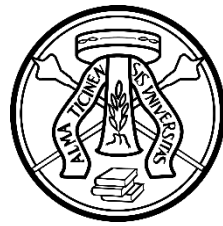


UNIVERSITY OF PAVIA – IUSS SCHOOL FOR ADVANCED STUDIES PAVIA

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INTERACTION BETWEEN INTEROCEPTION AND VESTIBULAR PROCESSING IN RISK-TAKING

**Neurocognitive Perspectives
and Criminological Implications**

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Abstract

Risk-taking behaviour is a complex type of decision-making influenced by cognitive, emotional and bodily processes. The current study investigated the potential role of vestibular disruption through high-frequency sinusoidal Galvanic Vestibular Stimulation (GVS) in risk-taking and its relationship with interoception. Ten healthy participants underwent two active and one sham GVS sessions, in which they performed two behavioural tasks: the Balloon Analogue Risk Task (BART) and the Heartbeat Counting Task (HCT). Moreover, they completed the Multidimensional Assessment of Interoceptive Awareness – Second Edition (MAIA – 2), the General Risk Propensity Scale (GRiPS), the State – Trait Anxiety Inventory (STAI X – 1 and X – 2), the Beck Depression Inventory – Second Edition (BDI – II), and the Simulator Sickness Questionnaire (SSQ). No significant differences in BART performance were found between active and sham stimulation conditions, as well as no significant differences in the HCT interoceptive accuracy and no interaction between vestibular stimulation and interoceptive measures emerged. However, participants with higher MAIA – 2 total scores (i.e., the sum of all items) showed high levels of risk-taking during the BART. Exploratory correlations further suggested associations between interoception and risk-taking behaviour. Overall, the findings do not support a generic effect of GVS on decision-making or interoception, but interoceptive sensibility may represent an individual-difference factor relevant for risky behaviours. Translational applicability of research in forensic and justice contexts is discussed, as in the literature risk-taking is overlapping with Gottfredson and Hirschi's self-control concept in the General Theory of Crime. Addressing risk-taking is relevant for informed and critical approaches to neuroprediction, social rehabilitation, and ultimately reintegration into society of criminal offenders.

1. Introduction & Background

1.1. Neuroscientific Background

1.1.1. Decision-Making

The ability to make decisions represents an essential cognitive ability for environment adaptation and for individual's autonomy (Morelli et al., 2022). Daily humans perform choices in conditions of uncertainty, and the quality and outcomes of our decisions impact quality of life profoundly. In this regard, decision-making is a crucial topic in diverse disciplines, from philosophy to economy, from psychology to neuroscience. Each contribution informed our present perspective of the processes leading to make choices (Morelli et al., 2022). According to the definition proposed by Ernst and Paulus (2005), a general structure of decision-making can be identified through three key points: the formation of preferences among the possible options, the selection and execution of the chosen option, and the evaluation of the outcome and subsequent integration of the feedback in the behaviour.

From a theoretical viewpoint, two main fields can be identified in the decision-making literature: the normative approach and the descriptive approach. The first framework is not influenced by ecological or empirical evidence and provides information on how a rational agent should behave to maximise outcomes (Von Neumann & Morgenstern, 1944); this top-down approach is based on mathematical analyses to derive the best possible decision in the plethora of preferences, reducing the process to variables (Johnson & Busemeyer, 2010). An example of normative approach is the *Expected Utility Theory* (Morelli et al., 2022; Von Neumann & Morgenstern, 1944).

Conversely, the descriptive approach considers the variability that characterises decision-making in ecological settings: for instance, real-life conditions of uncertainty or missed knowledge highlight the limitations of the normative framework, in favour of descriptions of violations of the proposed rules (Morelli et al., 2022). As an example, the *Prospect theory*,

proposed by Kahneman and Tversky (2013), focuses on decision weights rather than final assets. In particular, decision weights depend on perceived likelihood of events, whereas gain-framed decisions tend to be more risk-averse than loss-framed decisions, with reference points relying on past experiences that ultimately influence the subjective assessment of utility in a non-necessarily rational manner (Morelli et al., 2022).

In decision-making, there is a specific type of behaviour that is particularly studied: risk-taking behaviour. Specifically, risk-taking can be defined as “engagement in behaviours that are associated with some probability of undesirable results” (Boyer, 2006), including for instance anti-social or illegal behaviours, as well as those who pose a risk for one’s health (Magar et al., 2008). It involves choices under uncertainty, where potential rewards are weighed against possible negative outcomes, and the decisional process involves any potential harm or danger, while providing the opportunity to gain rewards as a result (De Maio et al., 2021; Leigh, 1999). Despite the interindividual variability, risk-taking has been investigated for its multi-faceted nature: certain levels of risk tendency can be considered evolutionary important and adapting to the point that explorative behaviour and risk-related traits (e.g., aggressiveness) are common characteristics of human and animal personalities (Wolf et al., 2007). However, the extreme manifestations of this kind of behaviour can be maladaptive and even represent pathological configurations (Levy, 2017): for instance, extreme avoidance of risk is associated with anxiety-based disorders independently from different types of the disorders (e.g., panic attack disorder, generalised anxiety disorder) (Giorgetta et al., 2012). Conversely, the other end of the spectrum is characterised by an excessive propensity to risk-related behaviour: while some authors did not find a relationship between internalising and externalising symptoms in mental disorders and risk-taking in children and adolescents (Bentivegna et al., 2024), other studies support an association between impulsivity and diverse disorders, such as bipolar and schizophrenia spectrum disorders, attention-deficit hyperactivity disorder (ADHD), borderline and antisocial

personality disorders and many others (Hjell et al., 2023). Moreover, excessive risk-related behaviour is also linked to potentially harmful behaviours, as for instance alcohol abuse (Leigh, 1999) and engagement in criminal activities since adolescence (Steinberg, 2007) as suggested by developmental neuroscience.

Because of the role of decision-making, and in particular risk-taking, in potentially negative behaviours with social repercussions, the study of risk-related behaviour has become widespread also to inform public policy: in particular, adolescent risk-taking has become acknowledged as a relevant public health issue worth of community-level interventions, such as improvement of living conditions, education and employment, tobacco prices increase, and mass media interventions. However, these changes only have a very limited success (Pound & Campbell, 2015), also due to the fact that heightened risk-taking in adolescence is a normative and biologically driven process rooted in the reward sensitivity taking place at puberty (Steinberg, 2008). Risk-taking behaviours are the product of logical reasoning and psychosocial factors: the former develop fully by 15 years of age, while the latter mature later in life, completing their development in young adulthood, contributing to impulse control, emotion regulation, delay of gratification, and resistance to peer influence (Steinberg, 2004, 2007).

Nevertheless, a high-risk-taking propensity in adolescence is associated to juvenile delinquency and adult offending (Basto-Pereira et al., 2024). Thus, the further investigation of how this subtype of decision-making can impact on future outcomes comes inevitable when aiming for an informed approach.

Despite the continuous growth of theories about decision-making processes, the neural basis of making decisions has remained unclarified until the last decades of research, when neuroscientists started investigating physiologically the arise of this type of behaviour (Platt, 2002). A meta-analysis suggests that the neural substrates of decision-making are widespread across the brain and vary based on the nature of the decision (Krain et al., 2006), with interesting

dissociations between risk-related and ambiguous-related decisions: an increased orbitofrontal cortex activity is associated with risky settings, while the dorsolateral prefrontal cortex seems more linked to ambiguity tasks. Similar distinctions happen between affective processes, with involvement of rostral anterior cingulate cortex (ACC), and pure cognitive processes, with activation of caudal portions of ACC. Moreover, parietal activations appear linked to decisional processes. Similar patterns of neural correlates are supported by other studies involving decision-making (Ernst & Paulus, 2005).

More recently, some scholars have linked vestibular cognition to the cognitive processes underlying decision-making: despite being traditionally associated with low-level reflex motor circuits, Ferrè and Haggard (2020) proposed that vestibular signals “form a ubiquitous background of all one’s activities and interactions” linked to cerebral functions ranging from autonomic regulation and sensorimotor control, thanks to the diffuse vestibular projections to multiple brain areas, including the frontal cortex (Agrawal, 2020) that represents a neural correlate of decision-making.

1.1.2. The Vestibular System

The vestibular system, the ensemble of balance organs of the inner ear, is characterised by five organs on each side of the head: three orthogonal semicircular canals and two otolith organs (utricle and saccule) located in the vestibule, which extends between the semicircular canals and the cochlea (Figure 1). The horizontal semicircular canal and the utricle are both tilted anterodorsally relative to the naso-occipital plane by approximately 30 degrees, perpendicularly to gravity, while the other planes are arranged to be orthogonal to this one (Dickman, 2018). These organs are able to detect acceleration: in particular, the semicircular canals are sensitive to angular acceleration (i.e., rotational head movements), while otolith organs can sense linear acceleration (i.e., translational head movements), being the utricle sensitive to horizontal plane accelerations and the saccule to vertical plane accelerations (Angelaki & Cullen, 2008).

For instance, gravity itself, a form of linear acceleration, is detected by the vestibular organs and provides information about head position in space (Yates et al., 2014) as in a three-dimensional plane.

The receptor cells in each endorgan are innervated by primary afferent fibers that join with the ones from the cochlea to comprise the vestibulocochlear – VIII – cranial nerve. While the cell bodies of these afferent neurons lie in the vestibular ganglion – Scarpa ganglion – of the internal acoustic meatus, their central processes enter the brainstem and reach the ipsilateral vestibular nuclei and cerebellum (Dickman, 2018).

Head position and movement in space is differentiated from information about body localisation through integration of inputs from vestibular endorgans and neck proprioceptors, which are typically antagonistic (Ezure & Wilson, 1984). Moreover, vestibular neurons receive proprioceptive inputs from peripheral sources, such as limbs and viscera (Jian et al., 2002).

For the above reasons, the vestibular system has been traditionally linked to spatial orienting behaviour. However, vestibular contribution goes far beyond a simple low-level reflex motor

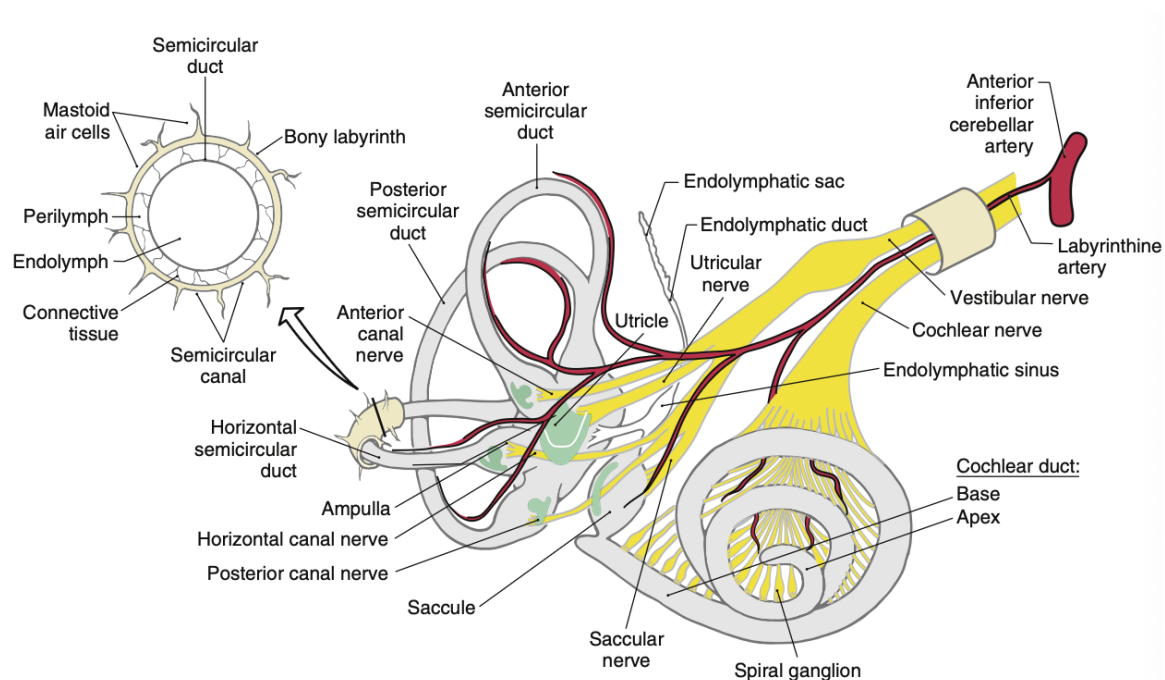


Figure 1
Detailed vestibular anatomy (Dickman, 2018)

circuit (Ferrè & Haggard, 2020): vestibular projections in the brain represent a broader background for cognition.

For instance, a PET activation study (Bottini et al., 1994), measuring regional cerebral blood flow changes, demonstrated how the vestibular system projects to multiple brain areas, producing a distributed network: the temporoparietal cortex, the insula, the putamen, and the anterior cingulate cortex. Some studies have tried to confirm a primary vestibular cortex, concluding that the cytoarchitectonic area OP 2 in the parietal operculum could be the human homologue to monkey's parietal insular vestibular cortex (Guldin & Grüsser, 1998; zu Eulenburg et al., 2012). This region is called Parieto-Insular-Vestibular-Cortex (PIVC) and extends into the posterior insular lobe, so that vestibular signals project to multiple areas traditionally linked to other cognitive functions and do not project to any primary unimodal cortex (Ferrè & Haggard, 2020).

Thus, as Ferrè and Haggard (2020) hypothesised, the vestibular system is involved in at least three main domains of function:

1. an *autonomic domain* regarding the current physiological condition of the body, which includes influence of the vestibular system on blood pressure, pain, heart rate and respiration; for instance, changes in heart rate and heart rate variability can be compromised or lost in persons with vestibular dysfunction, highlighting the vestibular role in cardiovascular regulation (Yates et al., 2014);
2. a *sensorimotor domain* related to the sensory integration of vestibular, visual, proprioceptive and somatosensory information and for modulation of motor responses;
3. a *cognitive domain* related to decision-making, attention, emotion and other higher order cognitive functions.

Ferrè and Haggard (2020) propose two different functional architectures to account for the above-mentioned domains: the “Enabling” model, in which vestibular inputs primarily reach

the autonomic domain, on which all of the other functions rely, and the “Independent Projections” model, which implies that vestibular signals reach independently each of the three domains. In the light of the scientific literature about the general right hemisphere specialisation of the vestibular system’s projections to the brain, another model has been recently proposed by Bottini and Salvato (2020): a “middle-ground” model taking into account independent projections to functionally connected areas in the vestibular network and the predominant role of the right hemisphere in the cortical processing of vestibular afferents. The lateralisation of vestibular projections mainly in the non-dominant hemisphere (Bottini et al., 1994; Dieterich et al., 2003) (i.e., the right hemisphere for right-handed persons), explains the *specific effect* of vestibular stimulation (Bottini & Salvato, 2020).

1.1.3. Linking Decision-Making to Vestibular Cognition: The Cognitive Domain

The interactions of the vestibular system with cognition come as a consequence of the widespread neuroanatomy of vestibular projections in the brain (Ferrè & Haggard, 2020). Therefore, vestibular influence on higher-order cognitive functions is pervasive.

Clear examples come from the clinical study of patients affected by vestibular disorders: in fact, vestibular loss can cause cognitive disorders (Smith & Zheng, 2013), since it interacts with multiple cognitive processes such as social cognition (Lopez et al., 2013), attention (Figliozzi et al., 2005) and memory (Smith et al., 2010). Despite the cognitive symptoms patients experience are typically downgraded to secondary consequences of psychological nature (Hanes & McCollum, 2006), there is evidence to support a vestibular influence on cognitive abilities, such as:

- *arithmetic abilities* (backwards counting) present in patients with central vestibular lesions and not in those with peripheral impairments concerning vestibular sensory organs of the inner ear (Risey & Briner, 1990); counting disorders resulted also in other

studies (Andersson et al., 2002, 2003). More recently, also a link between peripheral vestibular deficit and impaired numerical cognition has been found (Moser et al., 2017);

- *short-term and working memory*, whereas patients showed significantly reduced levels of performance on tests designed to measure complex abilities, while performing within normal range on simpler tasks (Erickson et al.);
- poor *concentration* and psychiatric difficulties (Yardley et al., 1998);
- dual tasks of cognitive and balance/orientation functions influence cognitive performance in patients and/or controls (Andersson et al., 1998; Maylor et al., 2001; Redfern et al., 2004; Yardley et al., 2001; Yardley et al., 2002).

