UNIVERSITY OF LJUBLJANA
SCHOOL OF ECONOMICS AND BUSINESS

URŠA FERJANČIČ

THE ASSOCIATION OF PSYCHOLOGICAL AND PHYSIOLOGICAL TRAITS WITH RISK PROPENSITY IN THE DECISION-MAKING PROCESS IN FINANCE

DOCTORAL DISSERTATION

Ljubljana, 2025

AUTHORSHIP STATEMENT

The undersigned Urša Ferjančič, a student at the University of Ljubljana, School of Economics and Business, (hereafter: SEB LU), author of this written final work of studies with the title *The Association of Psychological and Physiological Traits with Risk Propensity in the Decision-Making Process in Finance*, prepared under supervision of prof. Aljoša Valentinčič, PhD, and co-supervision of prof. Fajko Bajrović, PhD.

D E C L A R E

1. this doctoral dissertation to be based on the results of my own research;
2. the printed form of this doctoral dissertation to be identical to its electronic form;
3. the text of this doctoral dissertation to be language-edited and technically in adherence with the SEB LU's Technical Guidelines for Written Works, which means that I cited and / or quoted works and opinions of other authors in this written final work of studies in accordance with the SEB LU's Technical Guidelines for Written Works;
4. to be aware of the fact that plagiarism (in written or graphical form) is a criminal offence and can be prosecuted in accordance with the Criminal Code of the Republic of Slovenia;
5. to be aware of the consequences a proven plagiarism charge based on this doctoral dissertation could have for my status at the SEB LU in accordance with the relevant SEB LU Rules;
6. to have obtained all the necessary permits to use the data and works of other authors which are (in written or graphical form) referred to in this doctoral dissertation and to have clearly marked them;
7. to have acted in accordance with ethical principles during the preparation of this doctoral dissertation and to have, where necessary, obtained permission of the Ethics Committee;
8. my consent to use the electronic form of this doctoral dissertation for the detection of content similarity with other written works, using similarity detection software that is connected with the SEB LU Study Information System;
9. to transfer to the University of Ljubljana free of charge, non-exclusively, geographically and time-wise unlimited the right of saving this doctoral dissertation in the electronic form, the right of its reproduction, as well as the right of making this doctoral dissertation available to the public on the World Wide Web via the Repository of the University of Ljubljana;
10. my consent to publication of my personal data that are included in this doctoral dissertation and in this declaration, when this doctoral dissertation is published;
11. that I have verified the authenticity of the information derived from the records using artificial intelligence tools.

Ljubljana, January 16th, 2025 Author's signature: _____

ACKNOWLEDGEMENTS

"It takes a village to raise a child," as the saying goes, and I believe this is equally true for a PhD. The journey of completing this dissertation has been far from a solitary endeavor; it has been a collective effort supported by the knowledge, guidance, encouragement, and kindness of many. I owe a great deal of gratitude to those who have contributed in various ways to this achievement, and it is with deep appreciation that I thank:

My supervisor prof. Aljoša Valentinčič, PhD, for providing the framework that allowed me to pursue this interdisciplinary research and for trusting in my ability to navigate this complex work on my own. Special thanks also go to my co-supervisor prof. Fajko Bajrović, PhD, for his guidance, for ensuring I remained focused on the core ideas, and for his role in shaping my development as a researcher.

I would also like to thank assoc. prof. Uroš Kovačič, PhD, research assistant Maja Derlink, PhD, assist. prof. Riste Ichev, PhD, and assist. Katarina Sitar Šuštar, MBA, for their invaluable assistance with data collection and their moral support during my moments of doubt. A special thanks also goes to my colleague and friend assist. Ajda Merkuž, PhD, for her valuable feedback and encouragement.

I am also deeply grateful to researcher Stanko Štuhec and assoc. prof. Janez Vodičar, PhD, from the Faculty of Sport, University of Ljubljana, for generously providing the Polar watches and equipment necessary for the data collection.

To each individual, who responded and participated in this research, I extend my sincerest gratitude. Your involvement was crucial, and this PhD would not exist without your contribution.

Finally, I am beyond grateful for the support of my family and friends, who have stood by me throughout this journey, encouraging me, especially when I doubted myself. A special thanks goes to my partner, Jan, whose unconditional love and support have been my anchor through it all.

SUMMARY

Classical economic theories view decision-making as a purely cognitive process, governed by rationality and utility maximization (Bernoulli, 1954). However, real-world behavior often deviates from these models, as humans frequently make decisions that appear irrational, driven by emotions, biases, and external influences that traditional economic theories struggle to explain. In response to these challenges, an interdisciplinary field called neuroeconomics emerged, integrating insights from economics, psychology, sociology, and neuroscience to explain the underlying neurobiological mechanisms of decision-making (Bashir et al., 2023). Neuroeconomic research indicates, that decision-making is not based solely on cognitive processes, but requires an integration between cognition and emotion (Bechara & Damasio, 2005; Thayer & Lane, 2000, 2009; Welker et al., 2015).

