very similar forces and sensory information, which is why we define the strength of acceleration in terms of "g-force" (i.e., gravitational force-equivalent). To isolate the downward pull of gravity from other g-forces, the brain must first determine how the body and the external environment are moving in relation to each other by integrating vestibular signals with other sensory input from vision, proprioception, and viscera (Gallagher et al., 2021).

This primary graviceptive task requires higher-order abstraction and complex cognitive representation, which has flow-on effects for higher-order cognition and behavior. Traditionally thought of as the "balance system" controlling limited behavioral functions like posture, gait, and gaze, more recent studies have shown that the vestibular system contributes to autonomic function and higher-order cognitive processes like spatial navigation, learning and memory, and behavioral control (Cullen, 2019; Frank & Greenlee, 2018; Gallagher et al., 2019). It also affects phenomenological experiences of the self as anchored to the body (Ferrè et al., 2014), egocentrism (Pavlidou et al., 2018), perceived body weight (Ferrè et al., 2019), and perception of time and space (Clément, 2018; Ferre et al., 2013). As explained below, graviception is such an indispensable part of human experience that it can be considered a core cognitive capacity that drives much of higher-order human behavior (Section 3.2), especially with regard to language expression (Section 3.3), appraisals of positive and negative value (Section 3.4), and "gravity-like" behaviors (Section 3.5).

3.2. Cognitive gravitropism

Graviception is very deeply embedded in cognition about self-world relations, extending beyond physiological effects to underpin basic elements of embodied cognition and situatedness in the environment. Myachykov et al. (2014) explain the strength and depth of gravity's influence in terms of cognitive tropism, meaning how gravity is embedded in the most general, stable, and automated representations or knowledge about the world. Tropism in biology refers to an organism's tendency to move or grow in a particular direction in response to an environmental stimulus, including various forms of phototropism (response to light), hydrotropism (response to water), aerotropism (response to air), and gravitropism (response to gravity, sometimes called geotropism). Cognitive tropism extends the concept of biological tropism to argue that embodied minds are also inclined to represent world-based knowledge in certain specific ways derived from the environment, which includes, among other things, cognitive gravitropism – namely, the primacy of certain basic mental representations, simulations, and/or knowledge distributed along a vertical spatial axis, including emotional valence (good is up, bad is down), numerosity (more is up, less is down), and time (future is up, past is down) (Myachykov et al., 2014; Pfaltz et al., 2021).

Many psychophysical experiments confirm this gravitropism of human cognition, which may be explained by the inherent polarity or asymmetry of the gravitational field (Lakens, 2012). Gravitropism implies that vertical orientation of emotional valence, numerosity, time and other fundamental psychological constructs are not just convenient, metaphorical, or allegorical representations which are prone to rapid change through cultural evolution. Instead, they are more firmly-rooted in biological evolution as evidenced by gut-brain interactions with respect to gravity (Spiegel, 2022) and higher-order cognitve effects of a relatively-inflexible internal gravity model (Gallagher et al., 2021; Jörges & López-Moliner, 2017).

3.3. Gravitropic language and affect

The MG theory assumes that cognitive gravitropism structures key aspects of language, thought, and action related to highest-order abstraction of semantic, emotional, and social processes. Being UP indicates positive emotional valence across cultures and contexts (Hamdi, 2016). A systematic review of 33 studies found consistent associations between verticality metaphors and dimensions of power (dominance over submissiveness), valence (positive over negative), concreteness (light/abstract over heavy/concrete), and rationality (intellect over emotion) (Cian, 2017). Similarly, African languages use UP-type phrases to denote joy, certainty, courage or social value (i.e., pride), and DOWN-type meanings and phrases to denote lower social value (i.e., shame), calmness, or comfort (Dzokoto et al., 2016; Dzokoto & Okazaki, 2006).

Despite its ubiquity, some may yet consider patterns in language and metaphor as merely convenient or circumstantial evidence to support the MG theory. Metaphor is certainly a component of the argument presented here. The primary orientational English metaphors proposed by Lakoff and Johnson (2008) in their seminal work on the topic are "HAPPINESS IS UP, SAD IS DOWN", "CONSCIOUSNESS IS UP, UNCONSCIOUSNESS IS DOWN", "HEALTHY AND LIFE ARE UP, SICKNESS AND DEATH ARE DOWN." However, the MG theory maintains that gravitropism is embedded at deeper levels of cognition that extend semantics beyond superficial appearances in metaphor to more stable representations of knowledge about the world (Myachykov et al., 2014). For example, embodied-cognition experiments confirm that "GOOD IS UP" and "BAD IS DOWN" when perceiving vertically-directed objects and actions (Gottwald et al., 2015). The MG theory thus assumes that cognitive gravitropism, as mediated by the internal gravity model, constitutes a primary source of universal human value.

3.4. Gravitropic Universal Verticality Value (GUVV)

As with language and metaphor across different cultures (Dzokoto et al., 2016; Dzokoto & Okazaki, 2006; Hamdi, 2016; Lakoff, 2012), the MG theory assumes that cognitive gravitropism affords verticality (i.e., position and alignment) intrinsic human value – here dubbed Gravitropic Universal Verticality Value (GUVV). Higher vertical position and more vertical alignment equates to greater value, and lower vertical position and less vertical alignment equates to lesser or even negative value. This GUVV derives from evolutionary, developmental, and behavioral adaptation to the 1-g environment that is a necessary precondition for complex life – especially land-based, multicellular, embodied organisms such as humans (Spiegel, 2022). As such, GUVV is the basis for the asymmetry of spatial metaphors along the vertical dimension – "HAPPINESS IS UP, SAD IS DOWN", "CONSCIOUSNESS IS UP, UNCONSCIOUSNESS IS DOWN", "HEALTHY AND LIFE ARE UP, SICKNESS AND DEATH ARE DOWN" (Lakoff & Johnson, 2008).

That is not to say that being UP mentally is always a positive experience, nor that being DOWN is always a negative experience. Sleep and relaxation are colloquially DOWN states that are positive, and one can be in UP states that have less or negative value like anxiety, hyperactivity, or mania. Verticality in the mental realm mirrors the complexity of our experiences of verticality in the physical realm. Sometimes being physically UP is a joyous achievement (e.g., baby's first steps), sometimes it is a fearful predicament (e.g., being unstable at a height). Any mental assessment of GUVV depends on the embodied context or situation (Myachykov et al., 2014). However, situational circumstances do not negate the general rule that global, context-free assessments of value show a gravitropic preference for UP over DOWN. Another way to say this is that GUVV varies over the course of day-to-day life because, in terms of life's "ups and downs", variation is both natural and desirable. But in terms of *overall* quality of life, higher GUVV is always preferable to lower – "HEALTH AND LIFE ARE UP", "SICKNESS AND DEATH ARE DOWN" (Lakoff & Johnson, 2008).

This primal sense of GUVV goes to the core of what gravity means for life and survival. To be classified as alive, an organism has to be able to move, at least reflexively or unconsciously. To move, a living organism must overcome its inertial, gravitationally-bound bodyweight by harnessing electrochemical and mechanical energy to coordinate behavior (Spiegel, 2022). After death, organisms lose this ability and, especially for animals with a sense of self-preservation, life is preferable to death. Gravity imbues psychology with an innate sense of GUVV because it at least partially defines what it means to be alive.

3.5. From GUVV to gravity-like behaviors

For humans, being upright helps us interact with the physical environment. Lying down supine (i.e., being unaligned to gravity) is associated with a tendency to exhibit more "exploit" and less "explore" behaviors (Gallagher et al., 2019). In gravitropic terms, the asymmetry of the vertical spatial axis in mental representations means that being UP allows for more positive behaviors than when DOWN (Lakens, 2012; Myachykov et al., 2014). This implies that being mentally DOWN or MISALIGNED makes people *act as though* there is something preventing them from exploring their environment, namely physical gravity. That is to say that extrinsic, physical gravity constrains intrinsic, mental states. The MG theory posits that this is, in fact, a two-way relationship. Mental states can also affect how the mind/body interacts with physical gravity through the embodiment of *gravity-like* behaviors.

Imagine gravity was much stronger on Earth right now. Imagine everything felt heavier and every movement was more difficult, even breathing or talking. Imagine getting out of bed was an enormous effort that left you mentally or physically drained of energy. If this was your reality, you would tend not to engage in novel behaviors to explore your external environment. In strong gravity you would instead need to conserve energy by only engaging in slow, minimal, and deliberate movements. You would need to adopt a downcast posture (lowered head, eyes and shoulders), perhaps a softer and deeper tone of voice, and other behaviors that reflect the weightiness of the *environment*.

The word "gravity" – derived from the Latin word *gravis*, meaning *heavy* – also means treating a subject with due sense of seriousness, as in "the gravity of the situation", through the tone and content of speech or action. Conveying gravity with one's body, such as when experiencing grief, involves behaviors that match the weightiness of the *socio-emotional* environment which mirror those above for physical gravity – bodily heaviness, passivity, constricted movement, and so on (Fuchs, 2018). The contention here is that these "gravity-like" behaviors embody a physical language to communicate fundamental aspects of life, consciousness, and emotion.