As Hanes and McCollum (2006) highlight, this evidence supports the idea that “the vestibular/balance and cognitive systems do not operate entirely independently of one another”.

A review conducted by Li et al. (2024) analysed the association between vestibular disorders and cognitive impairments. Various types of vestibular disorders were included in the study: vestibular migraines, Meniere’s disease, benign paroxysmal positional vertigo, unilateral or bilateral chronic vestibular dysfunctions, tumor-induced vestibular dysfunctions, and acute vestibular dysfunction. The results suggest the presence of cognitive decline, especially in visuo-spatial abilities such as spatial memory and navigation, consistently with previous studies that linked spatial cognitive deficits associated with vestibular dysfunction to abnormalities in the structural functioning of the hippocampus (Brandt et al., 2005).

Among the vestibular contributions to high order cognition, the influence on decision-making is supported by neuroanatomical studies: decision-making builds on a widespread cortical-subcortical network (Figure 2) that includes prefrontal cortex (orbitofrontal cortex, ACC, dorsolateral prefrontal cortex), the limbic system, subcortical nuclei (basal ganglia, thalamus) and white matter projections (both cortico-cortical and cortico-subcortical) (Rosenbloom et al.,

2012). These neural correlates partially overlap with vestibular widespread projections in the brain.

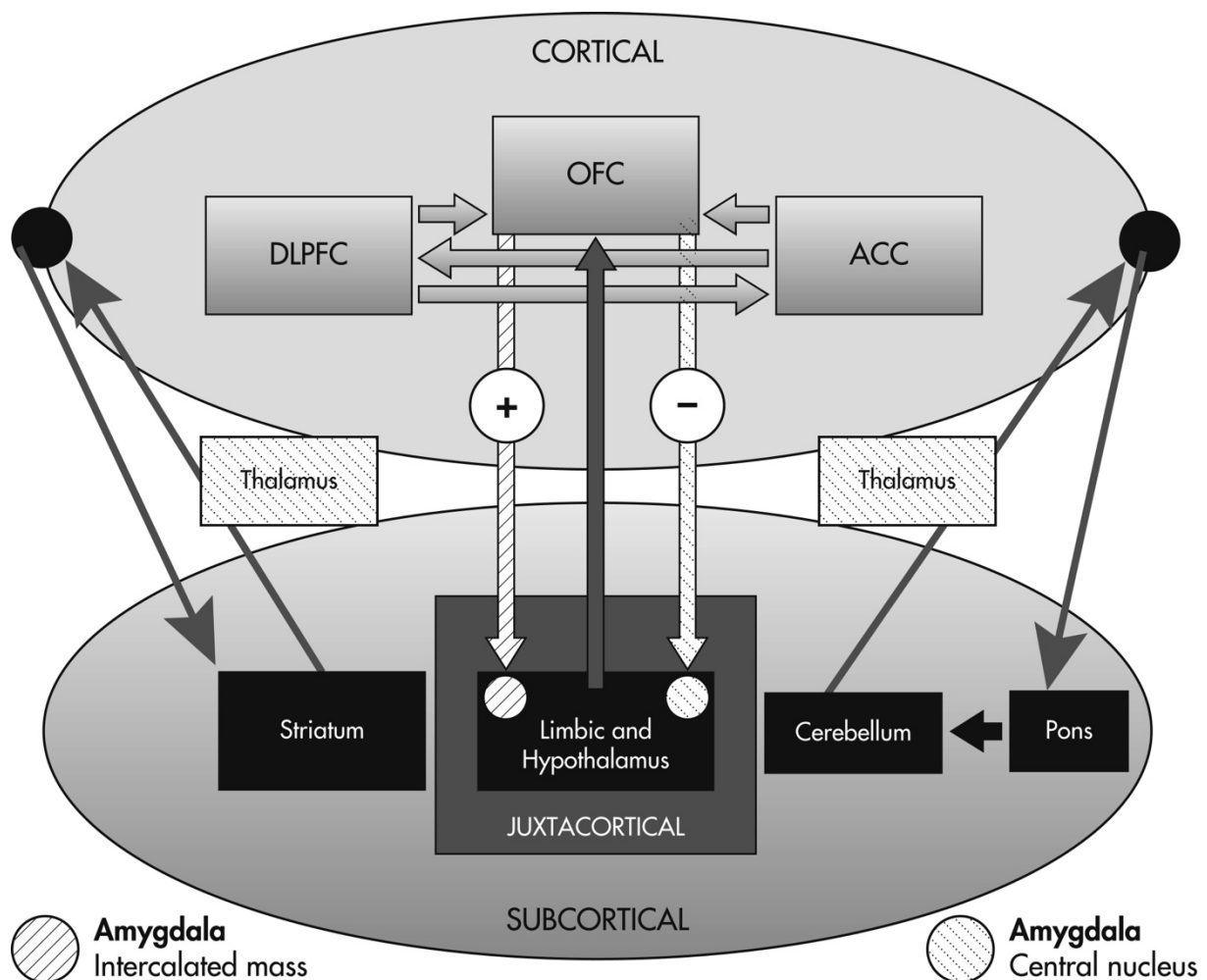


Figure 2
Decision-making network includes cortical regions, the limbic system, subcortical nuclei and white matter (Rosenbloom et al., 2012). DLPFC is the dorsolateral prefrontal cortex; OFC is the orbitofrontal cortex; ACC is the anterior cingulate cortex.

1.1.4. Risk-Taking Assessment in Experimental Settings

Scientific literature provides various instruments that could be used to elicit people's overall risk propensity according to different theoretical backgrounds. Still, risk-taking behaviour remains a difficult and elusive construct to measure (see Harrison et al., 2005 for a brief account of the most used instruments)

Self-report measures, like the *Domain-Specific Risk-Taking* (DOSPERT) scale (Blais & Weber, 2006), suffer from different biases that can lead to underestimates of risk-taking behaviour. For

instance, people can be affected by social desirability bias due to the stigmatising or “undesirable” aspects of such behaviours (Norwood et al., 2016) or the answer can be influenced by demand effects, inaccurate introspection and memory failures (Sebri et al., 2023). Using behavioural measures, it is possible to overcome these limitations and provide more accurate and implicit evaluations of risk-taking behaviour.

Among the most common behavioural decision-making tasks with good ecological validity, like the *Iowa Gambling Task* (Bechara et al., 2013) and the *Game of Dice Task* (Brand et al., 2005), one of the most widely used instruments (Lauriola et al., 2014) in the literature is the *Balloon Analogue Risk Task* (BART). The BART is a useful, computerised measure in which riskiness is rewarded up until a point at which further riskiness results in poorer outcomes, similarly to real-world scenarios (Lejuez et al., 2002). This allows the BART to have a better convergent validity with self-reported measures of risk-taking when compared to other instruments.

In the classical version of the BART, participants are told they would be facing 90 trials on a computer, being asked to pump up a balloon. In each trial a different balloon appears on screen and can be either blue, orange or yellow. Each colour corresponds to a different probability of exploding. The participant can click on the pump, and each click inflates the balloon and accrues 5 cents in the temporary reserve. The participant can either continue to inflate the balloon (until it reaches its own explosion point and all money in the temporary bank is lost) or stopping at any time during the trial and clicking on “collect the money”. The BART is essentially about being able to balance the potential gain of accruing more money against the potential risk of losing all the money accrued for that balloon. Following the money collection or the balloon explosion, a new trial appears with a new un-inflated balloon, and the participant is therefore able to start again. The index of risk-taking is calculated using the average number of pumps on balloons that did not reach the explosion point (Harrison et al., 2005).

This instrument has shown good correlation with various real-world risk-taking scenarios like alcohol (Rose et al., 2014) and tobacco consumption (Larsen et al., 2014), drug addiction (Hopko et al., 2006), gambling behaviour (Ciccarelli et al., 2016), risky sexual behaviour (Schuster et al., 2012), risky driving behaviour (Chee et al., 2017). Moreover, the BART shows great predictive performance for future substance use (Felton et al., 2015) and antisocial behaviour (Bai & Lee, 2017). The BART also extends its validity to adolescent samples (Lejuez et al., 2003).

The BART is sensitive to individual differences impacting decision-making: in particular, sex, whereas female participants tend to inflate the balloon less often than males participants (Sebri et al., 2023), and age, since age-related differences in performance appear to be a function of decreased learning performance (Mata et al., 2011; Wiesiolek et al., 2014). Moreover, even dynamic contextual factors can impact BART results: exploded balloon in the previous trial increased sub-sequent risk-taking behaviour on the next trial (Sebri et al., 2023).

Despite being one of the most widely behavioural tasks to assess risk-taking, the BART still suffers from methodological problems (De Groot, 2020). For instance, it's not clear whether decisions during the task are made under uncertainty or risk, since participants are not aware of explosion probabilities; participants learn about probabilities behind each balloon's colour as they progress through the task, so the first trials are basically completed under uncertainty. Moreover, risk propensity appears underestimated when using the original index (i.e., the average number of times participants pump the balloon), because when an explosion occurs participants are prevented from taking further risks since the task automatically switches to the next trial. Furthermore, maladaptive risk-taking is poorly represented, since participants collecting money before explosions leads only to higher earnings in the original paradigm.

Because of these limitations, it is necessary to adapt the original paradigm to specific research aims, modifying the task or using a different index to evaluate risk-taking (De Groot, 2020).

For instance, Salvato et al. (2019) replaced the balloon with a body silhouette in a modified version of the BART (i.e., the *Body Analogue Risk Task*) with the same experimental design as the original one (same instructions and same number of trials, blocks and coloured shapes) to investigate the role of interoceptive sensibility in cognitive functions. Another way of adapting the BART to specific goals is using scoring alternatives that overcome the conventional BART scoring, which neglects potentially relevant information (Schmitz et al., 2016).

Although some scholars call for further ecological validity research about how behavioural paradigms can effectively stand for real-world risky behaviour at present, highlighting how the specificity of the assessed behaviour matters (Buelow et al., 2024), the BART still has some interesting characteristics. Thanks to its intuitiveness and face validity, its ability to be reconducted to multiple theories of decision-making even in the criminological field and its relative complexity, the BART still remains one of the most used instruments in the field (Schmitz et al., 2016).

1.1.5. Decision-Making and Interoception

The concept of interoception originates from research on the relationship between bodily sensations and emotional experience and is generally defined as the sensitivity to stimuli arising from within the body (Garfinkel & Critchley, 2013). Although the original definition proposed by Sherrington in 1948 (Sherrington, 2023) distinguished interoception from exteroception and proprioception, the interoception literature has focused primarily on afferent information from the visceral organs and the vascular system. This allows for a parallel to be drawn between interoceptive signals and the autonomic nervous system, which largely operates pre-consciously, with some conscious exceptions (e.g., bladder fullness) (Garfinkel & Critchley, 2013).

While the change in visceral states can be accompanied by emotions whose intensity depends on the subject's sensitivity to internal states, the perception of these changes shows high inter-

subject variability, which has been described as an invariant constitutional trait. The internal physiological changes and the subject's ability to perceive them are therefore two distinct phenomena (Garfinkel & Critchley, 2013).

Three dimensions of interoception have been proposed (Garfinkel & Critchley, 2013; Garfinkel et al., 2015):

1. *Interoceptive accuracy*: objective accuracy in detecting internal bodily sensations, measurable through behavioural tasks. Two tasks are typically used: the “Heartbeat Tracking” or “Counting” task (Schandry, 1981), in which participants count their heartbeats by focusing solely on internal cardiac perception within specific time intervals, and the “Heartbeat Discrimination” task, in which participants judge whether heartbeat sensations are or are not simultaneous with exteroceptive stimuli presented at different delays following the onset of the electromechanical systole. However, recent studies have shown that these two of tasks are in fact distinct constructs (Ring & Brener, 2018);
2. *Interoceptive sensibility*: self-evaluated assessment of subjective interoception (e.g., the ability to perceive and focus on internal bodily signals), assessed through interviews and questionnaires such as the “Body perception questionnaire” (Porges, 1993), the “Autonomic Perception Questionnaire” (Mandler et al., 1958), or the “Multidimensional Assessment of Interoceptive Awareness” (Mehling et al., 2012). As it is necessarily assessed as a self-reported construct, interoceptive sensibility cannot be evaluated with full accuracy, due to subjective thresholds and biases (Garfinkel et al., 2015);
3. *Interoceptive awareness*: metacognitive awareness of one’s own interoceptive ability, the correspondence between the objective interoceptive accuracy and subjective report

(e.g., trial-by-trial subjective confidence in the behavioural task, or the area under the receiver operating characteristic curves) (Garfinkel et al., 2015).

From a neuroanatomical viewpoint (see Figure 3), differently to animal models where body-brainstem signalling is detailed, in humans the role of the Central Nervous System (CNS) is more comprehensive: the nucleus tractus solitarius (NTS) in the brainstem receives afferent signals from visceral organs and projects to multiple cortical and subcortical areas, including parabrachial nucleus, thalamus, hypothalamus, hippocampus, amygdala, insula, primary and secondary somatosensory cortex, ACC, and the orbitofrontal and medial prefrontal cortices

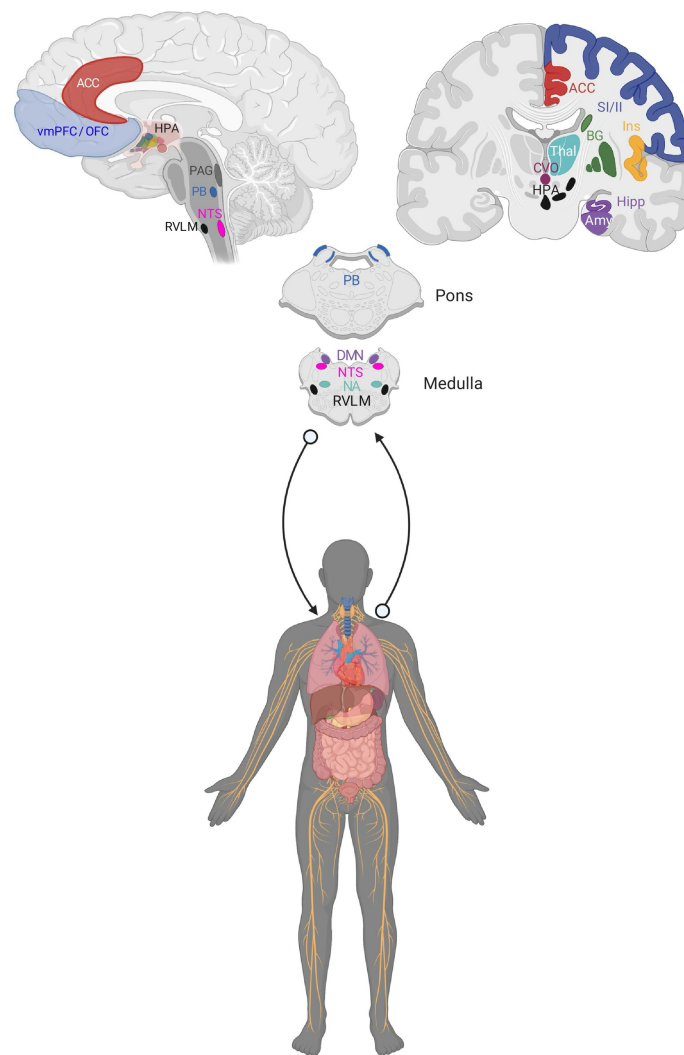


Figure 3

The vestibular nuclei in the Central Nervous System (CNS): from the distal body, afferent signals reach the brainstem and later multiple cortical and subcortical areas (Berntson & Khalsa, 2021)

(Berntson & Khalsa, 2021). Additionally, afferent signal modification by reciprocal efferent pathways is crucial for interoceptive regulatory systems (Berntson & Khalsa, 2021).