The central role in this cognition-emotion integration has been ascribed to the autonomic nervous system and the endocrine system. According to the neurovisceral integration model (Thayer & Lane, 2009), self-regulation and adaptability rely on a flexible neural network where the prefrontal cortex (PFC) plays a key role by exerting inhibitory control over subcortical structures. This control allows the suppression of impulsive and reflexive responses, promoting a more deliberate decision-making. One physiological marker of this inhibitory control is heart rate variability (HRV), which measures the variability in time intervals between consecutive heartbeats and reflects the balance between the parasympathetic and sympathetic nervous system activity (Malik, 1996). Higher parasympathetic modulation indicates better self-regulation and adaptability, as it reflects stronger inhibitory control by the PFC over subcortical structures, allowing individuals to better manage impulsive and reflexive responses. For decision-making in risky and uncertain situations, individuals with a higher resting parasympathetic modulation are better equipped to inhibit their initial response to reward cues, leading to less risky decisions. Research generally supports the notion that a higher basal parasympathetic modulation is associated with lower risk propensity, particularly in decisions under uncertainty (Bhatt et al., 2015; Forte et al., 2021). However, some studies do not support these findings (Prell et al., 2024; Ramírez et al., 2015) and results from studies involving decisions under risk are even less consistent (Drucaroff et al., 2011; Prell et al., 2024), suggesting that further research is necessary to draw firmer conclusions.

The second system involved in the integration of cognition and emotion is the endocrine system, which regulates hormonal responses. Testosterone, a steroid hormone, is commonly used to assess the hormonal mechanisms of behavioral dysregulation[1], as it affects risk-taking behavior by enhancing reward sensitivity through the modulation of dopaminergic

[1] Hormones are crucial in regulating behavior and can affect risk-taking, which may be adaptive in some contexts. However, certain hormone levels can also contribute to behavioral dysregulation, leading to maladaptive behaviors like excessive risk-taking. Given that this dissertation does not aim to distinguish between adaptive and maladaptive forms of risk-taking, the term 'behavioral dysregulation' is used more broadly to refer to risk-taking behavior in general.

pathways in reward-related brain regions (Welker et al., 2015). Existing studies generally suggest that a higher basal endogenous testosterone level or exogenously administered testosterone levels are positively associated with riskier financial decisions in the laboratory and in real life (Apicella et al., 2008; Coates & Herbert, 2008; Cueva et al., 2015; Nofsinger et al., 2018; Stanton, Liening & Schultheiss, 2011; Van Honk et al., 2004). However, the results are not consistent for both sexes and all risk-taking measures (Apicella et al., 2015). Some studies suggest the relationship between testosterone and financial risk-taking is more complex and dependent on psychological and other neurobiological systems (Cueva et al., 2015; Mehta et al., 2015; Nofsinger et al., 2018; Welker et al., 2015). Based on the positive affective neuroendocrinology (PANE) approach (Welker et al., 2015), the association between the hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) and the risk propensity could be moderated by individual differences in reward processing. This processing is related to the behavioral approach and inhibition systems, which are reflected in sociability and neuroticism-anxiety personality traits, respectively (Corr, 2004; DeYoung & Blain, 2020; Welker et al., 2015). Individuals who are oriented towards the behavioral approach system are more sensitive to reward clues, which should amplify the effect of testosterone on risk propensity, whereas individuals oriented towards the behavioral inhibition system are more sensitive to potential threats, which should inhibit the effect of testosterone on risk propensity. Studies on the potential moderating effects of individual differences in reward processing on the association between testosterone levels and risk propensity, are preliminary and should be systematically examined in more detail.

The purpose of this dissertation is to answer the main research question on how different physiological (HRV, associated with self-regulation and adaptability, and hormonal mechanism of behavioral dysregulation, as indicated by testosterone levels) and psychological mechanisms (neuroticism-anxiety and sociability personality traits related to behavioral approach and inhibition system, respectively) are associated with risk propensity in decisions under risk and decisions under uncertainty.