For instance, heaviness and lightness are key aspects of an artistic repertoire for expressing emotion in theatre, dance, and music (Murray, 2013; Walker et al., 2017). This behavioral repertoire extends into everyday emotional expression, too (Hartmann et al., 2022). Gravity works as a universal aspect of human emotion quite simply because gravity is a universal fact of life on Earth. Gravity-like behaviors involve *simulating* the strength and alignment of physical gravity to communicate the GUVV of internal, mental states in a meaningful, heuristic way. Individuals communicate their *social* or *emotional* response in relation environment to the prevailing mental content of their internal environment by simulating the gravitational relationship between their body and the *physical* environment. In effect, the MG theory draws a behavioral analogy between the external (physical), internal (mental), and relational (socio-emotional) environments.

Gravity-like behaviors can apply to both states and traits. The word "gravitas" – which also derives from the Latin *gravis* – is an expression of trait-like MG that is less situational and more related to an individual's personality characteristics – such as dignity, solemnity, nobility, authority, and severity – which are moderately correlated with Big Five traits Openness and Conscientiousness (Jackson, 2021). Gravitas was one of the imperial virtues of Ancient Rome (*Via Romana*) signifying desirable traits for someone in a position of responsibility or leadership, for example (Jackson, 2020). In terms of MG, rather than expressing the lowness of a grave situation (i.e., a DOWN position as opposed to UP states of joy or excitement), gravitas expresses the vertical stability of an individual – in other words, they can be trusted to *remain* upright. They are people worthy of social trust just like a stable object can be trusted not to fall.

Positive expressions of MG can thus apply to congruent or desirable gravity-like behaviors. Gravity-like behaviors or tendencies can also express negative or incongruent mental states like anxiety and depression by influencing emotional weight. Studies consistently show that sad or depressed emotional states are "heavier" than happy or neutral states (Hartmann et al., 2022). These are not just semantic or linguistic associations. The bodily sensations of lightness/heaviness and activation/deactivation systematically relate to motivational (Gallagher et al., 2019) and aesthetic states of mind (Gallagher & Ferrè, 2018) that express emotional states as gravity-like behaviors. These can in turn impact physiological embodiment and relation to physical gravity through a person's posture in depression (Canales et al., 2017; Dehcheshmeh et al., 2023), sense of balance in anxiety (Feldman et al., 2020), or other physiological effects such as gut health (Spiegel, 2022).

Gravity is part of our socio-emotional lexicon that directly stems from our gravitropic interaction with the environment. The following section will explore neurobiological and cognitive domains of the MG theory to explore the mechanics of this deep connection between physical gravity in the external environment, mentalisation of gravity in the internal environment, and socioemotional expression of mental gravity states in the relational environment. The preceding sections establish that such a connection exists but does not demonstrate how MG manifests in the brain and body.

4. Neurocognitive basis for mental gravity

This section discusses how MG manifests neurocognitively by specifying key neuroanatomical areas or networks, and explaining their associated functions. It begins by detailing how the anterior insular cortex simulates graviception, then discusses how the DMN serves as the notional "source" of MG defining concepts such as a "centre" of MG and mental "mass" in relation to autobiographical memory contents and personal narrative.

4.1. Graviception and the anterior insular cortex

In order to establish the isomorphism between physical, mental and socio-emotional worlds in MG, physical gravity needs to connect to its mental counterpart via a plausible neuroanatomical mechanism. Recall that the brain integrates vestibular, visual, proprioceptive, and visceral sensory input to create an internal gravity model of the body and the environment (Gallagher et al., 2021). The vestibular system includes parieto-insular cortex, with both posterior and anterior parts of the insular implicated in vestibular function (Dionisio et al., 2019; Uddin et al., 2017). Whereas the posterior insular is associated with perceptual inputs from various sensory pathways, the anterior insular cortex is more associated with cognitive control, emotion, mental imagery, and self-monitoring (Benarroch, 2019; Gomez-Andres et al., 2022; Mellet et al., 2000). As such, the MG theory assumes that the anterior insular cortex acts as the key network hub mediating the link between physical and mental forms of gravity due to its functional role in higher-order cognitive, emotional, and self-related processes.

One particular study has shown a specific, direct dissociation between posterior and anterior insular activity with respect to whether gravity is perceived or imagined. During either real (feedforward and feedback) or imagined (feedforward only) hand movements under different conditions of gravity (heavier versus lighter weights in the real condition, and imagined hypo- or hyper-gravity in the imagery condition), Rousseau et al. (2020) found that posterior insular cortex mediated bodily motion when there is graviceptive feedback, but that the anterior insular cortex mediated imaginary motion (i.e., simulation) when there is no graviceptive feedback from other parts of the vestibular system. The authors suggest two representations of gravity may subserve the internal gravity model: 1) an "online" representation for feedback functionality in the posterior insular; and 2) an "offline" representation for feedforward functionality in the anterior insular. The proposition here is that, by taking gravity "offline", the anterior insular cortex effectively co-opts the internal gravity model for other social, emotional, and self-related processes.

Importantly, the anterior insular cortex's association with mental imagery (Huang et al., 2021; Kaas et al., 2010; Mellet et al., 2000; Spagna et al., 2021) is in turn linked to emotional responses (Greening et al., 2022). The anterior insular cortex is implicated in the so-called multiple demand system that mediates intuitive physical inference, which is the capacity to process, predict, or understand physical scenes (i.e., objects in motion) according to implicit rules and regularities (Duncan, 2010; Fischer et al., 2016). Simulated digital environments use a "physics engine" to generate realistic behavior of moving objects, including rules governing gravity. The brain may implement a similar "intuitive physics engine" (Battaglia et al., 2013; Ullman et al., 2017), of which the internal gravity model and the anterior insular cortex would play a central role.

This distinction between posterior and anterior insula activity when simulating or imagining gravity's effects is key to understanding how physical gravity "becomes" mental – i.e., it is the neuroanatomical mechanism alluded to above. The anterior insular is a key hub in the functional neuroanatomy of interoception (Seth, 2013; Seth & Friston, 2016) and related functions of socio-emotional processing (Uddin et al., 2017). On the weight of direct and indirect evidence, it is highly likely that the anterior insular controls socio-emotional expressions of MG given its key functional role in the simulation of the physical-perceptual internal gravity model. The anterior insula cortex effectively decouples the internal gravity model from physical gravity in the external/-exteroceptive environment, meaning gravity can be imagined through mental simulation of MG's effects on the basis of the internal/-interoceptive environment.

4.2. *Mental gravity as simulated graviception*

Under these conditions of simulation, gravity is freed from the constraints of physical-perceptual-physiological input. The graviceptive system can instead manifest social or emotional responses to the GUVV of non-physical mental stimuli, including the GUVV of the primary self-world relation. The MG of increased gravity is not hallucinatory in the strict sense of incorrectly perceiving something "out there", because it is instead veridical with respect to something perceived "in here". Perceived GUVV is real even if the simulation is not prompted by physical stimuli. The anterior insula initiates MG behaviors by simulating the internal MG environment, not physically from the "outside-in" by way of the vestibular system and other sense organs, but mentally from the "inside-out" by way of memory-based simulation (i.e., self-stimulation) of the internal gravity model.

The anterior insular cortex is a key salience network hub associated with interoceptive subjective feelings (Craig, 2009), social emotions (Lamm & Singer, 2010), emotional awareness (Gu et al., 2013), and empathic pain perception (Gu et al., 2012). As such, MG simulation is used to communicate subjective feelings cued by perceived GUVV of the self, another person, a situation, or something more abstract like an idea, possibility, or counterfactual. The subject or object is not constrained, nor is the type of value judgement (e.g., aesthetic, motivational, emotional, etc), because it is always the relation between the subject or object and the self that drives the MG simulation – including the reflective self-relation (i.e., reflection on oneself). It is the interoceptive state that models self-world relations by evaluating how external states affect homeostasis and, in turn, how regulation of internal states affects allostasis (Seth & Friston, 2016). Perceived GUVV is not just perception of an object, but rather a type of appraisal of an object with respect to survival, adaptation, or other critical dimensions of human value.

Simulation based on appraised GUVV is thus a kind of mental projection of gravity, similar to the process of apperception, because it involves interpreting the meaning of a perceived object in terms of previous experience. An MG simulation interprets interoceptive states by projecting the internal gravity model back onto the mind-body. In other words, MG simulates the effects of physical gravity to communicate the GUVV of internal, autonomic, and interoceptive predictions or inferences regarding affective, allostatic, and emotional states (Barrett & Simmons, 2015; Seth & Friston, 2016). MG simulation is part of the non-verbal lexicon of GUVV that we can use to communicate a motivational, aesthetic, or emotional relations between internal (mental), relational (socioemotional), or external (physical) environments (Gallagher et al., 2019; Gallagher & Ferrè, 2018; Pfaltz et al., 2021).