Since the Somatic Marker Hypothesis (Damasio et al., 1990) proposed that emotional processes and bodily feelings influence cognitive outcomes and ultimately guide behaviour, the relationship between interoception and decision-making has been widely explored (Garfinkel & Critchley, 2013). Empirical evidence supports a positive influence of higher interoceptive accuracy on decision-making tasks even in childhood (Pollatos et al., 2023).

However, there is no consensus in the literature as to which of the three dimensions of interoception most influences decision-making processes; as summarised by Salvato and colleagues (2024), experimental evidence supports a role of both interoceptive accuracy and sensibility, but the direction of the influence of interoception on behaviour is conflicting. A recent field of research supports the hypothesis that heartbeat detection skills, as an interoceptive ability, predicts more effective risk-taking: for instance, in a sample of professional financial traders on a London trading floor, heartbeat counting accuracy predicted their financial success in the market, thus extending evidence to ecological settings (Kandasamy et al., 2016). Similar findings are found in studies incorporating skin conductance analysis, which can be considered as a somatic marker of decision-making (Crone et al., 2004). Other studies (Reader & Salvato, 2024) found that the ability to ignore or avoid becoming distressed by visceral signals of potentially negative nature is associated with increased risk-propensity in self-assessment questionnaires. As research on drug addiction suggests, altered interoceptive processing on multiple levels, neural, behavioural, and higher-order influences behaviour through impulsivity and maladaptive coping strategies (Herman, 2023).

1.1.6. The Contribution of Vestibular Stimulation

The vestibular system has received less scientific attention compared to other sensory systems, also due to the difficulties of its peripheral sensor stimulation which are naturally activated by

head motion (Ertl & Boegle, 2019). In addition to the already challenging incompatibility of motion platforms (i.e., rotatory chairs and whole-body motion platforms) with fMRI and PET, passive rotations and translations that were employed to evoke vestibular signals turned out to have different response characteristics from active movement (Klam & Graf, 2003).

This led to the employment for cognitive research purposes of techniques initially employed for diagnostics, such as caloric (CVS) and galvanic (GVS) vestibular stimulations, due to their safe, inexpensive, non-invasive and easy applicability (Palla & Lenggenhager, 2014).

CVS, also known as thermal vestibular stimulation, includes the irrigation of the external ear with warm ($\geq 44^{\circ}\text{C}$) or cool ($\leq 30^{\circ}\text{C}$) water or, more rarely, by gas (Nakul et al., 2021). The temperature change reaches the endolymphatic fluid of the semi-circular canals of the inner ear, creating a temperature gradient from one end to the other end of the canal, activating the hair cells in the crista ampullaris (Nakul et al., 2021; Wilkinson, 2021). As a consequence, the firing rate in the vestibular afferents respectively increases or decreases alongside temperature of the inner ear (Nakul et al., 2021).

Typically applied in a supine position with head tilted 30° forward, CVS can elicit a short-term sense of vertigo, nausea and sickness, sense of rotation, floating and tilting. The head orientation determines which semicircular canals are predominantly gathered (i.e., horizontal canal versus anterior or posterior canals). As a neurological sign, a nystagmus towards the contralateral ear (in case of cold stimulation; towards the ipsilateral ear, in case of hot stimulation) is evoked. The onset of the vestibular responses starts after seconds of stimulation and can last several minutes after the end; their manifestation diversity derives from the non-physiological nature of stimuli (Nakul et al., 2021; Palla & Lenggenhager, 2014). The well documented effects of CVS have been contributing to cognitive neuroscience advancements in multiple domains. For instance, the anatomical overlapping of vestibular cortex and somatosensory networks allowed the study of pathological manifestations such as visuospatial neglect and associated symptoms,

anosognosia, somatoparaphrenia, motor neglect, and tactile perception both in neurological patients and in healthy participants (Bottini et al., 2013).

The electrical counterpart is represented by GVS. Electrical therapy has a long history starting from 43-48 AD with the roman physician Scribonius Largus and including Italian scientists as Galvani and Volta (Utz et al., 2010), who later became known worldwide. GVS involves the application of low amplitude, transcutaneous direct or alternating current through electrodes applied to the mastoid processes behind the ears (or with the application additional electrodes) with the goal of modulating vestibular signals without head movements.

The process through which currents interact with the vestibular systems is multifaceted and debated (Ertl & Boegle, 2019), since both the otoliths and the semicircular canal appear to contribute to GVS-evoked responses in vestibulo-motor circuitries (Gensberger et al., 2016). This is one of the main differences with CVS, which only activates the semicircular canals

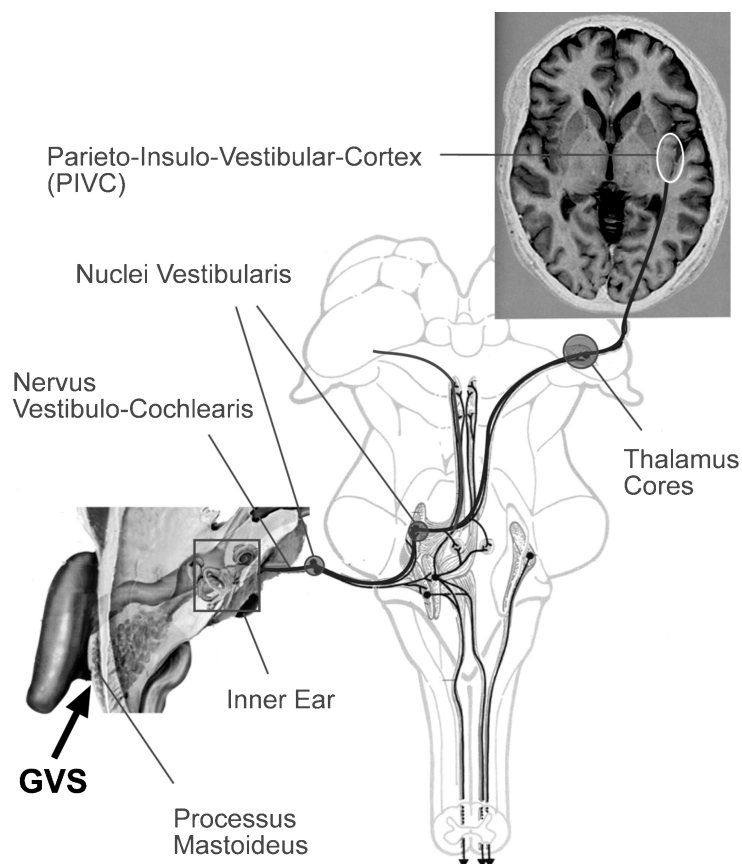


Figure 4
The anatomical pathways of GVS (Utz et al., 2010)

(Bottini et al., 1994; Utz et al., 2010). The current applied at the mastoids acts via polarisation effects on the vestibular nerve, reaches the nervus vestibulo-cochlearis, the vestibular nuclei of the brainstem, the thalamic nuclei and finally the PIVC, the temporo-parietal junction (TPJ) and the parietal cortex (see Figure 4) (Utz et al., 2010).

Additionally, a difference appears at afferent neurons-level: despite three-quarters of primary afferents are of the regular type (i.e., the resting discharge pattern is almost a continuum), GVS reaches the vestibular nuclei in the brain preferably through irregular afferents, subsequently distributing across multiple vestibular afferents, thus producing the sway response in which the body tilts toward the anodal electrode in case of unipolar stimulation (Fitzpatrick & Day, 2004; Goldberg, 2000). This anatomical account supports the transient side-effects of GVS, such as cutaneous itching and tingling at electrodes sites, vertigo and headache (Wilkinson, 2021).

The GVS multiple parameters setting allows for design optimisation to tailor stimulation for specific targets and to endure accuracy and reproducibility. In particular (Valter et al., 2025):

- *Electrode montage* in terms of anatomical positioning (e.g., unilateral, bilateral, additional electrodes on the neck, temples, or forehead) and polarity¹ pattern (e.g., leftward or rightward unipolar, thus anodal or cathodal, or bipolar); for a brief account see Figure 5 (Marchand et al., 2025).
- *Waveform*: different shapes of the electric current function, on which elicited responses depend (see Figure 6 for a brief account of the most used waveforms); specifically:
 - *Direct current* (DC-GVS; also known as *boxcar*) includes a constant current plateau intensity, reached in milliseconds and turned off after a certain time (Ertl & Boegle, 2019);

¹ GVS polarity is the parameter that determines if the firing rate of vestibular afferents increases or decreases: cathodal GVS results in excitation, anodal GVS results in inhibition through the spike trigger zone of primary afferents (Goldberg et al., 1984; Tohyama et al., 2021).

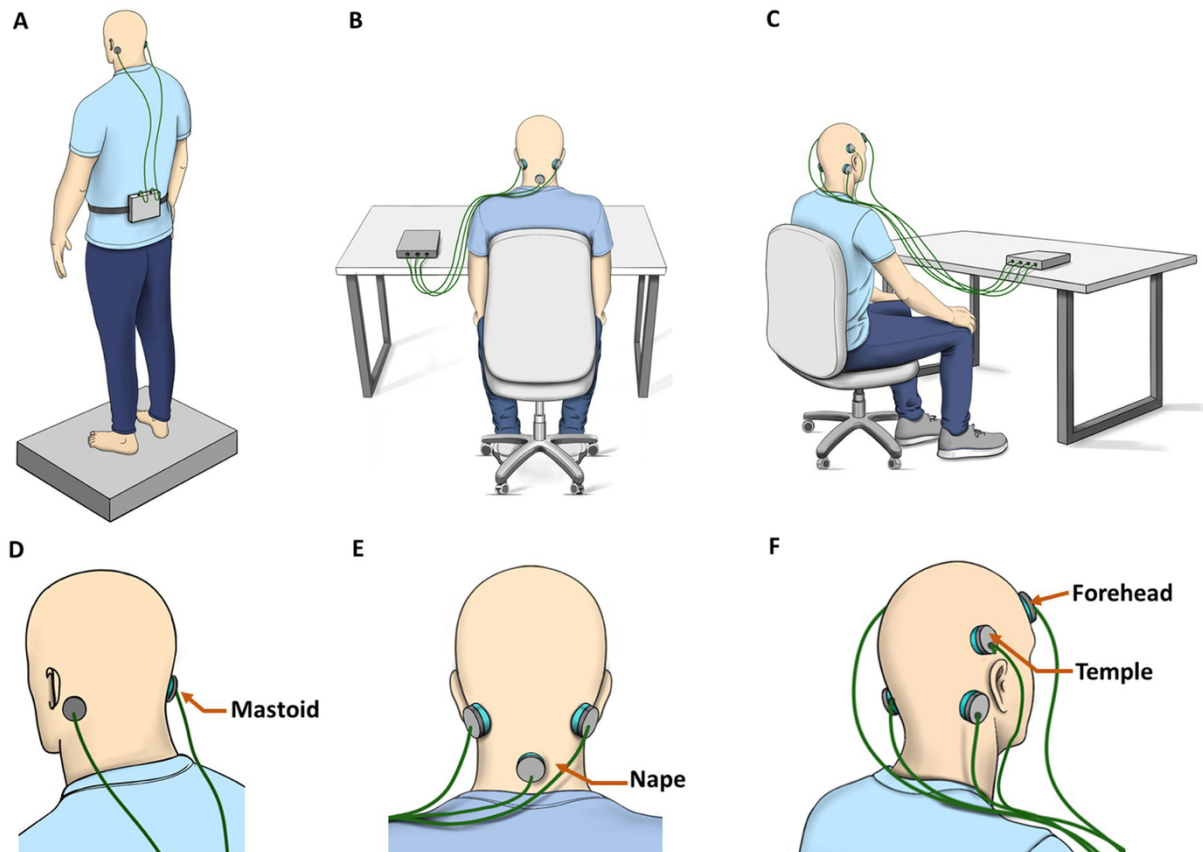


Figure 5

Visual examples of electrode montage (Valter et al., 2025). (A) and (D) represent a bilateral positioning with two electrodes; (B-C-E-F) show the placement of additional electrodes (e.g., on the seventh cervical vertebra, Marchand et al., 2025)

- *Sinusoidal waveform*: alternating current (AC-GVS) is delivered at a certain frequency (if multiple frequencies are combined into a single waveform, the delivered current is a *multisine*); evidence for the employment of AC-GVS comes from fMRI studies where the main BOLD effect of DC-GVS was observed predominantly after onset and offset of current (Cyran et al., 2016; Stephan et al., 2005); moreover, a study with high-frequency (35 Hz, 50 Hz, and 65 Hz) sinusoidal bursts of GVS found that this stimulation does not induce strong illusory sensations of self-motion (Smith et al., 2024);
- *Noisy waveform* (nGVS; also known as *stochastic GVS*): a zero-mean bilateral, random alternating current boosting weak physiological signal from vestibular apparatus through reduction of the firing threshold of irregular afferents;

different types of noise are available, the most common in the literature is *white noise*, which follows a Gaussian or normal distribution (McLaren et al., 2023);

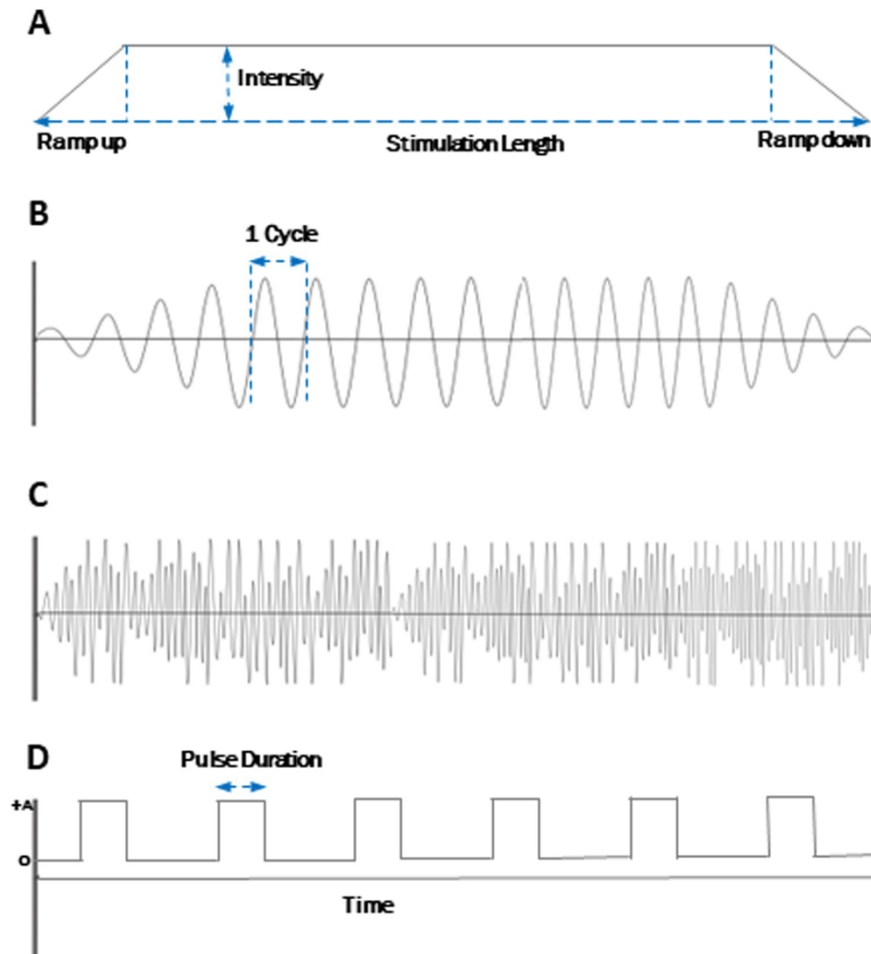


Figure 6
Example of the most common GVS waveforms. Graph A represents DC-GVS; B is a sinusoidal waveform (AC-GVS) with 0 mA offset DC; C is a noisy-GVS; D is DC pulses (Valter et al., 2025)

- **Frequency:** rate of oscillatory fluctuations of the waveform which is equal to 0 Hz for DC-GVS, at a specified frequency for sinusoidal GVS, and within a frequency spectrum in a bandwidth range for *multisine* and nGVS; in a perspective of custom GVS design, the recruitment of specific neuronal populations can be targeted through intensity and frequency of a sinusoidal (Nguyen et al., 2023), given the frequency-tuned organisation of vestibulomotor circuits (Dlugaiczky et al., 2019). While low-frequency GVS is particularly suitable for mimicking natural head motion activations (Dlugaiczky et al., 2019), in particular when below 30 Hz and reflecting the frequency range of endogenous

after-movements activations (Forbes et al., 2015), multisine GVS at higher frequencies (from 50 Hz up to 150 Hz) are associated to behavioural and electrophysiological enhancements in PD patients (Kazemi et al., 2021; Kia et al., 2025);

- *Intensity*: the amplitude of the electric current can be fixed across participants or individualised with respect of subjective thresholds, in order to evoke vestibular responses with the lowest stimuli possible, thus minimising the potential detrimental effects; a study employing DC-GVS identified the thresholds reported in Table 1 (Nguyen et al., 2022).