We conducted an experiment to collect data for two studies. The first study aims to investigate the relationship between HRV and risk propensity in decisions under risk (Game of Dice Task - GDT - Brand et al., 2004) and under uncertainty (Balloon Analogue Risk Task - BART - Lejuez et al., 2002). In a mixed-sex sample of 82 healthy inexperienced and experienced decision-makers we found no significant association between resting HRV parameters or HRV parameters during decision-making and risk propensity for decisions in both contexts. However, we observed a significant association between the interaction of resting HRV and HRV during decisions under uncertainty and risk propensity (high frequency HRV in normalized units – HFnu; ratio between low frequency and high frequency HRV - LF/HF). More specifically, we found that i) resting HFnu is positively associated with risk propensity only when HFnu during decisions under uncertainty is high, and that ii) resting LF/HF is negatively associated with risk propensity only when LF/HF during decisions under uncertainty is low. Taken together, these findings suggest that a

higher parasympathetic modulation is related to higher risk propensity in decisions under uncertainty only if the parasympathetic modulation did not decrease or is even slightly increased during decision-making. This suggests that individuals who exhibit better self-regulation and adaptability make riskier choices in decisions under uncertainty. These findings are in contrast to our predictions, but could be explained with potential modulating effects of motivational processes (Laborde et al., 2018; Prell et al., 2024).

The second study aims to investigate the effects of personality traits related to the behavioral approach and the inhibition system (sociability and neuroticism-anxiety personality traits, respectively) on the relationship between testosterone levels and risk propensity in decisions under risk (GDT) and decisions under uncertainty (BART). In a mixed-sex sample of 100 inexperienced and experienced decision-makers, we found that basal testosterone levels were positively correlated with risk propensity in decisions under risk in males with low neuroticism-anxiety scores, but were negatively correlated with risk propensity in decisions under risk in males with high neuroticism-anxiety score. However, they were not correlated in i) decisions under uncertainty in males, independent of neuroticism-anxiety, ii) decisions under risk or under uncertainty in males, independent of sociability, and iii) decisions under risk or under uncertainty in females, independent of sociability and neuroticism-anxiety. These results indicate that personality traits related to the behavioral inhibition system, but not behavioral approach system, may affect the relationship between the hormonal mechanism of behavioral dysregulation and risk propensity. However, only in decisions under risk, which provides evidence for the complexity of this relationship in males.

Taken together, our findings support the hypothesis that decision making under risk and under uncertainty is a complex process involving different psychological and neurobiological mechanisms. For firmer conclusions, future studies should aim to replicate these findings in larger sample sizes and considering inclusion of real-life risk-taking scenarios to enhance ecological validity.

Keywords: risk propensity, decisions under risk, decisions under uncertainty, heart rate variability, testosterone, personality traits, neuroticism-anxiety, sociability

POVZETEK

Klasične ekonomske teorije obravnavajo sprejemanje odločitev kot povsem kognitiven proces, v katerem prevladujeta racionalnost in maksimiranje koristnosti (Bernoulli, 1954). Vendar pa vedenje v vsakodnevnem življenju pogosto odstopa od teh modelov, saj ljudje sprejemajo odločitve, ki se zdijo iracionalne, pod vplivom čustev, pristranskosti in zunanjih dejavnikov ter jih klasične ekonomske teorije težko pojasnijo. Kot odgovor na te izzive, se je razvilo interdisciplinarno področje, imenovano nevroekonomija, ki združuje znanje iz ekonomije, psihologije, sociologije in nevroznanosti za pojasnjevanje nevrobioloških mehanizmov v procesu odločanja (Bashir et al., 2023). Raziskave v nevroekonomiji kažejo, da odločanje ni zgolj kognitiven proces, ampak zahteva integracijo med kognicijo in čustvi (Bechara & Damasio, 2005; Thayer & Lane, 2000, 2009; Welker et al., 2015).

Osrednja vloga v tej integraciji kognicije in čustev je pripisana avtonomnemu živčnemu sistemu in endokrinemu sistemu. Model nevrovisceralne integracije (Thayer & Lane, 2009) opredeljuje samoregulacijo in prilagodljivost v povezavi z možganskimi strukturami, v katerih prefrontalni korteks (PFC) izvaja inhibicijski nadzor nad subkortikalnimi strukturami. Ta nadzor omogoča zatiranje impulzivnih in refleksnih odzivov ter spodbuja bolj premišljeno odločanje. Eden od fizioloških kazalnikov tega zaviralnega nadzora je variabilnost srčnega utripa (angl. heart rate variability – HRV), ki meri nihanja v časovnih intervalih med zaporednimi srčnimi utripi in odraža ravnovesje med parasimpatičnim in simpatičnim živčnim sistemom (Malik, 1996). Višja modulatorna parasimpatična aktivnost kaže na boljšo samoregulacijo, saj odraža močnejši inhibicijski nadzor PFC nad subkortikalnimi strukturami, kar posamezniku omogoča boljše obvladovanje impulznih odzivov. Pri sprejemanju odločitev v razmerah tveganja in negotovosti so posamezniki z višjo bazalno modulatorno parasimpatično aktivnostjo bolje opremljeni za zaviranje začetnih odzivov na pričakovane nagrade, kar vodi do sprejemanja manj tveganih odločitev. Raziskave na splošno podpirajo trditev, da je višja bazalna modulatorna parasimpatična aktivnost povezana z nižjo nagnjenostjo k tveganju, zlasti pri odločitvah v razmerah negotovosti (Bhatt et al., 2015; Forte et al., 2021). Nekatere študije teh ugotovitev ne podpirajo (Prell et al., 2024; Ramírez et al., 2015), rezultati raziskav o sprejemanju odločitev v razmerah tveganja pa so še manj dosledni (Drucaroff et al., 2011; Prell et al., 2024), kar kaže na potrebo po nadaljnih raziskavah za trdnejše zaključke.