To summarise, the salience network is a key hub of the embodied mind and key regulator of emotions (Seth, 2013). Via the anterior insular cortex, the salience network mediates the expression of MG: interoceptive inference, emotional awareness, and simulation of the internal gravity model (Lamm & Singer, 2010; Rousseau et al., 2020; Seth, 2013). Connecting this fact to the next section, the salience network's more general function is to "gatekeep" various aspects of executive control (Molnar-Szakacs & Uddin, 2022) by switching attentional resources between primarily internal, self-related information processing of the Default Mode Network (DMN) and external, task-related information of the central executive network (Goulden et al., 2014). The salience network mediates the short-term, present-based tension between internal and external environmental demands, whereas the DMN integrates a sense of self over the longer-term of past, present, and future timeframes. As such, the DMN has a critical role to play in the MG theory as the centre of the internal world – the brain's "centre of gravity" (Davey & Harrison, 2018) – the self.

4.3. *The DMN self as the "centre" of mental gravity*

Whereas the salience network mediates the MG simulation, the DMN is the self-referential "centre" to which the salience network directs attentional resources. According to Menon (2023), the DMN's primary role is to create the self's internal narrative through episodic and autobiographical memory, social cognition, language, and semantic memory. While the salience network simulates graviception with respect to the GUVV of a salient socio-emotional stimulus, the DMN is the ultimate "source" of the GUVV. In basic terms, the DMN provides the raw material from which the salience network constructs the MG simulation. The DMN is the internal environment which we experience as an inner self. It regulates both mood and social behavior (Davey & Harrison, 2022), where primary deficits are most evident in depression (Dalgleish & Werner-Seidler, 2014). As illustrated below (Section 5), depression represents a stereotypical form of gravity-like behavior at the DOWN/-MISALIGNED end of the MG continuum (Kent, 2023).

The salience network and DMN both relate to aspects of the self but, as proposed by Davey and Harrison (2018, 2022), they play different roles and occupy different positions along a so-called "self-axis". The self-axis has two poles: the long-term narrative pole spanning past-to-future self-experience, and the short-term experiential pole of present self-experience. The salience network is located at the present-based experiential pole, which is sometimes called the "basic", "minimal", "somatic", or "pre-reflective" self. The DMN extends from the narrative pole along the entire self-axis to connect one's long-term narrative to present-based experience, sometimes called the "autobiographical", "cognitive", "empirical", "extended", or "integrated" self.

Just like the body is distributed in space and time, so is the sense of self. There are many aspects of selfhood and versions of oneself over time. The DMN integrates all these variations to construct a unified, single, and *stable* sense of self. This stability gives individuals an egocentric point of reference for all mental processing. The DMN is the central self, dubbed here the centre of MG. The body has a centre-of-gravity which organisms evolve, and children learn to manage in order to control movement in a gravitational environment. Through cognitive gravitropism, the mind has simply co-opted an isomorphic property of centrality to regulate the internal MG environment through DMN self-referential processing. The MG theory thus assumes the DMN is the mental equivalent of a body's centre of gravity in the same way that Davey and Harrison (2018) dubbed the DMN the "brain's centre of gravity" given its importance for self-referential processing.

Defined here as the internal GUVV environment to which the MG simulation refers, this central role of the DMN raises an interesting conundrum for the isomorphic approach. In physics, a centre of gravity is defined by the distribution of mass around a point in space, whether that is of a smaller, more dynamic object such as the human body or a larger, more static object such as planet Earth. Isomorphically, the same must be the case for MG except that the concept of mass, like the internal gravity model itself, must be decoupled from the concept of physical mass associated with the external environment. Instead, *mental* mass takes the form of memory contents mediated by the DMN.

4.4. Mental mass

The salience network decouples the internal gravity model from physical stimuli by substituting interoceptive input for external graviceptive input. The DMN also substitutes an internally-derived "substance" to simulate the role of physical mass, here dubbed mental mass. The size, distribution, and topography of mental mass is comprised of the memory contents from which the DMN constructs the autobiographical self-narrative, contents that stem from the integration of episodic, social, semantic and linguistic information (Menon, 2023).

Linked to the concept of mass, the idea that memory has weight is not a foreign psychological concept. The weighting of prior beliefs against present sensory input on the basis of likelihood is a key aspect of Bayesian inference, which includes inferences about interoceptive, affective and embodied states (Seth, 2013) pertaining to either the self (Hohwy, 2016) or others (Moutoussis et al., 2014). Synaptic weighting is also a key mechanism of long-term memory via synaptic plasticity and stability of both artificial (Abraham & Robins, 2005) and biological neural networks (Paulsen & Moser, 1998). The MG theory simply extends the idea of memory weight to a more substantive conceptualisation of memory mass.

An autobiographical narrative is the cohesion, accumulation, and distribution of the DMN's mental mass. The self is the hypothetical central point defined by this accumulated mass. Dennett (1992) described a similar cognitive view of the self as the "centre of narrative gravity" as the hypothetical point around which our personal "material" coheres – namely, our intuitive but illusory sense of self. The analogy to material here is an apt one for the MG theory. Assuming the self constitutes a centre of narrative gravity (i.e., the DMN), the material defining this central point is the accumulated "mass" of personal experiences and autobiographical memory. Just as physical gravity occurs in the presence of physical mass, MG occurs in relation to the mental mass constituted by the DMN's internal narrative (Menon, 2023). The relation between physical and mental mass in MG is therefore both a symbolic and substantive one. Gravity-like behaviors represent an embodied manifestation of the self-world relation in expressions that have intrinsic meaning according to GUVV, namely position (UP/DOWN) and alignment (ALIGNED/MISALIGNED). The following section will define how combinations of position and alignment relate to a hypothetical continuum of MG states to illustrate how salient mental mass defined by the DMN self manifests in stereotypical MG socioemotional expression.

5. The continuum of mental gravity states

The MG theory posits that there is a continuum of states from low to high MG, with stereotypically positive "up" and "down" states of wellbeing at one end of the continuum, and stereotypically negative "up" and "down" states at the other end. An MG state is not solely defined by a single UP/DOWN status because, just like in our experience of physical gravity, being higher is not always better. Increased height also comes with increased risk and so being UP can also be associated with aversive, fearful, or negative feelings. Being DOWN can also be associated with desirable, pleasant, or positive feelings depending on ALIGNMENT – namely, whether the MG environment is adaptive with respect to GUVV.

As such, positive feelings of wellbeing can stem from being mentally and physically UP or DOWN. People can communicate positive emotions by "jumping for joy" or giving each other "high fives" when they feel good about themselves, a situation, or each other. There are also positive associations for those who are "down to earth" or "grounded" in a relaxed, confident, comfortable way that promotes feelings of humility, stability, or trust. Following Spiegel (2022), stereotypically negative feelings are associated with falling when UP and succumbing to a fallen state when DOWN, which are akin to anxiety and depression, respectively (Kent, 2023). Fig. 2 summarises the MG continuum according to typical states and processes that lead to either positive or negative MG socioemotional expression. As such, four stereotypical states are used to illustrate different combinations of position and alignment along the MG continuum.

Human behavior is complex and counterexamples could be posed for each of the stereotypical affective states used as examples. While people stereotypically "jump for joy" when experiencing a burst of pleasant emotion, sometimes people can be so overcome with joy that they collapse to the ground. The argument is not that the embodiment of MG is performed robotically according to set rules without exception. Falling in this instance may convey something else about the person's mental state, namely that they are overwhelmed by the weight of the occasion or sheer volume of emotion they are feeling. The heuristic argument is intended only to describe the typical case, or cases where certain behaviors might stand out as inappropriate. For example, it would generally be considered inappropriate to express UP MG behaviors at a funeral by "jumping for joy" or giving "high fives" when everyone else is expressing DOWN MG behaviors (calmness/stability or sadness/depression).

5.1. Ecstasy: low MG in "high" states

Ecstasy is a stereotypically HIGH state of hedonic wellbeing, which can be associated with natural "highs" such as flow states (Nakamura & Csikszentmihalyi, 2002), happiness or joy (Hartmann et al., 2022), or artificial "highs" induced by serotonergic psychedelics and related substances such as MDMA, psilocybin, LSD, or Ayahuasca (Carhart-Harris et al., 2012; Palhano-Fontes et al., 2015). Being HIGH typically involves relaxing self-world boundaries and a positive self-world relation. The physical environment can also promote positive affect of this kind by encouraging people to "lose themselves" in vast or spacious natural landscapes, a process that loosens the embodied self-world boundary (van Rompay et al., 2023).