Table 1

Thresholds above which cutaneous sensations, vestibular perception and oculomotor responses emerged as described in Nguyen and colleagues (2022)

	<i>Left-anodal DC-GVS</i>	<i>Right-anodal DC-GVS</i>	<i>Mean stimulation intensity for both conditions</i>
Cutaneous perception i.e., cutaneous tingling or stinging	0.97 ± 0.5 mA	0.85 ± 0.35 mA	0.9 ± 0.29 mA
Vestibular perception i.e., dizziness, vertigo, whole-body angular rotation, sense of rotation of the environment, feeling of change in gravity	1.03 ± 0.52 mA	0.93 ± 0.33 mA	0.98 ± 0.29 mA
Oculomotor response i.e., short-latency eye movements, nystagmoid ocular movements	1.52 ± 0.54 mA	1.7 ± 0.28 mA	1.61 ± 0.35 mA

Additionally, other variables influencing the outcomes of a GVS paradigm are the stimulation length, the inter-session interval, and the number of sessions (Valter et al., 2025). Altogether these parameters allow for an almost total personalisation of the application with interesting implications from a therapeutic viewpoint. For instance, Nguyen and colleagues (2023) employed design optimisation methods to tailor GVS parameters to individual-specific characteristics. This methodology, widely used in pharmacology, allowed the maximisation of effectiveness using waveform, amplitude and duration variables in a cohort of patients with vestibulopathy and cerebellar disorders.

Regardless of custom paradigms, functional imaging studies of DC-GVS have demonstrated that it reaches multisensory cortical areas as the insular and retroinsular regions, the superior temporal gyrus, temporo-parietal cortex, the basal ganglia, the anterior cingulate gyrus, PIVC and TPJ (Bense et al., 2001; Bucher et al., 1998; Fink et al., 2003; Utz et al., 2010). With a left-anodal right-cathodal montage it is possible to reach unilaterally the right-hemispheric vestibular system, while left-cathodal right-anodal GVS is linked to a bilateral reaching of both vestibular cortices (Utz et al., 2010). For these reasons, GVS has been employed on a wide range clinical studies for potential therapeutic applications: for instance, GVS has shown beneficial effect on speed of recall in a visual memory task in healthy participants (Wilkinson et al., 2008) and improvements in motor functions (i.e., posture and gait) in Parkinson's Disease patients (Wilkinson, 2021).

In the decision-making scenario GVS contribution is supported by several studies. Firstly, it has been associated with event-related P300 potentials changes in a decision-making task of word-image matching (Lee et al., 2016), suggesting electrophysiological changes on multiple levels. Left-anodal right-cathodal GVS has been linked to increased framing susceptibility in a risky-choice paradigm (Preuss et al., 2017). De Maio and colleagues (2021) found a specific vestibular effect of the GVS polarity administered during the BART: left-anodal right-cathodal was associated to a reduction in risk propensity, coherently with previous studies on vestibular contribution to decision-making behaviour using CVS (Preuss et al., 2014). However, in the same study no generic vestibular effect (i.e., adjusted average of left-anodal right-cathodal and left-cathodal right-anodal conditions compared to sham) has been found, suggesting that non-specific vestibular contributions were to exclude. A replication and extension study (Minder et al., 2026) could not replicate the findings, challenging previous studies supporting a role of vestibular system in decision-making processes that go beyond the risk-taking sphere (see Paragraph 1.1.3). In addition, as Ferrè and Haggard (2020) highlight, the interaction between

vestibular system and cognition (including decision-making) is a logical consequence of the functional neuroanatomy of the vestibular projections (for an account see paragraph 1.1.2). For the same reason, left-anodal right-cathodal GVS influences multisensory integration, body ownership, proprioception and interoception (Ponzo, 2019; Ponzo et al., 2018), coherently with studies employing CVS (Bottini et al., 1995; Salvato et al., 2016; Salvato et al., 2018). Even though natural and artificial vestibular stimulations differ under many viewpoints, it has been multimodally demonstrated that interoceptive and vestibular systems are interconnected at both anatomical and functional levels (Nakul et al., 2021).

1.2. Criminological Perspective on Decision-Making

1.2.1. Risk-Taking Behaviour in Criminology

Engagement in criminal activity can be considered as a form of *risk-taking behaviour* that people may decide to engage in after perceiving the outcomes associated with it. For instance, shoplifting may provide the offender a much-desired product or an indirect means after selling it, while also possibly resulting in a criminal conviction and a prison sentence (Dhami & Mandel, 2012). This has led scholars to draw parallels between the neuroscientific concept of risk-taking and the criminological self-control, a concept derived from *The General Theory of Crime* (Gottfredson & Hirschi, 1990) and still widely researched. For instance, Forrest and colleagues (2019) connected self-control with Steinberg's *Dual Systems Model* of risk-taking (Steinberg, 2010). In this theory, two potentially coexisting dimensions are outlined: *risk-seeking* is the tendency towards seeking new and stimulating experiences (Steinberg, 2008), while *impulsivity* is the inability to delay gratification (Steinberg, 2010). Both, as authors highlight, are conceptualised similarly in the General Theory of Crime, whereas Steinberg's work distinguished the two dimensions while Gottfredson and Hirschi considered self-control as a unitary construct (Forrest et al., 2019; Gottfredson & Hirschi, 1990). Indeed, empirical evidence confirms the distinction and suggests a multidimensional nature of self-control and, thus, of risky behaviour (Forrest et al., 2019).

1.2.2. The General Theory of Crime: Self-Control Between Criminology and Neuroscience

Among the multiple currents that tried to explain the aetiology of crime, the *social control theories* remain one of the most influential still in modern times. Developed starting from the second half of XX century, their main assumption was that deviant behaviour is naturally part of human nature and every person can potentially commit criminal actions (Marotta, 2017). As Hirschi's *Causes of Delinquency* suggests, the focus is moved from the possible causes of

delinquency to the reasons of conformity. Social control is considered the reason why most individuals abstain from criminality (Costello & Laub, 2020).

In fact, Travis Hirschi developed his *social bond theory* focusing on the bond between individuals and society (Hirschi, 1969): the stronger the bond and the social attachment, the smaller the probability of deviating from socially accepted norms. In particular, the social bond comprises four elements that Hirschi argued are interrelated but analytically separable (Costello & Laub, 2020):

1. *attachment*: emotional connection to significant others; since social order is based on consensus, engaging in disapproved behaviours would lead to negative consequences on the individual;
2. *commitment*: when commitment to long-term occupational or educational goals is involved, there is compliance to social norms accepted by the institutions that provide the opportunity to reach those goals;
3. *involvement*: when an individual spends time in conventional activities, there is a reduction in the amount of time available for deviant actions;
4. and *belief*: from Hirschi's point of view, there is variation in belief in the moral validity of laws. In the case of *social control theories*, some people do not feel laws and rules as morally binding on their behaviour.

Indeed, those hypotheses have found support in Hirschi's survey research data, which highlighted a negative correlation between attachment to parents, school and commitment (Costello & Laub, 2020).

More recently, a revision of this theory has been proposed, the *General Theory of Crime* (Gottfredson & Hirschi, 1990), also known as *low self-control theory* (Lanier & Henry, 1998). It includes low self-control as a stable character trait that makes an individual more likely to commit crime to intentionally pursue an individual's own goal. In particular, Gottfredson and

Hirschi (1990) state that individuals with low self-control will be characterised by common elements: *impulsivity* – such as the tendency to “respond to tangible stimuli in the immediate environment”, *risk-taking*, *indifference* to others’ needs, *tendency to respond in a physical way* to conflict. These characteristics would make individuals more inclined to engage in criminal acts (Burt, 2020). According to the authors, who adopted a “child-rearing model”, criminality is established in the first 8-10 years of life in response to parenting styles and would remain stable across the lifespan.

Thanks to Gottfredson and Hirschi’s model, self-control became one of the most researched correlates of criminal behaviour and appears to be an important predictor of crime and deviance, as some meta-analyses confirmed (Pratt & Cullen, 2000; Vazsonyi et al., 2017).

This theory improved the previous *social control theories*, for instance allowing the inclusion of white-collar crimes: context of crime or offender’s status are not necessarily important, but instead every individual has the potential to commit deviant behaviour and the eventual inability to control is what makes the difference. Since self-control is learnt in the first years of life, family’s educational imprinting becomes fundamental in the explanation of deviant behaviour (Marotta, 2017). Nevertheless, white-collar and corporate crimes are still underrepresented in the *General Theory of Crime*’s conceptualisation: the focus on impulsive decision-making doesn’t entirely fit the phenomena, which can eventually involve deliberate and calculated long-term gains (Burt, 2020). This perspective sheds a light on the need of a broader concept of self-control and how crime does not necessarily involve impulsivity or immediate risk-taking but can also be widened to more deliberative and controlled forms of thinking. Moreover, impulsivity does not appear to be uniformly related to antisocial or negative behaviour (Wendel et al., 2022): as some scholars suggest (Dickman, 1990), impulsivity can be dissociated into *functional impulsivity* and *dysfunctional impulsivity*, whereas the latter lacks in the successful

completion of ultimately beneficial actions and seems to be linked to aggressive behaviour (Vigil-Colet & Codorniu-Raga, 2004; Vigil-Colet et al., 2008).

Furthermore, Gottfredson and Hirschi's ideas have been critiqued also for their self-control as stable trait: situation-specific variance treated as noise is an oversimplification that does not consider ecological situational precursors affecting decision-making. For instance, acute alcohol consumption, high-arousal emotional distress and exposure to immediate threats influence self-control processes and this is reflected in the legal categories of crime with mitigated culpability due to departure from normal reasoning process (see Burt, 2020 for a broader account) In addition, contrary to the stability of self-control in the original model, the importance of self-control's impact on criminal behaviour is confirmed by studies supporting self-control modification programs with delinquency reduction goals in youth (Piquero et al., 2016).

For the above reasons, research about the aetiology of criminal conducts continued and exceeded the original self-control concept, improving theories with experimental evidence of diverse nature. As some scholars suggest, neuroscience complements traditional criminological theories and, instead of confirming deterministic approaches, provides new perspectives (Trinh et al., 2024) with interesting neuroscientific findings. For instance, Friehe and Schildberg-Hörisch (2017) employed a widely used *ego-depletion task* before a risk-taking paradigm and found that low self-control promotes criminal behaviour to the extent that individuals with lower levels of self-control are less effectively deterred by probabilistic sanctions, highlighting once again the complex aetiology of criminal behaviour. Coherently, a meta-analysis by Vazsonyi and colleagues (2017) found associations between low self-control and general deviance, physical violence, verbal/interpersonal violence, substance use, academic/organ dishonesty, crime, theft, and online deviance among the others.

Consequently, growing interest relies on how direct and indirect indicators of neural functioning are associated to the low self-control construct and, thus, to delinquency (Meldrum et al., 2018). As indirect indicators, neuropsychological tests demonstrated that self-control has overlap with the concept of executive dysfunction and seems to have a strong genetic component (Jackson & Beaver, 2013), which is in contrast with the “child-rearing model”. However, research has demonstrated that self-control is not fixed after childhood or due to genetic influences, but instead continues to change into early adulthood, coherently with developmental perspectives of biological, behavioural and social changes through adolescence in addition to a distinct environmental sensibility (Burt et al., 2014).

As more direct indicators of brain function, functional neuroimaging provided evidence for greater activation in the ACC during failed inhibitory control in association with low self-control. The latter also mediated the association between ACC activity and later delinquency (Meldrum et al., 2018). Additionally, electrophysiological evidence suggests a reduced P300 brain response (the same evoked-potential mediated by GVS in risk-taking studies seen in paragraph 1.1.6) in association with antisocial and substance use behaviour (Yancey et al., 2013).

Regarding the genetic influence, scholarly focus has been on genes involved in the regulation of neurotransmitters as serotonin and dopamine. The gene Monoamine oxidase A (MAOA) encodes the MAOA enzyme metabolising neurotransmitters such as norepinephrine, serotonin, and dopamine (Belsky & Pluess, 2009; Watts & McNulty, 2016). MAOA is linked to antisocial phenotypes that include physical violence (Beaver et al., 2010) and has been explored in risk-taking paradigms: for instance, Zhong and colleagues (2009) found that individuals with the high activity allele (MAOA-H; i.e., one of the MAOA polymorphisms) prefer longshot lottery and less insurance purchasing than individuals with the low activity allele (MAOA-L). The MAOA-L is also linked to aggressive and impulsive behaviour in mice (Shih & Chen, 1999)

and humans (McDermott et al., 2009), as well as genotype-related structural and functional changes in corticolimbic circuits involving the amygdala, the cingulate and the orbitofrontal cortices (Meyer-Lindenberg et al., 2006). Another relevant gene is the dopamine transporter DAT1: two alleles, the 7 repeat (7R) and the 10 repeat (10R), are linked to reduced dopamine functioning and the presence of both polymorphisms is associated with Attention-Deficit Hyperactivity Disorder (ADHD) diagnosis (Mill et al., 2006; Schilling et al., 2011).

Despite the genetical and neurobiological underpinnings of self-control, it's important to highlight that those findings do not represent deterministic evidence: multiple studies identified early-life risk factors for a low self-control development (Meldrum et al., 2018) as birth complications (Beaver & Wright, 2005) and fetal exposure to harmful substances as cocaine (Minnes et al., 2016) and smoke (Meldrum & Barnes, 2017; Turner et al., 2011). Thus, environmental factors represent a fundamental step in the development of self-control, as MAOA and DAT1 research also suggests: the genes moderate (i.e., amplify) the effects of environmental adversities on the development of self-control and, eventually, of the later antisocial behaviour, making some individuals simply more sensitive to environmental factors (Watts & McNulty, 2016). This is what is also known as “*differential susceptibility hypothesis*” in the literature, stating that environment interactions (Shanahan & Hofer, 2005) are interpretable in a stress-diathesis perspective where a genetic risk is amplified or muted by, respectively, adverse or supportive environments. Therefore, whereas aggressive behaviour is the outcome of genetic predispositions that influence responses to the environment, the same sensitivity makes these individuals good candidates for intervention, since they are more likely to benefit from benign environments (Simons et al., 2011).

1.2.3. Research Applicability: Risk Assessment and the Risk-Need-Responsivity Model

The environmental influences highlight how risk factors can increase the probability of engagement in offending behaviour and, consequently, how acting on those factors can

effectively modify behaviour. In particular, when dealing with offenders it becomes crucial to tailor interventions to ensure the access to appropriate treatments and reduce recidivism probability in a rehabilitative approach, whereas recidivism is defined as the “tendency to relapse (...) in a criminal behaviour pattern” (Gordon et al., 2015).

Risk assessment falls exactly within this framework. It is a scientific practice of anticipatory and preparatory nature with respect to the intervention on the offender to reach the best possible outcome for that individual in conditions of uncertainty (Zara, 2016). Internationally these paradigms fall under the *Psychology of Criminal Conduct* (Bonta & Andrews, 2023) and its rediscovery of psychological background to inform forensic rehabilitation (Coppola & Martufi, 2023; Heffernan & Ward, 2023).

This approach has its roots in the comprehensive work of reviews of the “offender rehabilitation literature” of the 1980s (Gendreau & Ross, 1987), in the attempt to discover what key factors distinguished effective rehabilitation programs from ineffective ones, assessing different types of intervention, such as biomedical, diversion, early/family intervention, education, getting tough, individual differences, parole/probation, restitution, and work.