5.2. Mindfulness: mild MG in "balanced" states

To contrast the hedonic wellbeing (i.e., feeling good emotionally) of being UP or HIGH, being DOWN or LOW in a positive mental state is

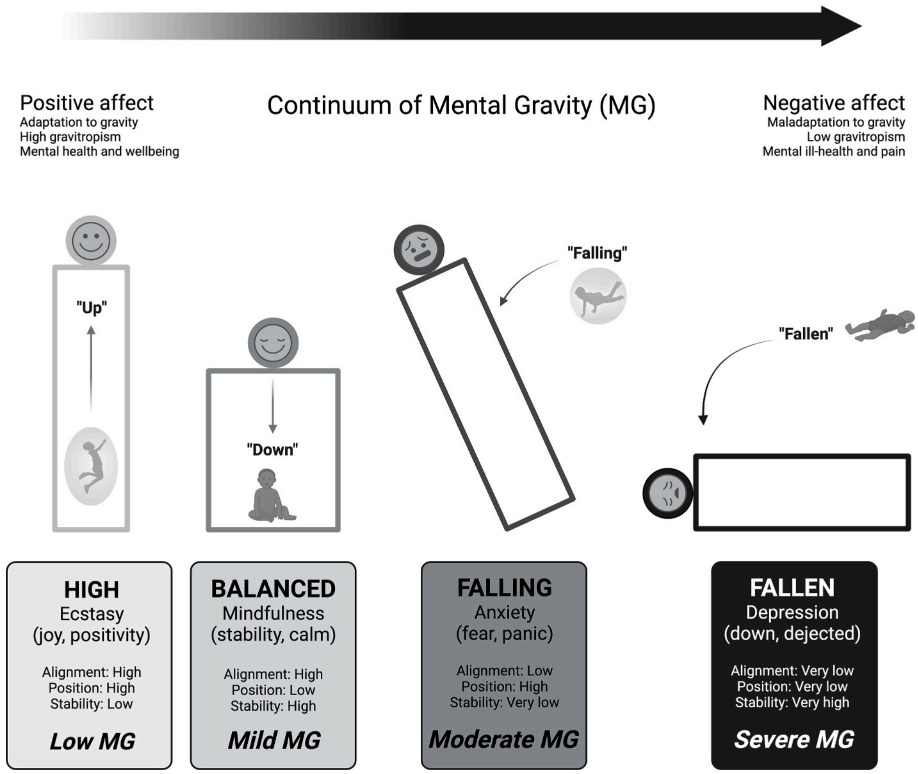

Fig. 2. The continuum of MG states ranging from low or mild MG states of positive affect (UP as joyous and DOWN as calm) to moderate or severe MG states of negative affect (UP as anxious and DOWN as depressed).

more reminiscent of eudaimonic wellbeing (i.e., being good socially or functioning well psychologically) (Lamers et al., 2011). A DOWN/-ALIGNED state is depicted in Fig. 2 as more stable due to a lower centre-of-gravity. Gravity-like behaviors of this kind express eudaimonic stability in the form of seriousness, calmness, or solemnity of the kind associated with *gravitas*, as explained above in Section 3.5 (Jackson, 2020, 2021). A stereotypical mental state of mild MG is mindfulness, which emphasises core facets of gravitas such as high attentiveness, calmness, and emotional control (Shapiro et al., 2006). Mindfulness also encourages positive self-regard through self-compassion (Hollis-Walker & Colosimo, 2011), which underpins the DOWN/ALIGNMENT of the MG state from a positive self-world or even reflective self-relation (i.e., reflection on oneself). Mindfulness meditation is typically undertaken while "sitting up/down", meaning in a DOWN position that is vertically ALIGNED. Sitting up/down is optimally stable and unlikely to fall due to a low centre of gravity. Connection to calm environments can also promote mindfulness (Lymeus et al., 2018), restore wellbeing (Lymeus et al., 2022), and positively decentre a person's sense of self (Macaulay et al., 2022). The key observation is that DOWN/ALIGNED states of mindfulness express an inherently BALANCED self-world relationship.

5.3. Anxiety: moderate MG in "unbalanced" or "falling" states

Negative feelings express some kind of MISALIGNMENT in the self-world relation. When the world is viewed as somehow threatening a person's safety (Spiegel, 2022), negative UP states represent the fear, panic, or desperation experienced in *grave* situations (i.e., also from the Latin *gravis*, meaning *heavy*). Anxiety is a stereotypical emotional response to grave, fearful situations that are either real or imagined. Anxiety is experienced as an UP mental state of nervous excitement from which individuals cannot intentionally calm DOWN (Brooks, 2014). This inability to regulate emotion is related to early experiences of diminished control over one's socio-emotional environment (Chorpita & Barlow, 1998), meaning that the external world dominates the self-world relationship, causing MISALIGNMENT. Anxiety expresses this UNBALANCED relationship through gravity-like behaviors associated with loss of bodily control in the gravitational environment, namely FALLING (Spiegel, 2022). In social anxiety, for example, this is construed as the "unstable social self" (Lucherini Angeletti et al., 2023), and so this instability at the centre of MG translates from the internal MG environment to the external gravitational environment through experiences of both disbalance and a fearful response to FALLING. Other gravity-like behaviors such as dizziness, disbalance, or vertigo are also commonly experienced when anxious (Balaban & Jacob, 2001; Feldman et al., 2020). This is especially the case for panic disorders where vertigo is a defining symptom, likely attributable to vestibular dysfunction (Teggi et al., 2010).

5.4. Depression: severe MG in "fallen" states

Depression is characterised here as a FALLEN state of severe MG that is both DOWN and MISALIGNED. Depression is defined by symptoms of low mood, loss of pleasure, fatigue, feeling bad about oneself, slowness, low energy, thoughts of death, and problems with sleep, appetite, and concentration (Kroenke et al., 2001). Whereas anxious individuals struggle to calm DOWN, depressed individuals struggle more to get UP, which includes common problems rousing from sleep (Kaplan & Harvey, 2009) and increased risk of sedentary behavior and physical inactivity (Roshanaei-Moghaddam et al., 2009). Lying DOWN closely resembles states of unconsciousness or even death that temporarily or permanently negate the individual's ability to get UP and overcome physical gravity through the energetic coordination of movement. People often subjectively report feeling like they have undergone a personal "descent" to a lower state of being when depressed (Coll-Florit et al., 2021). In extremely depressed states, patients can experience a nihilistic delusion, called Cotard's syndrome, where they believe that they or their body has died (Debruyne et al., 2009). If "HEALTHY AND LIFE ARE UP, SICKNESS AND DEATH ARE DOWN" in metaphorical language (Lakoff & Johnson, 2008), then depression is as DOWN as one can be while still alive. Consequently, depressed patients are also at elevated lifetime risk of suicide (Angst et al., 1999).

6. Discussion

The theory of mental gravity posits that language, thought, and experience are conceptually structured according to the experience of physical gravity (i.e., cognitive gravitropism of the internal gravity model). It draws a behavioral analogy between physical, mental, and socio-emotional environments to argue that physical gravity serves as a mental template to express the relation between the inner self and the outer world – namely position in, and alignment to the gravitational field (i.e., GUVV). Simulated graviception is performed by the anterior insula cortex of the salience network but is prompted by self-referential DMN activity. Autobiographical memory constitutes the mental mass that defines the central reference point for GUVV (i.e., the self), which is equivalent to the DMN serving as the brain's neural and narrative centre-of-gravity.

This model speaks to the primary research question posed near the outset of this review: Can gravity be used as a general, systematic and explanatory model in psychology in the same way that gravity models have been devised for economics and other special sciences (Anderson, 2011; Lewer & Van den Berg, 2008)? The theory outlined above has potential explanatory value in that it proposes neural and developmental mechanisms of MG that connect the experience of the outer world (i.e., graviception of the self embedded in the physical environment) to the experience of the inner world (i.e., GUVV of the self at the centre of MG) via intermediate relations in the socioemotional world (i.e., simulated graviception in relation to the GUVV of the self). It can also describe stereotypical positive and negative emotional states based on the characteristics and strength of the MG simulation along a hypothetical continuum ranging from positive feelings and behaviors associated with being HIGH and BALANCED, through tonegative feelings and behaviors associated with FALLING or having FALLEN.

Importantly for environmental psychology, MG states link complex "brain-mind-self" activity to the equally-complex "world-environment-other" interaction through the simple principle of cognitive gravitropism. We know that this interaction is two-way – the environment shapes our sense of self and selves in turn shape their environment. The MG theory offers biological, developmental, and neural mechanisms by which this reciprocal relationship is mediated for higher-order psychological constructs of socio-emotional experience and expression.

Making the connection between physical and mental forms of gravity has the potential to systematise many aspects of positive and negative socio-emotional experience, including by situating mental health and wellbeing within the context of self-world interactions. The MG theory provides a mechanism by which the self-world relation manifests in concrete terms. Environmental psychology could therefore bring relevant literature to a research programme intended to test the theory, especially through the design of environments or behavioral activations that aim to improve GUVV in systematic ways. In general, we already know that simply spending time in nature promotes general mental health and wellbeing (White et al., 2019). For example, restorative processes that offer a gravity-like, mindful sense of "mental balance" could reduce the severity of, or even prevent the onset of depression symptoms (Hartig, 2021; Lymeus et al., 2018). The MG theory could provide improved ways to conceive of or explain the use of blue (i.e., lakes, rivers, and ocean) and green (i.e., parks and woodlands) spaces to prevent and treat highly-prevalent and potentially disabling conditions like depression and anxiety (White et al., 2020), highlighting the intrinsic human value (and GUVV) derived from natural or built environments. It could also inform the construction of novel digital or built environments that invoke or remedy particular MG states, or unconsciously provoke favorable gravity-like behaviors.