The work of Lipsey & Cullen (2007) greatly represents the heterogeneity of literature (and outcomes) in the effects of treatments on reoffending. As the authors highlight, despite the diversity, there is consistency on some fundamental key points: firstly, recidivism outcomes for offenders receiving greater versus lesser or no sanctions has found modest mean recidivism reductions for the greater sanctions or even increased recidivism for that condition. Moreover, lower recidivism is associated with rehabilitation treatments and, interestingly, the least of rehabilitation mean reductions is greater than the largest mean reductions reported by any meta-analysis of sanctions.

The difference between effective and ineffective treatments lead to the theorisation of what constituted an *appropriate* (i.e., leading to the desired outcome) rehabilitative program, the *Risk-Need-Responsivity* (RNR) model (Andrews et al., 2011; Bonta & Andrews, 2023).

Finely developed by Canadian researchers James Bonta, Don Andrews, and Paul Gendreau, this model revolutionised the management of criminal conduct in Canada, Britain, Europe, Australia and New Zealand. The three key principles for an effective offender rehabilitation, that constitute the title of the approach, are (Ward et al., 2007):

1. *Risk* principle: the higher the risk of re-offending, the higher the intensity of the treatment, meaning that high intensity treatments should be dedicated only to those who represent the higher recidivism risk, thus would benefit more from the intervention. On the other hand, low risk offenders should be targeted by minimal or no intervention;
2. *Need* principle: criminogenic needs (also called *dynamic risk factors*) must be included when evaluating treatment options as factors associated with reduction in recidivism. They are different from *non-criminogenic needs*, which are “aspects of the individual or his or her circumstances that, if changed, are not expected to have a direct impact on recidivism rate”, as in the case of clinical mental health conditions according to the RNR model, even though some scholars argue that they could potentially impact on recidivism rates (Ogloff & Davis, 2004);
3. *Responsivity* principle: the correctional program should match offender’s learning style, motivation and individual circumstances. Adjusting the treatment to the individual should provide better learning rates.

Specifically, the focus on the *dynamic risk factors* is due to their intrinsic changeable nature as well as their statistical association with recidivism (Coppola & Martufi, 2023; Heffernan & Ward, 2023). As Heffernan & Ward highlight: “[...] the presence of these factors within a person and their lifestyle provides an indication of the level of need for intervention, and therefore they

should be the targets of (largely cognitive-behavioural) treatment which will change behaviour. The core mechanisms of change according to this perspective are shifts in cognition (such as challenging pro-criminal attitudes), learning skills and strategies to manage thoughts and emotions, problem solving, self-control, behavioural rehearsal, and reinforcement of pro-social alternatives [...]”.

Based on this model, the Level of Service instruments have been developed as evidence-based methodologies to assess individual risk and inform correctional treatments and validated across numerous meta-analyses while controlling for ethnicity, age, geographic region and recidivism type (Olver et al., 2014). These instruments distinguish eight subcomponents, the so-called Central Eight risk and need factors, seven dynamic factors and one static factor, subsequently divided into four empirically derived covariates of criminal conduct by Andrews and Bonta: criminal history, antisocial attitudes, antisocial associates and antisocial personality pattern. The latter is characterised by poor self-regulation, also known as *low self-control* in other criminological theories of antisocial behaviour (Cheng et al., 2019; Gottfredson & Hirschi, 1990). One of these instruments is the Level of Service/Case Management Inventory (LS/CMI; Andrews et al., 2000) a quantitative survey of offender attributes and situations whose items are in a no/yes format or in a 3-0 rating format (Andrews et al., 2000). The eight sections of the survey are briefly summarised in Table 2.

The eight risk factors that should predict reoffending, the so-called “Big Eight” or “Central Eight”, are detailed in the first section of the LS/CMI assessment. The *static factor* is represented by the criminal history of the individual, which obviously cannot be modified by correctional treatments, such as the number of past offences. On the other hand, the seven *dynamic factors* are considered the starting point of an effective rehabilitative treatment.

Table 2
The main sections of the LS/CMI assessment (Andrews et al., 2000)

Section 1 General Risk/Need Factors	Total Risk/Need score 1. Criminal History 2. Education/Employment 3. Family/Marital 4. Leisure/Recreation 5. Companions 6. Alcohol/Drug Problem 7. Procriminal Attitude/Orientation 8. Antisocial Pattern
Section 2 Specific Risk/Need Factors	1. Personal Problems with Criminogenic Potential (e.g., racist behaviour) 2. History of Perpetration a. Sexual Assault b. Nonsexual Physical Assault and Other Forms of Violence c. Other Forms of Antisocial Behaviour
Section 3 Prison Experience – Institutional Factors	Crucial institutional considerations 1. History of Incarceration a. Past Incarceration b. Present Incarceration 2. Barriers to Release
Section 4 Other Client Issues	Supplementary psychological and physical health, financial, accommodation, and victimization items
Section 5 Special Responsivity Considerations	Dominant responsivity considerations from clinical research and correctional opinion. Responsivity factors reflect differences in learning styles and/or personal interests and are not to be interpreted as risk, need, or problematic characteristics.
Section 6 Risk/Need Summary and Override	This section summarises the offender's risk/need scores and assesses the need for client-based or administrative/policy overrides. 1. Score-Based Risk/Need Level (from Section 1) 2. Client-Based/Clinical Override 3. Administrative/Policy Override 4. Final LS/CMI Risk/Need Level
Section 7 Risk/Need Profile	Graphically summary of the Section 1 subcomponent and risk/need level scores.
Section 8 Program/Placement Decision	Record of major classification decisions (e.g., program placement) 1. Institutional Offenders 2. Community Offenders 3. Presentence Report
Section 9 Case Management Plan	Criminogenic needs, non-criminogenic needs, and special responsivity considerations
Section 10 Progress Record	Log of activities designed to measure change resulting from case management strategies
Section 11 Discharge Summary	Summary of information useful if the offender returns to custody or community supervision

For instance, Ward and colleagues (2007) define those factors as “attributes of the individual or of his or her situation that are able to be modified in some important respects, for example, impulsiveness or deviant sexual preferences”. From this standpoint, the problems at educational/employment level, an antisocial personality pattern, relationships complications both at familiar or peer levels, substance abuse and maladaptive use of recreative time can be modified to decrease the probabilities of resorting back to crime.

The link between the static risk factor and the dynamic risk factor is represented by a neuropsychological construct whose impairment can be associated to behavioural dysfunction (Cheng et al., 2019): *executive functions* (EFs). In particular, Cheng and colleagues (2019) find the overlap between the “Central Eight” and EFs in offenders with *Anti-Social Personality Disorder* (American Psychiatric Association, 2013). In fact, cognitive models of EFs suggest their relevance for the creation of plans for efficient problem solving, and the activation and sustainment of self-regulatory attentional control, behavioural control, and emotional control (Garcia-Barrera et al., 2011), all of which can be impaired in case of antisocial behaviour.

However, despite the encouraging findings and the high predictive validity of LS/CMI even in real-word scenarios (Dyck et al., 2018), some critical issues have been discussed in the literature. Tony Ward (2016) highlighted a number of conceptual problems related to dynamic risk factors, starting from their definition and inclusion in risk management principles. Firstly, they are normative concepts, meaning that ethical and legal norms are intrinsic to them, which ultimately makes them strictly dependent on the social, political, legal institutions. Moreover, in their current conceptualisation dynamic risk factors do not correspond entirely to scientific constructs, even though some of them could be interpreted as markers for psychological impairment: as the scholar suggests, dynamic risk factors are not explanatory concepts but predictive constructs, ultimately challenging the aim of the punishment for which they are used. Indeed, the prediction of future behaviour can be challenging and eventually harmful if

misinterpreted under the lens of scientific (statistical) validity. Thus, risk assessment needs research-based enhancements that can influence its scientific reliability.

Interestingly, the neuropredictive lens is one of the main focuses of recent neurocriminology: in particular, the inclusion of neural variables is considered a complement to behavioural measures of risk assessment to enhance accuracy and targeted treatments. However, as Federica Coppola highlights (2018), the inclusion of neuroprediction in forensic and justice contexts is challenging and requires a cautious approach. When considering neural correlates as structural and functional brain findings, many issues arise. For instance, the risk of “marking criminals as different from law-abiding individuals” (Coppola, 2018) is a problem going far beyond the use of neuroscientific evidence: labelling is a widespread weakness that starts with the use of linguistic labels that identify individuals with past offending behaviour, ultimately falling in dehumanisation and undermining rehabilitation and reintegration (Willis, 2018). When dealing with neuroprediction, the labelling problem is accompanied by other equally relevant issues, as the violation of cognitive liberty, the misconception of neuroscience (i.e., overreliance on neuroscientific findings), the privilege against self-incrimination, the presumption of innocence, and the right to refuse a medical treatment (see Coppola, 2018 for a detailed account). Interestingly, many of these issues are shared with other relevant and discussed topics in forensic contexts, as for instance the offering of neurointerventions to criminal offenders which, as Ligthart suggests (2023), appears in contrast with diverse human rights principles. However, while current correctional practices have failed, the inclusion of neuroscientific variables that tailors individualised treatments more efficiently could help identify and implement alternative sentences (Coppola, 2018).

1.2.4. The Perceived Sanction: Can Neuroscience Inform Effectiveness?

According to *Rational Choice Theory* (Cornish & Clarke, 2014; Hirschi, 2017) individuals are rational decision-makers using *compensatory* decision strategies, weighting and integrating

information to maximise rewards while minimising costs. These decisions are based on situational circumstances including their perception of self and others (Taylor & Nee, 1988). Thus, the notion of “limited” or “bounded” rationality has been cast to nuance prior conclusions of *Rational Choice Theory*: criminal decision-making involves uncertainty; thus, offenders are rarely in possession of all the necessary facts to carry out a properly rational cost-benefit analysis (Paternoster, 2001). Moreover, as experimental evidence on youths’ past and forecasted engagement in a range of illegal behaviours suggests (Dhami & Mandel, 2012), intentions to take risks are better explained by the perceptions of the expected benefits than the costs, possibly thanks to the short-term nature of perceived potential benefits of illegal behaviours, rather than the long-term nature of perceived potential drawbacks. Thus, the perception of sanctions becomes central in understanding how effective treatments can be in terms of rehabilitation.

Interestingly, a review by Cornet and colleagues (2014) found an association between neurobiological factors and predicted outcome of cognitive-behavioural therapy in individuals showing antisocial behaviour. Notably, physiological arousal levels and neuropsychological variables seem to have a role in the effectiveness of this treatment option.

Research on self-control further supports the idea of differential deterrability, whereas the perception of the sanction is influenced by the individual’s propensity to commit crime. In particular, individuals with low self-control are more restrained from offending by their sanction certainty perceptions (i.e., perceived risk of apprehension when committing four different types of crime) than individuals with high self-control (Hirtenlehner, 2020) in line with the *Situational Action Theory* of criminology (Wikström & Treiber, 2015). This theory, focused on the interaction between individual traits and situational trigger factors, states that “acts of crime tend to occur when crime-prone people are introduced to criminogenic settings” (Wikström, 2012), of which a case in point is the *peer effect* for skill-intensive offenses in the

“prison as school of crime research” (Ouss, 2011). Coherently, prison environment itself represents a risk factor for EFs deterioration: the cognitively impoverished setting due to sedentary lifestyle, social isolation and lack of cognitive challenges affects negatively brain functioning (Meijers et al., 2015; Scherder et al., 2010). A study by Meijers et al. (2018) investigated the influence of imprisonment on EFs and self-control: the results show a significant deterioration in self-control and attention after 3 months of imprisonment, consistently with studies suggesting that harsher (i.e., more impoverished) prison conditions can lead to higher post-release offending rates (Hen & Shapiro, 2007).

Neuroscientific evidence on risk-taking behaviour further supports alternatives to detention by providing scientific-based approaches to rehabilitation. Given the overlap between risky behaviour and interoception, a study explored the effects of a biocueing app in a forensic outpatient population (Ter Harmsel et al., 2023). Wearable and mobile devices were used to collect and display physiological biomarkers, such as heart rate variability or cardiac coherence, that participants have been trained to influence in a biofeedback perspective. The results were interesting: on a quantitative viewpoint, significant decrease in aggression was found only between pre- and post-test, and not for the comparison with follow-up (where the biocueing app was discontinued). On a qualitative standpoint, participants reported positive changes in interoceptive awareness, perceived support in the use of coping strategies, and prevention of some aggressive accidents, with increased insight into physiological signals. These results are coherent with previous studies (Ter Harmsel et al., 2021) with significant decreases in trait anger with biocueing as addition to regular therapy.

1.3. Translational Research: the Multidisciplinary Approach

As previously mentioned, the neuroscientific contribution to criminology can inform about new perspectives to better understand antecedents of criminal behaviour and to develop tailored treatments for rehabilitation. This strongly multidisciplinary approach is rooted in the need for

complementing criminological theories with a scientific background that considers neurobiological and neurocognitive evidence without a deterministic lens (Coppola, 2020).

The two main topics developed in the previous paragraphs are risk-taking behaviour, that belongs to the neuroscientific decision-making scenario, and self-control, derived from Gottfredson and Hirschi's General Theory of Crime (Gottfredson & Hirschi, 1990). Interestingly, risk-taking behaviour is often coupled with the criminological concept of self-control, both for the behavioural outcomes associated with them (i.e., engagement in criminal activity) and for the similar conceptualisations (Forrest et al., 2019). This parallel is confirmed by research, that supports shared cognitive mechanisms, neural correlates and similar sensitivity to exogenous interventions.

Specifically, non-invasive brain stimulation techniques, the Caloric Vestibular Stimulation or the Galvanic Vestibular Stimulation, allow the investigation of risky behaviour through its effect on the vestibular system: while electric current hyperpolarises or depolarises irregular afferents to the vestibular nuclei, it is possible to assess how those brain areas influence decision-making, and precisely the propensity to take risks.

The current study fits in this literature overview investigating the role of vestibular inputs, namely through GVS, in the Balloon Analogue Risk Task (Lejuez et al., 2002) and the Heartbeat Counting Task, respectively assessing risk-taking and interoception. As many other studies in this field, results could aid the understanding of neural correlates of behaviour and, ultimately, improve the design of treatment intervention for criminal behaviour.

2. Research Hypothesis

The present study investigates the effects of the vestibular system on risk-taking behaviour as measured through a behavioural task, the Balloon Analogue Risk Task (BART), through the implementation of a non-invasive brain stimulation technique, the Galvanic Vestibular Stimulation (GVS). Moreover, the relationship between interoception, assessed through the Heartbeat Counting Task (HCT), and risk-taking behaviour will be investigated.

2.1. Aims and Hypotheses

In consideration of potential stressors effects on BART due to the perception of active stimulation (see paragraph 1.1.6), a preliminary paired samples t-test will be conducted to assess the eventual significant difference between the two active conditions. If no statistically significant difference is found, all subsequent analyses involving active sessions data will be performed using the mean of the two active conditions, which will provide a more stable and reliable measure through the principle of aggregation (Rushton et al., 1983). Conversely, if a significance occurs, paired samples t-tests will be substituted by repeated-measured ANOVA including all three sessions.

2.1.1. Main aim and hypothesis

The main aim is to compare BART performance between active and sham GVS stimulation, within a three-session, within-subject design in which each participant underwent two sessions of active stimulation and one session of sham stimulation, administered in a randomised order. It is hypothesised that the BART performance will differ between active and sham stimulation conditions. Active GVS is expected to perturb vestibular processing and, consequently, the multidimensional integration of vestibular information with sensory and cognitive processes, among which decision-making. Given the involvement of vestibular networks in multisensory integration and their functional association with brain regions implicated in cognitive and

affective processes, the transient perturbation of vestibular signalling may influence risk-taking behaviour as measured through the BART performance. To date, no study has employed alternating current GVS to stimulate vestibular system in a risk-taking behavioural task.

2.1.2. Secondary aim and hypothesis

Previous studies have demonstrated an association between interoception and risk-taking behaviour (Kandasamy et al., 2016; Reader & Salvato, 2024; Salvato et al., 2019). Thus, it is hypothesised that interoception will modulate risk-taking behaviour in two distinct ways:

- higher interoceptive accuracy, assessed through the HCT, will be associated with higher risk-taking scores at the BART (Kandasamy et al., 2016);
- higher interoceptive sensibility, assessed through the MAIA – 2, and in particular higher *Non-distracting* and *Non-worrying* scores, will be associated with increased risk-taking at the BART (Reader & Salvato, 2024).

Moreover, a common neural substrate between interoception and vestibular activations has been found in the literature (Craig, 2002; Craig, 2011; zu Eulenburg et al., 2013). Thus, it is expected to find an effect of GVS on HCT and MAIA – 2 scores.

2.1.3. Exploratory analyses

Furthermore, exploratory analyses will be conducted to assess possible associations between risk-taking at the BART and other variables concerning emotional-behavioural status of participants during the sessions, such as state and trait anxiety (STAI X-1 and STAI X-2), depressive symptomatology (BDI-II) and general risk propensity (GRiPS). These analyses are not driven by a-priori hypotheses and will be considered exploratory for future research.

3. Methodology and Materials

3.1. Participants

A total of 12 participants were initially recruited for the study. Participants were considered eligible for the study if they met all the following criteria:

- age between 18 and 65 years;
- absence of metallic implants;
- absence of pre-existing neurological, psychiatric, vestibular, or hearing disorders;
- absence of neurodevelopmental disorders;
- absence of current pregnancy;
- no concurrent use of psychotropic medication during the experimental sessions;
- no recent participation in experiments involving the BART;
- no nail polish on the fingernails for the three experimental sessions.

Participants were excluded if they did not meet any of the aforementioned eligibility criteria.

Two participants were subsequently excluded from the analyses due to impedance-related issues during one GVS session (active condition). The final sample therefore consisted of $N = 10$ participants (90% female, 10% male), with a mean age of 25.90 ($SD = 11.46$ years, range 20.00–58.00) and a mean level of education of 15.40 years ($SD = 1.27$, range 13.00–18.00).

All participants provided written informed consent prior to participation. The study was conducted in accordance with the relevant ethical guidelines and approved by the Ethics Committee of the Department of Brain and Behavioural Sciences (University of Pavia). Psychology students participating in the experiment were awarded one university credit upon completion of the three experimental sessions.

3.2. Materials and Measures

During the three experimental sessions participants were administered the following test and questionnaires to assess cognitive and emotional-behavioural status. Two behavioural tasks were also included in the three sessions.

3.2.1. Montreal Cognitive Assessment (MoCA)

A brief screening tool developed with high sensitivity and specificity for mild cognitive impairment detection in patients with normal-range performance in other cognitive tests (Nasreddine et al., 2005). It is a 30-point test that provides a general account of diverse cognitive areas as visuospatial abilities, language, memory, attention. The examination is conducted with the following items: alternation task adapted from the Trail Making B (Tombaugh, 2004); three-dimensional cube copy; clock-drawing task; three-item confrontation naming task with low-familiarity animals; two learning trials of five nouns; digits forward and backward; target detection using tapping; serial subtraction task; repetition of two syntactically complex sentences; phonemic fluency task; two-item verbal abstraction task; delayed recall of the five nouns learnt in the aforementioned task; temporal and spatial orientation (Nasreddine et al., 2005).

Recently, multiple Italian validations have been published (Dapor et al., 2025; Pirani et al., 2022; Santangelo et al., 2015). Some scholars (Aiello et al., 2021) highlighted the presence of a relevant inter-regional diversity across Italy, reflecting divergences between validations on Northern Italy-specific pools and broader recruiting areas, consistently with documented issues in neuropsychological testing (Manly, 2008) already found in Italy for instance in the case of one of the most recent Italian validations of the Mini-Mental State Examination (Mazzi et al., 2020). Therefore, due to the geographic area of recruitment of the present study, the standardisation conducted by Aiello and colleagues (2021) has been chosen for the cognitive screening of participants, administering to participants the Italian translation by Pirani and

colleagues (2006). The aforementioned validation, motivated by recent changes in demographic composition and socio-cultural features of the population, is likely to be more representative and generalisable than previous validations (Conti et al., 2015; Santangelo et al., 2015) due to the nature of its sample (Aiello et al., 2021). The calculation of sub-scores dividing the tasks according to the cognitive functions investigated (even though some tasks can be informative of more than one function at a time) was not considered in the present study, while using the total score for screening participants cognitive status and correcting using regression equations. Indeed, the MoCA appears more sensible in detecting age-related physiological decline than the most widespread cognitive screening test worldwide, the Mini-Mental State Examination (Aiello et al., 2022).

3.2.2. General Risk Propensity Scale (GRiPS)

Risk propensity was assessed using the GRiPS (Zhang et al., 2019), a brief self-report measure consisting of 8 items covering different situations (e.g., “Taking risks makes life more fun”) in which people can adopt risk-taking behaviours on a 5-point Likert scale ranging from 1 (“Strongly disagree”) to 5 (“Strongly agree”). GRiPS total score, given by the mean of the 8 items scores, represents risk-taking as a broad construct and predicts work, academic and life outcomes. It is useful to assess broad engagement in risky behaviours and is associated with financial, health, and recreational risks, such as excused absence or alcohol abuse (Zhang et al., 2019).

3.2.3. Multidimensional Assessment of Interoceptive Awareness 2 (MAIA-2)

The MAIA-2 (Mehling et al., 2018) is the second version of a self-report measure of interoceptive body awareness (Mehling et al., 2012), including 37 items to measure 8 different dimensions:

1. *Noticing*: awareness of body sensations;

2. *Not-Distracting*: tendency to not being distracted by body sensations of negative nature (e.g., pain, discomfort);
3. *Not-Worrying*: emotional distress or worry correlated with body sensations of negative nature (e.g., pain, discomfort);
4. *Attention Regulation*: ability to control attention and maintain focus when sensory stimuli require attention;
5. *Emotional Awareness*: awareness around the relationship between body sensations and emotional states;
6. *Self-Regulation*: ability to regulate psychological distress addressing attention to body sensations;
7. *Body Listening*: tendency to actively pay attention to body sensations;
8. *Trusting*: experience of body as safe and trustworthy.

Participants rate each item on a Likert scale from 0 (“Never”) to 5 (“Always”). The average items scores for each scale provides partial scores for each dimension, ranging 0-5; higher scores indicate higher awareness of internal body sensations (Crocetto et al., 2026). In the present study the Italian version of the test has been employed (Crocetto et al., 2026); partial scores for each dimension were calculated. Moreover, a global score as sum of all the partial scores has been calculated; even though the original validation (Mehling et al., 2012) advises against the calculation of a global score using MAIA items given the multidimensionality of the construct, the employment of a total score has already been used in the literature for the quantification of positive awareness levels. For instance, Montoya-Hurtado and colleagues (2023) calculated a “MAIA Total” as sum of all 32-item MAIA.

3.2.4. State-Trait Anxiety Inventory (STAI)

This self-report measure of anxiety (Spielberger, 1983) contains two subscales: the State Anxiety Scale (STAI X-1) and the Trait Anxiety Scale (STAI X-2) (Spielberger, 1970). The

former is informative on feeling of apprehension, tension, nervousness, worry, arousal of the autonomic nervous system exactly while filling out the questionnaire; the latter investigates general and stable anxiety aspects in the daily life of the subject (Julian, 2011). The STAI includes 40 items (20 for each subscale) to be rated by the participant on a Likert scale ranging from 1 (“Not at all” in STAI X-1; “Almost never” in STAI X-2) to 4 (“Very much so” in STAI X-1; “Almost always” in STAI X-2). The Italian version has been employed in this study (Biagiarelli et al., 1984)

Scores range for the two subtests is 20-80, whereas higher scores indicate greater presence of anxiety symptomatology; diverse cut-off scores have been suggested for the detection of clinically significant anxiety levels (Julian, 2011), but in the present study scores were employed as continuous variables to screen for anxiety influence on task performance.

3.2.5. Beck Depression Inventory – II (BDI-II)

This questionnaire provides a quantitative assessment of the intensity of depression symptoms (Beck et al., 1961). In particular, in the second edition included in the present study participants are asked to answer the 21 items based on the two previous weeks (including the day of the assessment), rather than only the one preceding the moment of filling out (Beck et al., 1996). Items are scored ranging 0-3; the global score is the sum of all items. Some studies tried to identify optimal cut-offs to detect pathological symptomatology (Von Glischinski et al., 2019); in the present study the Italian version was employed (Montano & Flebus, 2006) and total scores were considered as continuous variables to screen for depression influence on task performance.

3.2.6. Simulator Sickness Questionnaire (SSQ)

This questionnaire, developed specifically for the assessment of simulator sickness symptomatology, includes three clusters of symptoms: nausea, oculomotor, and disorientation (Kennedy et al., 1993). Each cluster includes the sum of 7 of the 16 items scores assigned by

the subject on a 4-point Likert scale. Each cluster value is then weighted using the conversion formulas (Kennedy et al., 1993). Thus, the SSQ provides four scores: Nausea-related subscore (N), Oculomotor-related subscore (O), Disorientation-related subscore (D), and a Total Score (TS) representing the overall severity of symptoms (Walter et al., 2019). Over the years and various applications of this scale, scholars provided some classification to clusterise the intensity of symptoms; for instance, a categorisation based on central tendency has been proposed in military aviation applications (Kennedy et al., 2003). However, these procedures are based on the assumption that “individuals in other than their usual state of fitness are eliminated from the sample, and that only postexposure data are scored”, as suggested by the authors (Kennedy et al., 1993).

During the three experimental sessions, the participants were asked to perform two behavioural tasks, the BART and the HCT, described in the following paragraphs.

3.2.7. Balloon Analogue Risk Task (BART)

As a behavioural measure of RT, the BART is a computerised task requiring the participant to interact with a simulated balloon on a screen (Lejuez et al., 2002). In the present study, the BART was administered through PsychoPy v2026.1.3 (<https://www.psychopy.org>); participants were asked to look at a computer screen (13.3” screen configured at 1920 x 1080 resolution and 60 Hz refreshing rate; MacBook Air M1, 2020, 8GB RAM) placed in front of them. At the start of each session, instructions for the task completion were presented.

In each trial, a red balloon was presented at the centre of the screen (Figure 7). Each click of the participant on the space bar of the computer corresponded to a pump of the current balloon, thus a €0.05 virtual reward increase of the current total, displayed at the bottom of the screen (“*Denaro virtuale per questo palloncino*”). The total virtual reward of all the trials was displayed at the top of the screen (“*Hai guadagnato*”). At any time, participants could decide

whether to keep on clicking and pumping the current balloon to increase the gains but risking exploding the balloon, and thus not being able to gain the accumulated amount of virtual reward, or permanently collect the accumulated amount of the current trial. In case of balloon explosion, a bursting sound was emitted and, on the screen, appeared a message alerting the participant of the null gain (“*Oops! Hai guadagnato €0.00!*”). On the other hand, when the virtual reward was collected by the participant before the explosion, a message alerting about the amount gained appeared on screen (“*Hai guadagnato €...*”). After each trial (i.e., balloon), a new balloon appeared until a total of 40 trials had been completed. As in the original paradigm (Lejuez et al., 2002), the number of maximum pumps of each balloon varied between 1-128 in a standard distribution.

As in other studies (De Maio et al., 2021), a 10 trials-practice block was completed by participants in order to get familiar with the task and avoid possible learning effects.

The adjusted average pumps (i.e., the average number of pumps for the unexploded balloons), as in the original BART (Lejuez et al., 2002), was taken into account as index of riskiness.

To account for the risk-taking performance at the BART, analyses will be conducted on average data from the two of active stimulation: previous studies have demonstrated a delayed effect of psychosocial stress on BART performance, leading to a decrease of risk-taking in unfamiliar but not familiar conditions (Nowacki et al., 2019). Moreover, the eventual presence of non-vestibular side effects of GVS (i.e., cutaneous tingling or itching) lasting longer than in the sham condition during the active stimulation could have a distracting effect (Dilda et al., 2012).

Thus, in case of non-significant difference between the two active conditions, the BART performance during active GVS will be defined as follows:

$$\frac{1st\ active\ session + 2nd\ active\ session}{2}.$$



Figure 7

Screen interface for BART paradigm administration through PsychoPy v2026.1.3

3.2.8. Heartbeat Counting Task (HCT)

The HCT is a heartbeat tracking task that allows to determine interoceptive accuracy. While heart rate was monitored through a pulse oximeter attached to the participant's left index finger, participants were asked to silently count the perceived heartbeat as in Garfinkel and colleagues (2015). The task was repeated five times in the following time-windows in a randomised order: 25s, 30s, 35s, 40s, and 45s. The signals of beginning and end of each time window were given vocally by the experimenter using a digital stopwatch.

According to the formula presented by Garfinkel and colleagues (2015) and reported in Equation 1, an accuracy score was derived for each trial and later averaged over the 5 trials (Garfinkel et al., 2015; Hart et al., 2013) to obtain an average awareness value for each participant in each session.

$$1 - (|nbeats_{real} - nbeats_{reported}|) / (\frac{nbeats_{real} + nbeats_{reported}}{2})$$

Equation 1

The accuracy score is derived through this formula according to Garfinkel and colleagues (2015)

3.2.9. Galvanic Vestibular Stimulation (GVS)

Galvanic vestibular stimulation was delivered using a Soterix Medical 1x1 Galvanic Vestibular Stimulator (Soterix Medical, USA; bench-top model).

Mastoid processes were cleaned with surgical spirit-soaked cotton wool and carbon rubber electrodes (area $\sim 20\text{cm}^2$), previously prepared with electrode gel (HD-GEL; Soterix Medical, USA) to reduce skin impedance, were placed binaurally and fixed with medical adhesive tape. Bipolar GVS was administered with the following parameters: sinusoidal waveform (Alternating Current, AC) with 1mA intensity peak at 50Hz. A sham stimulation was applied on the mastoids through sham waveform (Soterix Medical, USA), which mimics the skin sensation of active GVS with a current ramping up for 30 s to full-intensity (1mA) peak after the start and then ramping down for 30 s before the end of the stimulation session, without active stimulation.

Stimulation duration was consistent with the BART and HCT completion and limited to maximum 20 minutes, as safety literature indications state for GVS and other non-invasive brain stimulation techniques (Valter et al., 2025).

Every participant underwent each stimulation condition (two active and one sham) in three sessions in a randomised order.

3.3. Study Design

The study employed a within-subject, repeated-measures design in which each participant underwent three experimental sessions, corresponding to two different stimulation conditions: two active and one sham stimulation. The stimulation conditions were administered in a randomised order across participants.

3.4. Experimental Procedure

Participants who expressed interest in participating in the study were contacted by the experimenter to schedule three appointments, with at least 72 hours between sessions to minimise potential carry-over effects (Valter et al., 2025). At the first experimental session, participants were given verbal and written information about non-invasive brain stimulation and signed informed consent. Subsequently, the experimenter assessed cognitive and emotional status through the administration of the measures described in the paragraphs from 3.2.1 to 3.2.6, in the following order: MoCA, GRiPS, MAIA-2, STAI X-1, STAI X-2, BDI-II. After completing these measures, participants were prepared for the stimulation session as described in paragraph 3.2.9 (i.e., skin preparation, electrode placement). After the onset of the active GVS or sham GVS stimulation, participants performed the two behavioural tasks, the BART and the HCT. The stimulation session ended upon completion of both tasks. Thereafter, electrodes were removed and participants filled out the post-stimulation SSQ.

At the beginning of the second and third sessions, the participants were re-administered the STAI X-1. Afterward, they underwent stimulation, during which they performed the BART and the HCT. After the conclusion of the behavioural tasks and the stimulation, they filled out the post-stimulation SSQ.

3.5. Data Analysis

Statistical analyses were performed on JASP (Version 0.98.1) [Apple Silicon]. The level of statistical significance was set at $\alpha = .05$. Descriptive statistics were calculated for all study variables. Prior to the main analyses, data were screened for missing values, outliers, and violations of the assumptions underlying the statistical tests employed. Corrections for multiple comparisons were applied to analyses involving multiple related tests.

4. Results

4.1. Preliminary Analyses

This section reports descriptive statistics for the main study variables and the results of assumption-checking procedures preliminary to inferential analyses.

Descriptive statistics were calculated for all demographic, behavioural and psychometric variables. Continuous variables were summarised using means and standard deviations (SD); minimum and maximum values for each variable were provided. Normality of distributions was assessed through Shapiro-Wilk test: no significant deviations from normality emerged for any score of the variables examined ($p > .05$).