6.1. Limitations and opportunities for further research

As a prospective theoretical proposal, MG lacks a specific evidence base and as such remains speculative. It rests on several assumptions and connects many seemingly unrelated observations across different literatures. This may simplify or even obfuscate some technical subtleties within specific disciplines. The continuum of MG states, for example, is very heuristic and only represents stereotypical behavioral and affective states. The risk in doing this qualitative, thematic analysis of the literature is that the evidence presented in favour of each isolated point does not warrant or justify the existence of MG as a real psychological phenomenon.

For instance, where previous researchers put forward concepts like the "brain's centre of gravity" (Davey & Harrison, 2018) allegorically, metaphorically, or even euphemistically, the analogy here between physical and mental environments takes these concepts literally. In order to formalise the analogy, which is similar to that posited by "gravity models" in economics and other special sciences (Anderson, 2011; Lewer & Van den Berg, 2008; Lowe & Sen, 1996; Zhou, 2011), the MG theory needs to extend the use of physical terms like gravity, mass, weight, and falling beyond informal and isolated examples dotted across the psychological literature. The process of joining those dots can only sketch a very rough outline that needs to be tested but the theory is inherently testable. Table 2 lists a number of relevant themes which could feature in future MG research.

Falsifiable hypotheses could be ventured in any of these diverse fields of study, too, especially regarding serotonin. According to Spiegel (2022), serotonin evolved in part to manage gravity, with the term derived from its ability to increase muscular and visceral tone for basic tasks such as standing up, staying upright, maintaining balance, pumping blood, and digesting food in a 1-g environment (i.e., *sero-tonin* from Latin for *tone of serum*). Dysregulated serotonin can therefore make people vulnerable to gravity intolerance and a variety of musculoskeletal, gustatory, immunological, perceptual, affective and behavioral symptoms including IBS, vertigo/dizziness, anxiety, and depression. Serotonin regulates the vestibular system (Day & Fitzpatrick, 2005) and many other biological functions such as cardiovascular function, bowel motility, ejaculatory latency, and bladder control (Berger et al., 2009).

While 95% of serotonin is produced in the gut, it is often used pharmacologically to treat vestibular disorders (e.g., dizziness or vertigo) (Smith & Darlington, 2010; Teggi et al., 2010). More often still, serotonin is routinely used to treat the most common mental disorders – anxiety and depression (Harmer & Cowen, 2013; Murphy et al., 2021; Smith & Darlington, 2010). The serotonin hypothesis for depression, in particular, remains controversial in terms of both cause and treatment (Kendrick & Collinson, 2022; Moncrieff et al., 2022). Perhaps gravity is the right explanatory model, with MG an extension of the gravity hypothesis put forward by Spiegel (2022). Dysregulated serotonin in anxiety and depression could plausibly lead to the misperception of gravity by the "gut-brain accelerometer" and the embodied cognition of

Table 2
Research themes relevant to the mental gravity (MG) theory and associated continuum.

Domain	Low MG (positive high)	Mild MG (positive low)	High MG (negative high)	Severe MG (negative low)
Environment	•Spaceflight and microgravity •Spaciousness and immersion •Adventure and exploration	•Sacred spaces •Restorative environments •Aesthetics of verticality	•Psychosocial risk •Falling experiences •Climate change anxiety	•Isolation or confinement •Blue/green-space therapy •Hypergravity
Biology, physics and chemistry	•Altered states (MDMA, psychedelics) •Gut-brain regulation •Transient high serotonin activity	•Parasympathetic nervous system (relaxation) •Allostatic regulation •Gravity tolerance •Stable serotonin activity	•Sympathetic nervous system •Abdominal butterflies •Vertigo/disbalance •Unstable serotonin activity	•Psychomotor retardation •Gut-brain dysregulation •Posture, spinal alignment •Metabolic problems •Low serotonin activity
Behavior and language	•"UP" language •Physical activity (explore behaviors) •Natural states (flow, orgasm) •Music and dance •Hedonic wellbeing •Social connection	•"DOWN" language •Sedentary lifestyles (exploit behaviors) •Mindfulness or meditation •Contemplative practices •Eudaimonic wellbeing •Self-reflection	•"FALLING" language •Hyperarousal, agitation •Anxiety and addiction •Repetitive behaviors •Phobias and avoidance behaviors •Self-efficacy	•"FALLEN" language •Fatigue, sleep issues •Depression, suicide •Rumination, anergia •Anhedonia •Social isolation, disconnection
Cognition and emotion	•Self-transcendence, love •Euphoria and ecstasy •Lightness mental imagery •Openness traits	•Self) Compassion •Hope and awe •Grounded mental imagery •Conscientious traits	•Self-preservation •Fear, panic, dread •Future negative bias •Graviceptive inaccuracy	•Self-loathing •Flat affect •Time perception (slowness) •Autobiographical memory
Neuroanatomy	•Low salience and default mode network activity •Vestibular function	•Increased integration of salience, executive, and default mode networks	•High salience and default mode network activity •Vestibular dysfunction	•High default mode network activity, less integration between networks

g-force hypervigilance, feelings of falling, gravity intolerance, and so on. This suggests a plausible direct link between the perception of physical gravity and biopsychosocial health and wellbeing as mediated by serotonin. A study in mice suggests that the link between physical gravity and dysregulated serotonin could be causal from the outside-in, with altered gravity changing genetic expression for serotonin receptors in rodent brains (Ishikawa et al., 2017). The same could be the case if changes in MG have causal, affective power in the reverse direction from inside-out.

7. Conclusion

Much like "gravity models" used in economics and other special sciences (Anderson, 2011; Lewer & Van den Berg, 2008; Lowe & Sen, 1996; Zhou, 2011), the MG theory takes physical gravity as a model for other non-physical processes – in this case for the phenomenological, linguistic, cognitive, neurobiological, and wellbeing domains of mental processing. The theory draws a behavioral and phenomenological analogy between the physical and mental worlds as mediated by the relational socioemotional expression of a gravitropically embodied mind. Mental gravity explains not only what is expressed in states related to core facets of the self-world relationship (i.e., GUVV of the central MG self in thought, language, and behavior), but also how (i.e., simulated graviception), why (i.e., prompted by autobiographical mental mass), where (i.e., the salience and default-mode networks), and when (i.e., continuum of MG states) these expressions occur.

CRediT authorship contribution statement

Lachlan Kent: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing.

Acknowledgements

Many thanks to Niccolo Negro, Georg Northoff and Denis Le Bihan for thoughtful comments and feedback on recent drafts. Thanks also to Liz Temple, Britt Klein, George van Doorn, Terry Caelli, and Mark Bennett for their contributions to previous versions of the theory. Many thanks also to Terry Hartig for recommending the manuscript for JEVP. The figures were created using Biorender.com.

References

Abraham, W. C., & Robins, A. (2005). Memory retention the synaptic stability versus plasticity dilemma. *Trends in Neurosciences, 28*(2), 73–78. https://doi.org/10.1016/j.tins.2004.12.003

Adamopoulos, K., Koutsouris, D., Zaravinos, A., & Lambrou, G. I. (2021). Gravitational influence on human living systems and the evolution of species on earth. *Molecules, 26*(9), 2784. https://www.mdpi.com/1420-3049/26/9/2784.

Albi, E., Krüger, M., Hemmersbach, R., Lazzarini, A., Cataldi, S., Codini, M., Beccari, T., Ambesi-Impiombato, F. S., & Curcio, F. (2017). Impact of gravity on thyroid cells. *International Journal of Molecular Sciences, 18*(5), 972. https://www.mdpi.com/1422-0067/18/5/972.

Anderson, J. E. (2011). The gravity model. *Annual Review of Economics, 3*(1), 133–160. https://doi.org/10.1146/annurev-economics-111809-125114

Angelaki, D. E., & Cullen, K. E. (2008). Vestibular system: The many facets of a multimodal sense. *Annual Review of Neuroscience, 31*(1), 125–150. https://doi.org/10.1146/annurev.neuro.31.060407.125555

Angst, J., Angst, F., & Stassen, H. H. (1999). Suicide risk in patients with major depressive disorder. *The Journal of Clinical Psychiatry, 60*(Suppl 2), 57–62.

Balaban, C. D., & Jacob, R. G. (2001). Background and history of the interface between anxiety and vertigo. *Journal of Anxiety Disorders, 15*(1), 27–51.

Barrett, L. F., & Simmons, W. K. (2015). Interoceptive predictions in the brain. *Nature Reviews Neuroscience, 16*(7), 419. https://doi.org/10.1038/nrn3950

Battaglia, P. W., Hamrick, J. B., & Tenenbaum, J. B. (2013). Simulation as an engine of physical scene understanding. *Proceedings of the National Academy of Sciences, 110*(45), 18327–18332.