The following measures were included in the analyses: BART adjusted average pumps – first active session (21.14 ± 13.15 , range: 5.27 – 48.18), BART adjusted average pumps – second active session (25.46 ± 11.84 , range: 7.03 – 42.04), BART adjusted average pumps – average active sessions (23.30 ± 11.93 , range: 6.24 – 45.11), BART average adjusted pumps – sham session (26.83 ± 11.68 , range: 5.37 – 40.65), total GRiPS scale (2.55 ± 0.94 , range: 1.38 – 4.375), total MAIA – 2 questionnaire (24.25 ± 3.075 , range: 19.57 – 28.16), MAIA – 2 *Noticing* (3.80 ± 0.56 , range: 2.50 – 4.50), MAIA – 2 *Not-Distracting* (2.22 ± 0.92 , range: 0.33 – 3.33), MAIA – 2 *Not-Worrying* (2.34 ± 0.79 , range: 1.40 – 3.80), MAIA – 2 *Attention Regulation* (2.83 ± 0.88 , range: 1.43 – 4.14), MAIA – 2 *Emotional Awareness* (4.02 ± 0.85 , range: 2.600– 5.00), MAIA – 2 *Self-Regulation* (3.05 ± 0.90 , range: 1.50 – 4.50), MAIA – 2 *Body Listening* (3.13 ± 0.67 , range: 2.00 – 4.33), MAIA – 2 *Trusting* (2.87 ± 1.00 , range: 1.33 – 5.00), total BDI – II questionnaire (9.20 ± 5.05 , range: 2.00 – 17.00), STAI X – 1 – average active sessions (34.65 ± 4.90 , range: 24.00 – 42.00), STAI X – 1 – sham session (31.30 ± 6.93 , range: 23.00 – 44.00), STAI X – 2 (46.00 ± 8.66 , range: 31.00 – 58.00), HCT accuracy – average active sessions (0.51 ± 0.34 , 0.00 – 0.97), HCT accuracy – sham session (0.48 ± 0.37 , 0.00 – 1.00).

4.2. Main Analysis: Effect of GVS on Risk-Taking Behaviour

Firstly, a paired sample t-test was conducted to compare BART performance (i.e., adjusted average pumps) between the two active conditions, revealing no significant difference ($t(9) = -1.82, p = .10, d = -0.57$). Thus, a Wilcoxon signed-rank test (normality violation has been found for this comparison; Shapiro-Wilk $W = 0.84, p = .040$) was conducted to compare BART performance (i.e., adjusted average pumps) between average active conditions and sham condition. No significant difference was observed between the two conditions ($W = 21.00, p = .557$).

4.3. Secondary Analyses: the Role of Interoception in Risk-Taking Behaviour

To investigate the potential role of interoception in the BART performance, two types of analysis were performed.

To account for interoceptive sensibility, participants were divided into two groups based on their MAIA – 2 scores using a mean split procedure: participants with a score below the sample mean were assigned to the low interoceptive sensibility group, whereas participants with a score above the sample mean were assigned to the high interoceptive sensibility group. Therefore, a repeated-measures ANOVA was conducted to examine the effect of interoceptive sensibility group on BART performance (i.e., adjusted average pumps) across stimulation conditions (Figure 8). The main within subjects effect of stimulation conditions on BART was not significant ($F_{1,8} = 1.63, p = .238$), as well as the interaction between stimulation conditions and interoceptive sensibility scores ($F_{1,8} = 0.08, p = .791$). A significant between-subjects main effect of MAIA – 2 groups was observed ($F_{1,8} = 26.06, p < .001$) relative to a difference in BART performance between the two interoceptive sensibility groups.

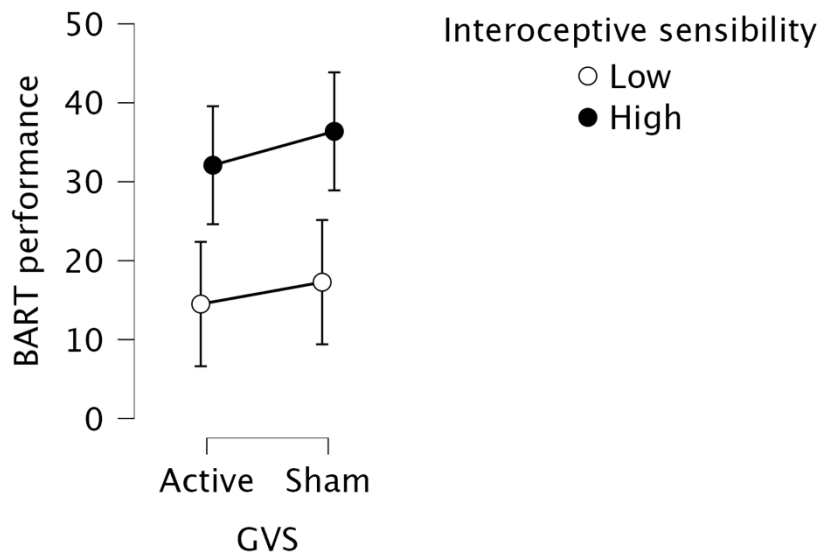


Figure 8
Descriptive plot of the effect of GVS on risk-taking behaviour between the two interoceptive sensibility groups

To account for interoceptive accuracy, participants were divided into two groups based on their average accuracy at the HCT over the three sessions using a mean split procedure: participants who scored below the sample mean were assigned to a low interoceptive accuracy group, whereas participants with a score above the sample mean were assigned to the high interoceptive accuracy group. Subsequently, a repeated measures ANOVA was conducted to examine the effect of interoceptive accuracy group on BART performance (i.e., adjusted average pumps) across stimulation conditions (Figure 9). The main within-subjects effect of stimulation conditions on BART was not significant ($F_{1,8} = 1.23, p = .299$), as well as the interaction between stimulation conditions and interoceptive sensibility scores ($F_{1,8} = 2.34, p = .164$). No significance was also observed ($F_{1,8} = 2.55, p = .149$) in relation to a difference in BART performance between the two interoceptive accuracy groups as between-subject effect.

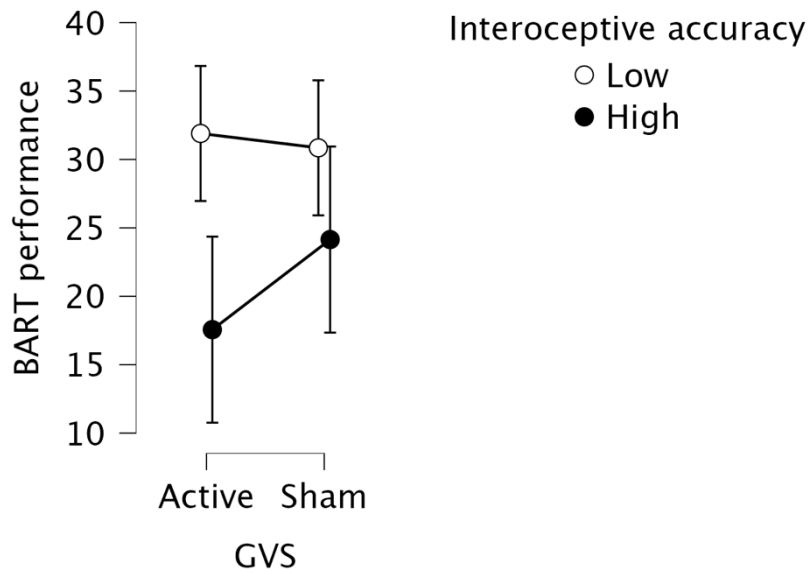


Figure 9
Descriptive plot of the effect of GVS on risk-taking behaviour between the two interoceptive accuracy groups

4.4. Exploratory Analyses

These analyses were conducted to investigate potential differences in terms of behavioural, emotional and interoceptive measures between stimulation conditions. Given the explorative nature of these analyses, they were not driven by a priori hypothesis.

A Student's paired samples t-test was conducted to compare the scores at the STAI X – 1 in active and sham sessions. No significant difference emerged between the two conditions ($t(9) = 1.88, p = .093, d = 0.60$).

To compare the SSQ total scores of the active and sham conditions, a Student's paired samples t-test was conducted, and no significant difference emerged ($t(9) = 1.65, p = .134, d = 0.52$).

Finally, a Student's paired samples t-test was conducted to compare the interoceptive accuracy scores during the HCT between the active and sham stimulation conditions. No significant difference emerged ($t(9) = 0.76, p = .468, d = 0.24$).

Additionally, exploratory correlation analyses were conducted to investigate potential associations between risk-taking behaviour, interoception, and emotional-behavioural variables. Several significant correlations between the variables emerged. The BART average score (i.e., adjusted average pumps) in the active GVS session positively correlated with MAIA – 2 *Noticing* ($r = .70, p = .027$), *Body Listening* ($r = .67, p = .034$) and total score ($r = .81, p = .004$). Scatter plots are represented in Figure 10, 11, and 12, respectively.

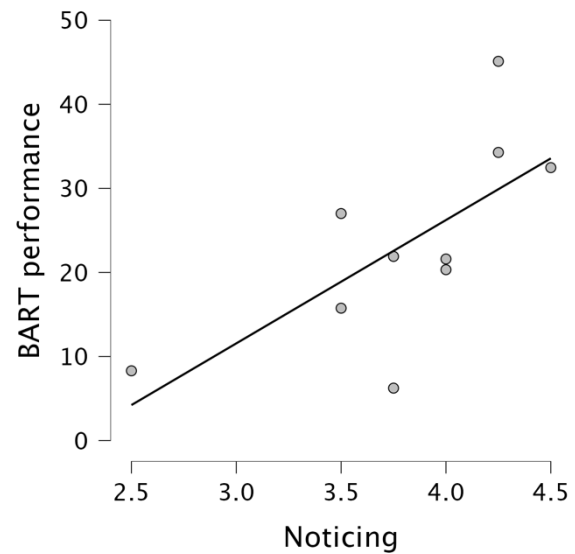


Figure 10
BART performance under active GVS positively correlated with MAIA - 2 Noticing

BART average score in the active GVS condition did also positively correlate with the BART score in the sham session ($r = .75, p = .012$).

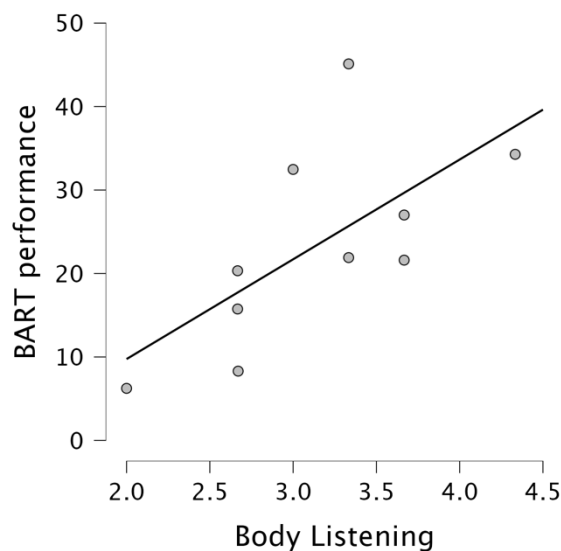


Figure 11
BART performance under active GVS positively correlated with MAIA - 2 Body Listening

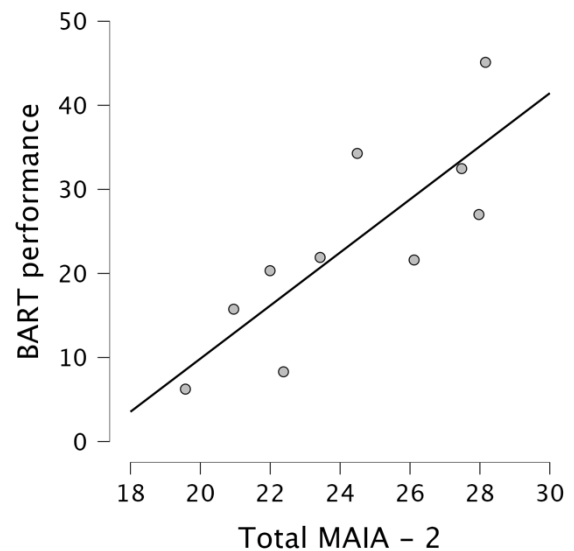


Figure 12
BART performance under active GVS positively correlated with MAIA - 2 total score

The BART score in the sham session correlated positively with MAIA – 2 *Attention Regulation* ($r = .64, p = .047$), *Self-Regulation* ($r = .87, p < .001$), *Body Listening* ($r = .69, p = .029$) and total score ($r = .94, p < .001$). Scatter plots are represented in Figure 13, 14, 15, and 16, respectively.

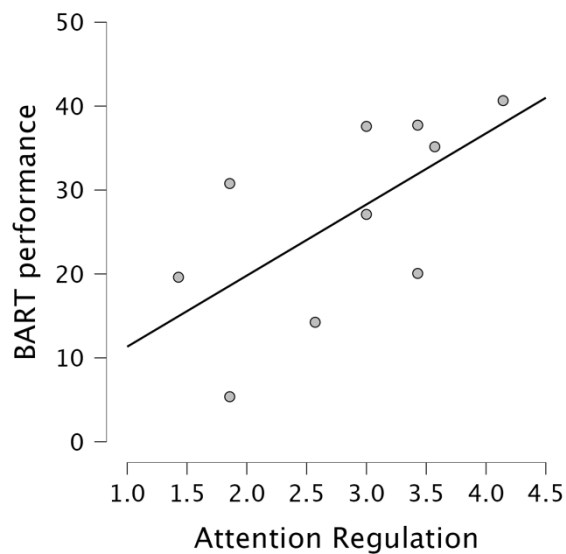


Figure 13
BART performance under sham GVS positively correlated with MAIA - 2 Attention Regulation

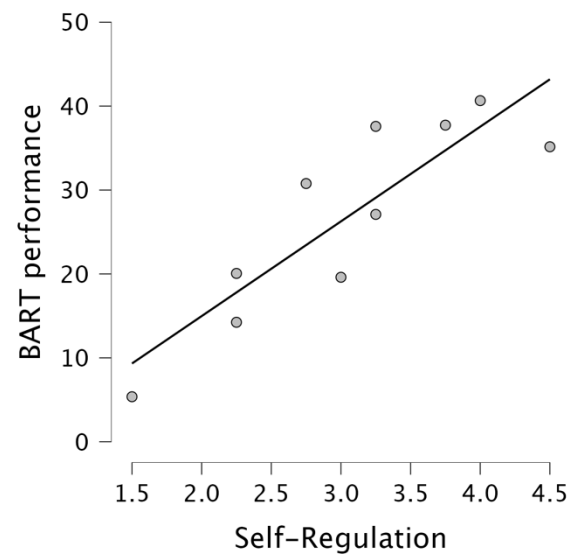


Figure 14
BART performance under sham GVS positively correlated with MAIA - 2 Self-Regulation

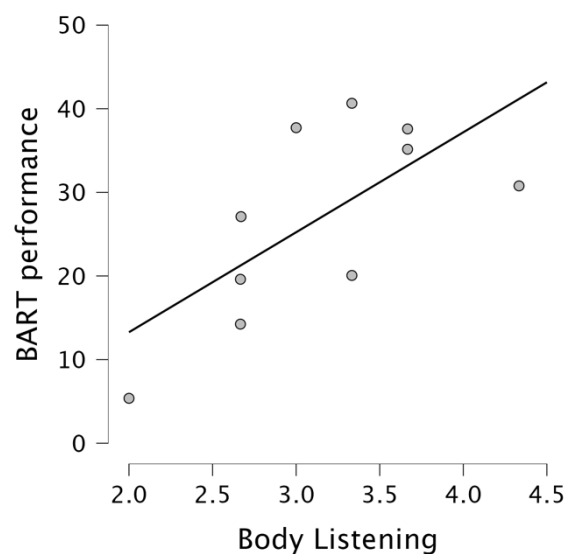


Figure 15
BART performance under sham GVS positively correlated with MAIA - 2 Body Listening

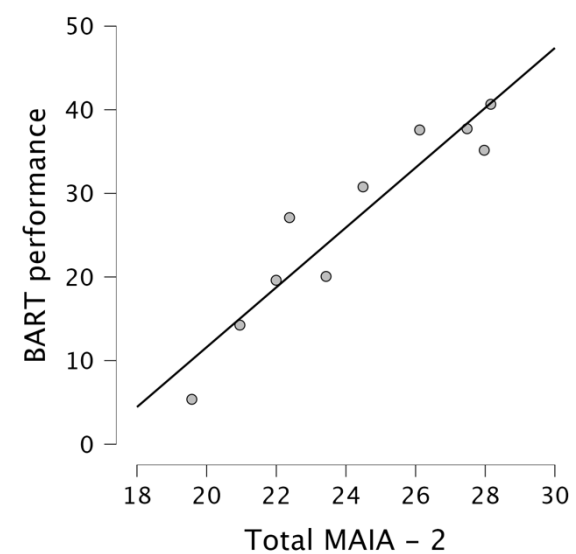


Figure 16
BART performance under sham GVS positively correlated with MAIA – 2 total score

The interoceptive accuracy at the HCT during the active session negatively correlated with MAIA – 2 *Not Distracting* ($r = -.73, p = .017$), as in Figure 17.

The interoceptive accuracy at the HCT during the sham session negatively correlated with MAIA – 2 *Not Distracting* ($r = -.70, p = .024$) and with the STAI X – 2 score ($r = -.69, p = .028$); scatter plots are in Figure 18 and 19, respectively. It also positively correlated with the accuracy during the active session ($r = .93, p < .001$).

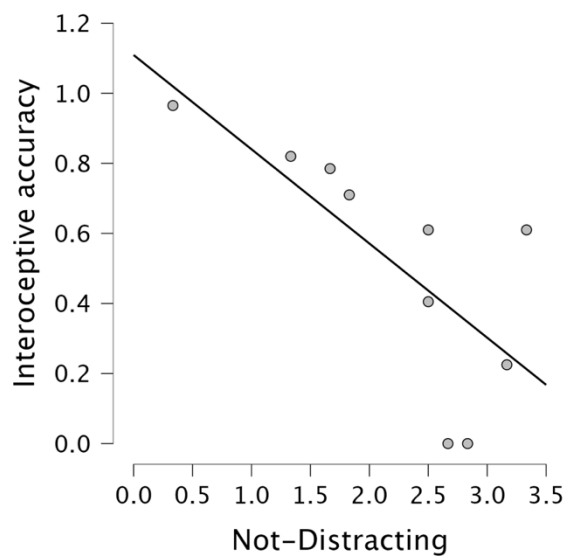


Figure 17
Interoceptive accuracy negatively correlated with MAIA - 2 Not-Distracting during active GVS

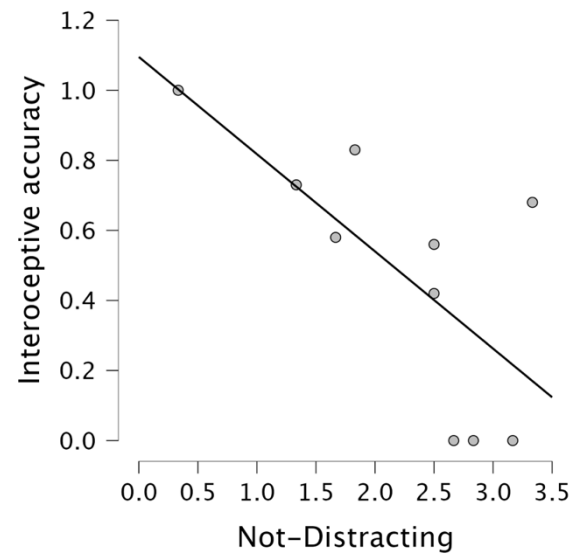


Figure 18
Interoceptive accuracy negatively correlated with MAIA - 2 Not-Distracting during sham GVS



Figure 19
Interoceptive accuracy during sham GVS negatively correlated with trait anxiety

5. Discussion

The current study aimed at addressing the role of vestibular system in risk-taking behaviour and interoception, employing GVS during two behavioural tasks, the BART and the HCT.

Regarding the vestibular influence on the risk-taking paradigm, two main findings were reported: firstly, no statistically significant difference has been found between the two active BART sessions. This preliminary test has been carried out to verify the possible presence of stressors on the BART performance, since this behavioural task is sensitive to psychosocial stress. Given the negative results, a comparison between the mean active conditions and the sham condition has been performed, finding no statistically significant difference. The overlap between risky behavior and vestibular neural correlates would possibly suggest a role of vestibular afferents in the modulation of this behaviour as explained in the Introduction of this work and demonstrated by other studies. This absence of significant findings can be explained considering methodological differences with other paradigms. For instance, to date no study has ever employed AC-GVS for the modulation of risky behaviour in order to investigate a potential role of vestibular disruption, while previous studies who found a significant role of vestibular stimulation employed DC-GVS with bipolar montage. De Maio and colleagues (2021) found a significant polarity-specific effect, while no generic vestibular effect has been found. The latter suggests that only polarisation of electrodes (i.e., left-anodal right-cathodal stimulation, which prevalently stimulates the right hemisphere) is interfering with decision-making behaviour and thus the results of the current study could be explained coherently this hypothesis. Thus, future studies are necessary to further investigate the role of the vestibular system in risk-taking behaviour: a direct comparison between different GVS paradigms (e.g., DC-GVS versus AC-GVS) could deepen the knowledge about how vestibular signals inform decision-making: for instance, left-anodal right-cathodal GVS is known to affect primarily the right hemisphere vestibular nuclei, while AC-GVS in bipolar setting, as employed in the current

study, leads to a broad vestibular disruption involving bilateral vestibular neural correlates. In addition, high-frequency GVS is known to continuously stimulate vestibular system, thus should rule out possible adaptive effects of continuous direct current stimulation (Cyran et al., 2016; Stephan et al., 2005).

The secondary aim of the study was the investigation of the relationship between interoception and risk-taking behaviour. In particular, regarding interoceptive sensibility, no within-subjects main effects and interaction have been found statistically significant. However, a between-subjects main effect resulted statistically significant: specifically, participants who had higher total scores at the MAIA – 2 were more risk-takers in the BART (see Figure 8). This expected result is coherent with previous literature that found an association between MAIA – 2 scores and the GRiPS (Reader & Salvato, 2024). The authors suggest that a positive relationship between a global MAIA – 2 factor could be interpreted in multiple ways: the simplest interpretation is that greater interoceptive sensibility is associated with greater risk-taking behaviour. However, as no global MAIA – 2 factor has been officially validated with the instrument, it is also possible that this measure is reflective of other behaviours, whereas Reader and Salvato (2024) hypothesise that the ability to flexibly engage with interoceptive sensations could be important for risk propensity. The current study is not a replication of the study by Reader and Salvato (2024) due to the use of a behavioural task for risk-taking behaviour and to the different global MAIA – 2 factor calculation methods (i.e., the mean of the items for six factors, excluding *Non-distracting* and *Not-worrying* in the other study). However, the findings of the present study appear coherent with the previous results and could be explained in light of Reader and Salvato's hypothesis: the reinterpretation of visceral sensations could lead the subjects to eventually prioritise potentially positive outcomes of risky behaviour over physiological warnings. Thus, as the authors suggests, extreme sports lovers and general

population will reinterpret body signals, for instance, tachycardia, as signs of excitement or of anxiety and fear, respectively.

Concerning the relationship between interoceptive accuracy during the HCT and the BART, no statistically significant finding has been found, contrary to the expected outcomes: given the neural overlaps between interoception and risky behaviour, the absence of statistically significant results could be attributed to the methodological reasons explained at the start of the current paragraph.

As exploratory findings, no statistically significant difference emerged between the measures of state anxiety during active and sham conditions, ruling out a potential effect of anxiety on the results. Moreover, no statistically significant difference emerged between the simulator sickness symptomatology reported by participants after the active and sham sessions, suggesting that vestibular symptoms did not violate blinding, and consistently with the absence of statistically significant differences during the BART of the two active conditions, which should not have been influenced by eventual symptomatology stressors. Lastly, no statistically significant difference emerged between interoceptive accuracy during active and sham sessions. This could be explained through the same lens of the absence of significance between BART in active and sham conditions, thus due to methodological differences in comparison to previous studies, which could hypothetically rely on the use of AC-GVS instead of polarised DC-GVS. The exploratory analysis regarding emotional-behavioural variables, general measures of risk propensity, interoceptive sensibility, and the risk-taking behaviour found some statistically significant correlations. Among the others, the BART in active GVS positively correlated with sham BART score, MAIA – 2 *Noticing*, *Body Listening*, and total score. Conversely, the BART score in the sham session correlated positively with MAIA – 2 *Attention Regulation*, *Self Regulation*, *Body Listening*, and total score. This complementary pattern between the two conditions, the active and the sham, would suggest a differential role of vestibular signalling in

MAIA – 2 subscales. Specifically, the active stimulation could have ruled out possible vestibular signals influencing the interoceptive sensibility as measured through the MAIA – 2 and as previous studies suggest. For instance, a fMRI study employed Sound-Evoked Vestibular Stimulation (SEVS) to elicit vestibular responses in a sample of chronic subjective dizziness (CSD) patients (Indovina et al., 2015). CSD, also known as persistent postural-perceptual dizziness (PPPD), is a chronic vestibular disorder characterised by non-vertiginous dizziness and unsteadiness precipitated by events causing acute vestibular symptoms or balance disruption, and lasting at least 3 months. Interestingly, CSD patients showed reduced activation of anterior and posterior insula, frontal operculum in the inferior frontal gyrus, hippocampus and ACC. Moreover, negative functional connectivity changes were located between anterior insula/inferior frontal gyrus and PIVC, anterior insula and middle occipital cortex, and ACC and PIVC. Partial overlap between these functional findings and the neural correlates of interoception (namely, hippocampus, insula, and ACC; see Berntson and Khalsa, 2021) suggests a potential role of vestibular signalling in interoceptive processes. Furthermore, Garfinkel and colleagues (2015) already hypothesised a dissociation of neural correlates encoding discrete bodily changes and their perception and interpretation, respectively in the right anterior insula and in the ACC and orbitofrontal cortex.

The interoceptive accuracy at the HCT during the active and sham conditions negatively correlated with MAIA – 2 *Not Distracting*, while only during the sham session HCT it correlated negatively also with the STAI X – 2 score. During the sham session, the integration of sensory processes relative to current physiological body condition (Balaban et al., 2011) is intact, meaning the somatoperception based on multisensory inputs (Ferrè et al., 2014), which in the active condition is influenced by the irregular afferents saturation of high-frequency AC-GVS. This could explain differences between the results of the current study and literature findings. The research supports a role of vestibular signalling in anxiety symptomatology and

disorders (Hilber, 2022), hypothesising that anxiety could be a manifestation of distorted multisensory integration: in animal and human models, vestibular information integration for spatial perception is modulated by trait anxiety, whereas anxious individuals interpret vestibular information differently being tied to an egocentric frame of reference instead of multiple reference frames as non-anxious individuals (Viaud-Delmon et al., 2011). Furthermore, a study by Pollatos and colleagues (2007) found a positive association between trait anxiety and the score of a heartbeat detection task, suggesting that the perception of visceral signals could play a significant role in the pathophysiology of anxiety disorders.

6. Conclusion

The current study investigated the relationship between risk-taking behaviour and interoception by combining two behavioural measures, the Balloon Analogue Risk Task (BART) and the Heartbeat Counting Task (HCT), respectively assessing risky behaviours and interoceptive accuracy. The inclusion of alternating current Galvanic Vestibular Stimulation (AC-GVS) allowed to modulate vestibular signalling, which overlap between risk-taking and interoceptive neural correlates, and therefore to better understand their role in decision-making and perception of visceral signals. The main hypothesis predicted that active vestibular stimulation would modulate risk-taking compared with sham condition. This hypothesis was not supported by statistical analyses. Similarly, no significant effect of stimulation was observed on interoceptive accuracy derived from HCT. Therefore, those findings do not provide evidence for a generic effect of the AC-GVS on risk-taking. However, this should not be interpreted as evidence against the vestibular contribution to decision-making, which is supported by previous research methodologically different from the current study. For instance, direct current GVS is commonly employed in the investigation of vestibular contributions to high order cognitive processes.

The secondary finding demonstrated that participants with higher interoceptive sensibility showed higher risk-taking across stimulation conditions, coherently with previous literature. On the other hand, interoceptive accuracy was not significantly associated with behavioural risk-taking, failing to support the corresponding hypothesis.

Overall, the current study suggests that subjective interoceptive experience may be related to behavioural risk-taking, highlighting the importance of vestibular signals, interoception, and decision-making as a multidimensional system.

6.1. Limitations

Several limitations of the current study should be acknowledged. Firstly, the modest sample size may have influenced statistical power determining an increased risk of Type II Errors. Moreover, the sample was characterised by an unbalanced sex distribution and predominantly composed by young and highly educated individuals, variables to which BART is sensitive (Mata et al., 2011; Sebri et al., 2023; Wiesiolek et al., 2014).

Other limitations could derive from the accuracy of the behavioural task for risk-taking. Specifically, the BART suffers from several potentially confounding factors, including task unfamiliarity, practice effects, psychosocial stress influence (Nowacki et al., 2019), and limited generalisability. Thus, to overcome some of these limitations, in the current study a brief practice trial was administered before each BART performance to ensure familiarisation as in previous studies (De Maio et al., 2021). Moreover, the use of the classical BART index (i.e., adjusted average pumps) could neglect potentially relevant information (De Groot, 2020; Schmitz et al., 2016), thus future research should include more informative BART indices, for instance including the number of not exploded balloons.

To assess situational stressors, which could potentially arise from vestibular symptoms of active GVS, two identical active sessions were conducted, and, given the lack of significant differences, their mean was employed to provide a more stable index of risk-taking during active GVS. Furthermore, high-frequency GVS is associated with diminished vestibular stimulation perception, thereby enhancing the blinding of the study.

Since previous studies have found significant vestibular contributions to risk-taking during vestibular stimulation, the absence of significant effects could be explained through methodological differences with the current research: to date, no study has employed high-frequency AC-GVS to assess contributions to decision-making.

In addition, other possible limitations are the use of split mean procedures and the absence of an officially validated MAIA – 2 total score.

6.2. Translational Research

The integration of criminological and neuroscientific theories and, therefore, evidence may contribute to a more comprehensive understanding of risk-taking behaviour, which is ultimately associated with criminal behaviour in the literature. Previous research demonstrated an overlap between the neuroscientific concept of risk-taking and the criminological self-control derived from the General Theory of crime (Gottfredson & Hirschi, 1990). Cognitive, behavioural and neurobiological mechanisms contribute to the multidisciplinary approach, whose evidence may contribute to the development of more accurate and predictive theories of offending. The present findings support an association between interoception, specifically interoceptive sensibility, and risky behaviours, coherently with previous studies. This evidence could contribute to an informed approach to social rehabilitation and reintegration of offenders into society. Notably, training on the control of body signals perceptions and wearables have already been used to ameliorate aggressive behaviour in forensic samples (Ter Harmsel et al., 2021; Ter Harmsel et al., 2023). The further investigation of interoceptive training and reinterpretation of internal signals is therefore leading to translational research applications in forensic and justice contexts (Coppola, 2018).

6.3. Implications and Future Directions

Future research should replicate the present paradigm employing larger and more balanced samples to directly compare different GVS protocols, notably AC-GVS and polarity-specific DC-GVS, to clarify whether and how general vestibular signalling affects risk-taking behaviour. In addition, combining behavioural measures with physiological recordings,

neuroimaging or neurophysiological measures could provide an account of the mechanisms linking vestibular system, interoception and decision-making.

Furthermore, the extension beyond laboratory risk-taking tasks (lacking generalisability) could help understand whether current findings are ecologically relevant. The applicability of research paradigms to real-world scenarios could help bridging the gap between neuroscience, psychology and criminology, while maintaining and supporting a non-deterministic interpretation of the findings. Additionally, the research on criminal behaviour could inform correctional treatments, addressing the problem of the perception of the sanction, which is essential to a rehabilitative-guided reintegration to society.

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As my dear high school teacher used to say: *ad maiora!*