Benarroch, E. E. (2019). Insular cortex. *Functional complexity and clinical correlations, 93*(21), 932–938. https://doi.org/10.1212/wnl.0000000000008525

Berger, M., Gray, J. A., & Roth, B. L. (2009). The expanded biology of serotonin. *Annual Review of Medicine, 60*(1), 355–366. https://doi.org/10.1146/annurev.med.60.042307.110802

Brooks, A. W. (2014). Get excited: Reappraising pre-performance anxiety as excitement. *Journal of Experimental Psychology: General, 143*(3), 1144–1158. https://doi.org/10.1037/a0035325
Camilleri, M. (2009). Serotonin in the gastrointestinal tract. *Current Opinion in Endocrinology Diabetes and Obesity, 16*(1), 53–59. https://doi.org/10.1097/MED.0b013e32831e9c8e
Canales, J. Z., Fiquer, J. T., Campos, R. N., Soeiro-de-Souza, M. G., & Moreno, R. A. (2017). Investigation of associations between recurrence of major depressive disorder and spinal posture alignment: A quantitative cross-sectional study. *Gait & Posture, 52*, 258–264.
Carhart-Harris, R. L., Erritzoe, D., Williams, T., Stone, J. M., Reed, L. J., Colasanti, A., Tyacke, R. J., Leech, R., Malizia, A. L., Murphy, K., Hobden, P., Evans, J., Feilding, A., Wise, R. G., & Nutt, D. J. (2012). Neural correlates of the psychedelic state as determined by fMRI studies with psilocybin. *Proceedings of the National Academy of Sciences, 109*(6), 2138–2143.
Chorpita, B. F., & Barlow, D. H. (1998). The development of anxiety: The role of control in the early environment. *Psychological Bulletin, 124*(1), 3–21. https://doi.org/10.1037/0033-2909.124.1.3
Cian, L. (2017). Verticality and conceptual metaphors: A systematic review. *Journal of the Association for Consumer Research, 2*(4), 444–459. https://doi.org/10.1086/694082
Clément, G. (2018). Perception of time in microgravity and hypergravity during parabolic flight. *NeuroReport, 29*(4), 247–251. https://doi.org/10.1097/wnr.0000000000000923
Coll-Florit, M., Climent, S., Sanfilippo, M., & Hernández-Encuentra, E. (2021). Metaphors of depression. Studying first person accounts of life with depression published in blogs. *Metaphor and Symbol, 36*(1), 1–19. https://doi.org/10.1080/10926488.2020.1845096
Costa, M., & Bonetti, L. (2016). Geometrical factors in the perception of sacredness. *Perception, 45*(11), 1240–1266. https://doi.org/10.1177/0301006616654159
Craig, A. D. (2009). How do you feel–now? The anterior insula and human awareness. *Nature Reviews Neuroscience, 10*(1), 59–70. https://doi.org/10.1038/nrn2555
Cullen, K. E. (2019). Vestibular processing during natural self-motion: Implications for perception and action. *Nature Reviews Neuroscience, 20*(6), 346–363. https://doi.org/10.1038/s41583-019-0153-1
Dalgleish, T., & Werner-Seidler, A. (2014). Disruptions in autobiographical memory processing in depression and the emergence of memory therapeutics. *Trends in Cognitive Sciences, 18*(11), 596–604. https://doi.org/10.1016/j.tics.2014.06.010
Davey, C. G., & Harrison, B. J. (2018). The brain's center of gravity: How the default mode network helps us to understand the self. *World Psychiatry: Official Journal of the World Psychiatric Association (WPA), 17*(3), 278–279. https://doi.org/10.1002/wps.20553
Davey, C. G., & Harrison, B. J. (2022). The self on its axis: A framework for understanding depression. *Translational Psychiatry, 12*(1), 23. https://doi.org/10.1038/s41398-022-01790-8
Day, B. L., & Fitzpatrick, R. C. (2005). The vestibular system. *Current Biology, 15*(15), R583–R586. https://doi.org/10.1016/j.cub.2005.07.053
Debruyne, H., Portzky, M., Van den Eynde, F., & Audenaert, K. (2009). Cotard's syndrome: A review. *Current Psychiatry Reports, 11*(3), 197–202. https://doi.org/10.1007/s11920-009-0031-z
Dehcheshmeh, T. F., Majelan, A. S., & Maleki, B. (2023). Correlation between depression and posture (A systematic review). *Current Psychology*. https://doi.org/10.1007/s12144-023-04630-0
Dennett, D. (1992). The self as a center of narrative gravity. In F. S. Kessel, P. M. Cole, & D. L. Johnson (Eds.), *Self and consciousness: Multiple perspectives*. Lawrence Erlbaum.
Dionisio, S., Mayoglou, L., Cho, S.-M., Prime, D., Flanigan, P. M., Lega, B., Mosher, J., Leahy, R., Gonzalez-Martinez, J., & Nair, D. (2019). Connectivity of the human insula: A cortico-cortical evoked potential (CCEP) study. *Cortex, 120*, 419–442.
Duncan, J. (2010). The multiple-demand (MD) system of the primate brain: Mental programs for intelligent behaviour. *Trends in Cognitive Sciences, 14*(4), 172–179.
Dzokoto, V. A., & Okazaki, S. (2006). Happiness in the eye and the heart: Somatic referencing in west African emotion lexica. *Journal of Black Psychology, 32*(2), 17–140. https://doi.org/10.1177/0095798406286799
Dzokoto, V., Senft, N., Kpobi, L., & Washington-Nortey, P.-M. (2016). Their hands have lost their bones: Exploring cultural scripts in two west African affect lexica. *Journal of Psycholinguistic Research, 45*(6), 1473–1497. https://doi.org/10.1007/s10936-016-9415-5
Einstein, A., & Fokker, A. D. (1914). Die nordströmsche gravitationstheorie vom standpunkt des absoluten differentialkalküls. *Annalen der Physik, 349*(10), 321–328.
Feldman, R., Schreiber, S., Pick, C., & Been, E. (2020). Gait, balance and posture in major mental illnesses: Depression, anxiety and schizophrenia. *Austin Medical Sciences, 5*(1), 1–6.
Ferrè, E. R., Frett, T., Haggard, P., & Longo, M. R. (2019). A gravitational contribution to perceived body weight. *Scientific Reports, 9*(1), Article 11448. https://doi.org/10.1038/s41598-019-47663-x
Ferre, E., Longo, M., Fiori, F., & Haggard, P. (2013). 2013-October-10). Vestibular modulation of spatial perception [Original Research]. *Frontiers in Human Neuroscience, 7*. https://doi.org/10.3389/fnhum.2013.00660
Ferrè, E. R., Lopez, C., & Haggard, P. (2014). Anchoring the self to the body: Vestibular contribution to the sense of self. *Psychological Science, 25*(11), 2106–2108. https://doi.org/10.1177/0956797614547917
Fischer, J., Mikhael, J. G., Tenenbaum, J. B., & Kanwisher, N. (2016). Functional neuroanatomy of intuitive physical inference. *Proceedings of the National Academy of Sciences, 113*(34), E5072–E5081.
Frank, S. M., & Greenlee, M. W. (2018). The parieto-insular vestibular cortex in humans: More than a single area? *Journal of Neurophysiology, 120*(3), 1438–1450. https://doi.org/10.1152/jn.00907.2017
Fuchs, T. (2018). Presence in absence. The ambiguous phenomenology of grief. *Phenomenology and the Cognitive Sciences, 17*(1), 43–63. https://doi.org/10.1007/s11097-017-9506-2
Gallagher, M., Arshad, I., & Ferrè, E. R. (2019). Gravity modulates behaviour control strategy. *Experimental Brain Research, 237*(4), 989–994. https://doi.org/10.1007/s00221-019-05479-1
Gallagher, M., & Ferrè, E. R. (2018). The aesthetics of verticality: A gravitational contribution to aesthetic preference. *Quarterly Journal of Experimental Psychology, 71*(12), 2655–2664. https://doi.org/10.1177/1747021817751353
Gallagher, M., Kearney, B., & Ferrè, E. R. (2021). Where is my hand in space? The internal model of gravity influences proprioception. *Biology Letters, 17*(6), Article 20210115. https://doi.org/10.1098/rsbl.2021.0115
Gomez-Andres, A., Cunillera, T., Rico, I., Naval-Baudin, P., Camins, A., Fernandez-Coello, A., Gabarrós, A., & Rodriguez-Fornells, A. (2022). The role of the anterior insular cortex in self-monitoring: A novel study protocol with electrical stimulation mapping and functional magnetic resonance imaging. *Cortex, 157*, 231–244.
Gottwald, J. M., Elsner, B., & Pollatos, O. (2015). 2015-October-20). Good is up—spatial metaphors in action observation [Original Research]. *Frontiers in Psychology, 6*. https://doi.org/10.3389/fpsyg.2015.01605
Goulden, N., Khusnulina, A., Davis, N. J., Bracewell, R. M., Bokde, A. L., McNulty, J. P., & Mullins, P. G. (2014). The salience network is responsible for switching between the default mode network and the central executive network: Replication from DCM. *NeuroImage, 99*, 180–190. https://doi.org/10.1016/j.neuroimage.2014.05.052
Greening, S. G., Lee, T.-H., Burleigh, L., Grégoire, L., Robinson, T., Jiang, X., Mather, M., & Kaplan, J. (2022). Mental imagery can generate and regulate acquired differential fear conditioned reactivity. *Scientific Reports, 12*(1), 997. https://doi.org/10.1038/s41598-022-05019-y
Gu, X., Gao, Z., Wang, X., Liu, X., Knight, R. T., Hof, P. R., & Fan, J. (2012). Anterior insular cortex is necessary for empathetic pain perception. *Brain, 135*(9), 2726–2735. https://doi.org/10.1093/brain/aws199
Gu, X., Hof, P. R., Friston, K. J., & Fan, J. (2013). Anterior insular cortex and emotional awareness. *Journal of Comparative Neurology, 521*(15), 3371–3388.
Hamdi, S. (2016). A cognitive study of happiness metaphors in English, Tunisian Arabic and Spanish. *Arab World English Journal, 6*(1), 132–143. https://doi.org/10.2139/ssrn.2834437
Hameroff, S. R., Craddock, T. J., & Tuszynski, J. A. (2014). Quantum effects in the understanding of consciousness. *Journal of Integrative Neuroscience, 13*(2), 229–252. https://doi.org/10.1142/S0219635214400093
Harmer, C. J., & Cowen, P. J. (2013). 'It's the way that you look at it'—a cognitive neuropsychological account of SSRI action in depression. *Philosophical Transactions of the Royal Society of London B Biological Sciences, 368*(1615), Article 20120407.
Hartig, T. (2021). Restoration in nature: Beyond the conventional narrative. In A. R. Schutte, J. C. Torquati, & J. R. Stevens (Eds.), *Nature and psychology: Biological, cognitive, developmental, and social pathways to well-being* (pp. 89–151). Springer International Publishing. https://doi.org/10.1007/978-3-030-69020-5_5.
Hartmann, M., Lenggenhager, B., & Stocker, K. (2022). Happiness feels light and sadness feels heavy: Introducing valence-related bodily sensation maps of emotions. *Psychological Research*. https://doi.org/10.1007/s00426-022-01661-3
Hauschild, S., Tauber, S., Lauber, B., Thiel, C. S., Layer, L. E., & Ullrich, O. (2014). T cell regulation in microgravity – the current knowledge from in vitro experiments conducted in space, parabolic flights and ground-based facilities. *Acta Astronautica, 104*(1), 365–377.
Hohwy, J. (2016). The self-evidencing brain. *Noûs, 50*(2), 259–285. https://doi.org/10.1111/nous.12062
Hollis-Walker, L., & Colosimo, K. (2011). Mindfulness, self-compassion, and happiness in non-meditators: A theoretical and empirical examination. *Personality and Individual Differences, 50*(2), 222–227.
Huang, Z., Tarnal, V., Vlisides, P. E., Janke, E. L., McKinney, A. M., Picton, P., Mashour, G. A., & Hudetz, A. G. (2021). Anterior insula regulates brain network transitions that gate conscious access. *Cell Reports, 35*(5). https://doi.org/10.1016/j.celrep.2021.109081
Ishikawa, C., Li, H., Ogura, R., Yoshimura, Y., Kudo, T., Shirakawa, M., Shiba, D., Takahashi, S., Morita, H., & Shiga, T. (2017). Effects of gravity changes on gene expression of BDNF and serotonin receptors in the mouse brain. *PLoS One, 12*(6), Article e0177833. https://doi.org/10.1371/journal.pone.0177833
Jackson, C. J. (2020). Transformational leadership and gravitas: 2000 years of no development? *Personality and Individual Differences, 156*, Article 109760.
Jackson, C. J. (2021). What have the romans done for us? Pliny "the younger's" imperial virtues and their convergent validity with contemporary models of personality. *Personality and Individual Differences, 178*, Article 110860.
Jörges, B., & López-Moliner, J. (2017). Gravity as a strong prior: Implications for perception and action. *Frontiers in Human Neuroscience, 11*. https://doi.org/10.3389/fnhum.2017.00203
Kaas, A., Weigelt, S., Roebroeck, A., Kohler, A., & Muckli, L. (2010). Imagery of a moving object: The role of occipital cortex and human MT/V5+. *NeuroImage, 49*(1), 794–804.
Kaplan, K. A., & Harvey, A. G. (2009). Hypersomnia across mood disorders: A review and synthesis. *Sleep Medicine Reviews, 13*(4), 275–285.
Kendrick, T., & Collinson, S. (2022). Antidepressants and the serotonin hypothesis of depression. *BMJ, 378*, o1993. https://doi.org/10.1136/bmj.o1993
Kent, L. (2023). Mental gravity: Depression as spacetime curvature of the self, mind, and brain. *Entropy, 25*(9), 1275. https://www.mdpi.com/1099-4300/25/9/1275.
Kornilova, L. N., & Kozlovskaya, I. B. (2003). Neurosensory mechanisms of space adaptation syndrome. *Human Physiology, 29*(5), 527–538. https://doi.org/10.1023/A:1025899413655

Kroenke, K., Spitzer, R. L., & Williams, J. B. W. (2001). The PHQ-9. *Journal of General Internal Medicine, 16*(9), 606–613. https://doi.org/10.1046/j.1525-1497.2001.016009606.x

Kubricht, J. R., Holyoak, K. J., & Lu, H. (2017). Intuitive physics: Current research and controversies. *Trends in Cognitive Sciences, 21*(10), 749–759.

Lakens, D. (2012). Polarity correspondence in metaphor congruency effects: Structural overlap predicts categorization times for bipolar concepts presented in vertical space. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(3), 726–736. https://doi.org/10.1037/a0024955

Lakoff, G. (2012). Explaining embodied cognition results. *Topics in Cognitive Science, 4*(4), 773–785.

Lakoff, G., & Johnson, M. (2008). *Metaphors we live by*. University of Chicago Press.

Lamers, S. M. A., Westerhof, G. J., Bohlmeijer, E. T., ten Klooster, P. M., & Keyes, C. L. M. (2011). Evaluating the psychometric properties of the mental health Continuum-Short Form (MHC-SF). *Journal of Clinical Psychology, 67*(1), 99–110.

Lamm, C., & Singer, T. (2010). The role of anterior insular cortex in social emotions. *Brain Structure and Function, 214*(5), 579–591. https://doi.org/10.1007/s00429-010-0251-3

Lewer, J. J., & Van den Berg, H. (2008). A gravity model of immigration. *Economics Letters, 99*(1), 164–167. https://doi.org/10.1016/j.econlet.2007.06.019

Lowe, J., & Sen, A. (1996). Gravity model applications in health planning: Analysis of an urban hospital market. *Journal of Regional Science, 36*, 437–461. https://doi.org/10.1111/j.1467-9787.1996.tb01111.x

Lucherini Angeletti, L., Scalabrini, A., Ricca, V., & Northoff, G. (2023). Topography of the anxious self: Abnormal rest-task modulation in social anxiety disorder. *The Neuroscientist, 29*(2), 221–244. https://doi.org/10.1177/10738584211030497

Lymeus, F., Lindberg, P., & Hartig, T. (2018). Building mindfulness bottom-up: Meditation in natural settings supports open monitoring and attention restoration. *Consciousness and Cognition, 59*, 40–56.

Lymeus, F., White, M. P., Lindberg, P., & Hartig, T. (2022). Restoration skills training in a natural setting compared to conventional mindfulness training: Sustained advantages at a 6-month follow-up [original research]. *Frontiers in Psychology, 13*. https://doi.org/10.3389/fpsyg.2022.763650

Macaulay, R., Lee, K., Johnson, K., & Williams, K. (2022). Mindful engagement, psychological restoration, and connection with nature in constrained nature experiences. *Landscape and Urban Planning, 217*, Article 104263.

Matsnev, E. I., Yakovleva, I. Y., Tarasov, I. K., Alekseev, V. N., Kornilova, L. N., Mateev, A. D., & Gorgiladze, G. I. (1983). Space motion sickness: Phenomenology, countermeasures, and mechanisms. *Aviation Space & Environmental Medicine, 54*(4), 312–317.

McIntyre, J., Zago, M., Berthoz, A., & Lacquaniti, F. (2001). Does the brain model Newton's laws? *Nature Neuroscience, 4*(7), 693–694. https://doi.org/10.1038/89477

McMullen, L. M., & Conway, J. B. (2002). Conventional metaphors for depression. In S. R. Fussell (Ed.), *The verbal communication of emotions: Interdisciplinary perspectives* (pp. 167–181). Lawren Erlbaum Associates.

Mellet, E., Tzourio-Mazoyer, N., Bricogne, S., Mazoyer, B., Kosslyn, S. M., & Denis, M. (2000). Functional anatomy of high-resolution visual mental imagery. *Journal of Cognitive Neuroscience, 12*(1), 98–109. https://doi.org/10.1162/08989290051137620

Menon, V. (2023). 20 years of the default mode network: A review and synthesis. *Neuron, 111*(16), 2469–2487.

Molnar-Szakacs, I., & Uddin, L. Q. (2022). Anterior insula as a gatekeeper of executive control. *Neuroscience & Biobehavioral Reviews*, Article 104736.

Moncrieff, J., Cooper, R. E., Stockmann, T., Amendola, S., Hengartner, M. P., & Horowitz, M. A. (2022). The serotonin theory of depression: A systematic umbrella review of the evidence. *Molecular Psychiatry*. https://doi.org/10.1038/s41380-022-01661-0

Moutoussis, M., Fearon, P., El-Deredy, W., Dolan, R. J., & Friston, K. J. (2014). Bayesian inferences about the self (and others): A review. *Consciousness and Cognition, 25*, 67–76.

Murphy, S. E., Capitão, L. P., Giles, S. L. C., Cowen, P. J., Stringaris, A., & Harmer, C. J. (2021). The knowns and unknowns of SSRI treatment in young people with depression and anxiety: Efficacy, predictors, and mechanisms of action. *The Lancet Psychiatry, 8*(9), 824–835.

Murray, S. (2013). Embracing lightness: Dispositions, corporealities and metaphors in contemporary theatre and performance. *Contemporary Theatre Review, 23*(2), 206–219. https://doi.org/10.1080/10486801.2013.777051

Myachykov, A., Scheepers, C., Fischer, M. H., & Kessler, K. (2014). Test: A tropic, embodied, and situated theory of cognition. *Topics in Cognitive Science, 6*(3), 442–460.

Najrana, T., & Sanchez-Esteban, J. (2016). 2016-December-26). Mechanotransduction as an adaptation to gravity. *Frontiers in Pediatrics, 4*. https://doi.org/10.3389/fped.2016.00140

Nakamura, J., & Csikszentmihalyi, M. (2002). The concept of flow. In C. R. Snyder, & S. J. Lopez (Eds.), *Handbook of positive psychology* (pp. 89–105). Oxford University Press.

Newton, I. (1687). *Philosophiae naturalis principia mathematica ("Mathematical Principles of natural philosophy")*. Royal Society Press.

Palhano-Fontes, F., Andrade, K. C., Tofoli, L. F., Santos, A. C., Crippa, J. A. S., Hallak, J. E. C., Ribeiro, S., & de Araujo, D. B. (2015). The psychedelic state induced by Ayahuasca modulates the activity and connectivity of the default mode network. *PLoS One, 10*(2), Article e0118143. https://doi.org/10.1371/journal.pone.0118143

Paulsen, O., & Moser, E. (1998). A model of hippocampal memory encoding and retrieval: GABAergic control of synaptic plasticity. *Trends in Neurosciences, 21*(7), 273–278. https://doi.org/10.1016/S0166-2236(97)01205-8

Pavlidou, A., Ferrè, E. R., & Lopez, C. (2018). Vestibular stimulation makes people more egocentric. *Cortex, 101*, 302–305.

Pfaltz, M. C., Plichta, M. M., Bockisch, C. J., Jellestad, L., Schnyder, U., & Stocker, K. (2021). Processing of an ambiguous time phrase in posttraumatic stress disorder: Eye movements suggest a passive, oncoming perception of the future. *Psychiatry Research, 299*, Article 113845.

Roshanaei-Moghaddam, B., Katon, W. J., & Russo, J. (2009). The longitudinal effects of depression on physical activity. *General Hospital Psychiatry, 31*(4), 306–315.

Rousseau, C., Barbiero, M., Pozzo, T., Papaxanthis, C., & White, O. (2020). Actual and imagined movements reveal a dual role of the insular cortex for motor control. *Cerebral Cortex, 31*(5), 2586–2594. https://doi.org/10.1093/cercor/bhaa376

Seth, A. K. (2013). Interoceptive inference, emotion, and the embodied self. *Trends in Cognitive Sciences, 17*(11), 565–573.

Seth, A. K., & Friston, K. J. (2016). Active interoceptive inference and the emotional brain. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*(1708), Article 20160007.

Shapiro, S. L., Carlson, L. E., Astin, J. A., & Freedman, B. (2006). Mechanisms of mindfulness. *Journal of Clinical Psychology, 62*(3), 373–386.

Smith, P. F., & Darlington, C. L. (2010). A possible explanation for dizziness following SSRI discontinuation. *Acta Oto-Laryngologica, 130*(9), 981–983. https://doi.org/10.3109/00016481003602082

Spagna, A., Hajhajate, D., Liu, J., & Bartolomeo, P. (2021). Visual mental imagery engages the left fusiform gyrus, but not the early visual cortex: A meta-analysis of neuroimaging evidence. *Neuroscience & Biobehavioral Reviews, 122*, 201–217.

Spiegel, B. (2022). Gravity and the gut: A hypothesis of irritable bowel syndrome. *Official journal of the American College of Gastroenterology | ACG, 117*(12). https://journals.lww.com/ajg/fulltext/2022/12000/gravity_and_the_gut_a_hypothesis_of_irritable.15.aspx.

Steel, Z., Marnane, C., Iranpour, C., Chey, T., Jackson, J. W., Patel, V., & Silove, D. (2014). The global prevalence of common mental disorders: A systematic review and meta-analysis 1980–2013. *International Journal of Epidemiology, 43*(2), 476–493. https://doi.org/10.1093/ije/dyu038

Teggi, R., Caldirola, D., Colombo, B., Perna, G., Comi, G., Bellodi, L., & Bussi, M. (2010). Dizziness, migrainous vertigo and psychiatric disorders. *Journal of Laryngology & Otology, 124*(3), 285–290. https://doi.org/10.1017/S0022215109991976

Uddin, L. Q., Nomi, J. S., Hébert-Seropian, B., Ghaziri, J., & Boucher, O. (2017). Structure and function of the human insula. *Journal of Clinical Neurophysiology, 34*(4), 300–306. https://doi.org/10.1097/wnp.0000000000000377

Ullman, T. D., Spelke, E., Battaglia, P., & Tenenbaum, J. B. (2017). Mind games: Game engines as an architecture for intuitive physics. *Trends in Cognitive Sciences, 21*(9), 649–665. https://doi.org/10.1016/j.tics.2017.05.012

van Rompay, T. J. L., Oran, S., Galetzka, M., & van den Berg, A. E. (2023). Lose yourself: Spacious nature and the connected self. *Journal of Environmental Psychology, 91*, Article 102108.

Walker, P., Scallon, G., & Francis, B. (2017). Cross-sensory correspondences: Heaviness is dark and low-pitched. *Perception, 46*(7), 772–792. https://doi.org/10.1177/0301006616684369

White, M. P., Alcock, I., Grellier, J., Wheeler, B. W., Hartig, T., Warber, S. L., Bone, A., Depledge, M. H., & Fleming, L. E. (2019). Spending at least 120 minutes a week in nature is associated with good health and wellbeing. *Scientific Reports, 9*(1), 7730. https://doi.org/10.1038/s41598-019-44097-3

White, M. P., Elliott, L. R., Gascon, M., Roberts, B., & Fleming, L. E. (2020). Blue space, health and well-being: A narrative overview and synthesis of potential benefits. *Environmental Research, 191*, Article 110169.

Whitehead, W. E., Palsson, O., & Jones, K. R. (2002). Systematic review of the comorbidity of irritable bowel syndrome with other disorders: What are the causes and implications? *Gastroenterology, 122*(4), 1140–1156.

Wnorowski, A., Sharma, A., Chen, H., Wu, H., Shao, N.-Y., Sayed, N., Liu, C., Countryman, S., Stodieck, L. S., Rubins, K. H., Wu, S. M., Lee, P. H. U., & Wu, J. C. (2019). Effects of spaceflight on human induced pluripotent stem cell-derived cardiomyocyte structure and function. *Stem Cell Reports, 13*(6), 960–969. https://doi.org/10.1016/j.stemcr.2019.10.006

Yang, J.-Q., Jiang, N., Li, Z.-P., Guo, S., Chen, Z.-Y., Li, B.-B., Chai, S.-B., Lu, S.-Y., Yan, H.-F., Sun, P.-M., Zhang, T., Sun, H.-W., Yang, J.-W., Zhou, J.-L., Yang, H.-M., & Cui, Y. (2020). The effects of microgravity on the digestive system and the new insights it brings to the life sciences. *Life Sciences and Space Research, 27*, 74–82.

Young, L. R., Oman, C. M., Watt, D. G. D., Money, K. E., & Lichtenberg, B. K. (1984). Spatial orientation in weightlessness and readaptation to earth's gravity. *Science, 225*(4658), 205–208.

Zhou, M. (2011). Intensification of geo-cultural homophily in global trade: Evidence from the gravity model. *Social Science Research, 40*(1), 193–209. https://doi.org/10.1016/j.ssresearch.2010.07.002