Drugi sistem, ki je vključen v integracijo kognicije in čustev, je endokrini sistem, ki upravlja hormonske odzive. Testosteron je steroidni hormon, ki predstavlja hormonski mehanizem vedenjske disregulacije[2], saj lahko povečuje nagnjenost k tveganju z večanjem občutljivosti na nagrade prek modulacije dopaminskih poti v možganskih regijah, povezanih z

[2] Hormoni imajo ključno vlogo pri uravnavanju vedenja in lahko vplivajo na tveganje, ki je v določenih kontekstih lahko prilagodljivo. Vendar lahko določene ravni hormonov prispevajo tudi k vedenjski disregulaciji, kar vodi do neprilagodljivih vedenj, kot je pretirano tveganje. Glede na to, da namen te disertacije ni razlikovati med prilagodljivimi in neprilagodljivimi oblikami tveganja, se izraz 'vedenjska disregulacija' uporablja v širšem kontekstu in za opis tveganega vedenja na splošno.

nagrajevanjem (Welker et al., 2015). Obstoječe študije na splošno kažejo, da so višje ravni bazalnega endogenega ali eksogeno apliciranega testosterona pozitivno povezane z bolj tveganimi finančnimi odločitvami v laboratoriju in v vsakdanjem življenju (Apicella et al., 2008; Coates & Herbert, 2008; Cueva et al., 2015; Nofsinger et al., 2018; Stanton, Liening & Schultheiss, 2011; Van Honk et al., 2004). Vendar rezultati niso konsistentni za oba spola in za vse mere sprejemanja odločitev v razmerah tveganja in negotovosti (Apicella et al., 2015). Nekatere študije nakazujejo, da je povezava med testosteronom in finančnim tveganjem bolj kompleksna in odvisna od psiholoških in drugih nevrobioloških sistemov (Cueva et al., 2015; Mehta et al., 2015; Nofsinger et al., 2018; Welker et al., 2015). Na podlagi nevroendokrinološkega teoretičnega okvirja PANE (Welker et al., 2015) bi lahko na povezavo med hormonskim mehanizmom vedenjske disregulacije in nagnjenostjo k tveganju vplivale tudi individualne razlike v procesiranju nagrad, ki so povezane z vedenjskimi sistemi približevanja in umika ter se odražajo v osebnostnih lastnostih družabnosti in nevroticizma-anksioznosti (Corr, 2004; DeYoung & Blain, 2020; Welker et al., 2015). Posamezniki z visoko aktivnim vedenjskim sistemom približevanja so bolj občutljivi na nagradne dražljaje, kar bi moralo okrepiti učinek testosterona na nagnjenost k tveganju, medtem ko so posamezniki z visoko aktivnim vedenjskim sistemom umika bolj občutljivi na potencialne nevarnosti, kar bi moralo zavirati učinek testosterona na nagnjenost k tveganju. Študije o možnih moderacijskih učinkih individualnih razlik v procesiranju nagrad na povezavo med ravnmi testosterona in nagnjenostjo k tveganju so preliminarne in bi jih bilo treba sistematično podrobneje preučiti.

Namen te disertacije je odgovoriti na glavno raziskovalno vprašanje, kako so različni fiziološki (HRV, ki je povezan s samoregulacijo in prilagodljivostjo, in hormonski mehanizem vedenjske disregulacije, merjen s testosteronom) in psihološki mehanizmi (osebnostne lastnosti, nevroticizem-anksioznost in družabnost povezane z vedenjskim sistemom približevanja in umika) povezani z nagnjenostjo k tveganju pri odločitvah v razmerah tveganja in odločitvah v razmerah negotovosti.

Izvedli smo eksperiment, s katerim smo zbrali podatke za dve študiji. Namen prve študije je bil raziskati povezavo med HRV in nagnjenostjo k tveganju pri odločitvah v razmerah tveganja (z uporabo naloge igre s kockami, angl. Game of Dice Task – GDT – Brand et al., 2004) in negotovosti (z uporabo naloge tveganja z baloni, angl. Balloon Analogue Risk Task – BART – Lejuez et al., 2002). V mešanem vzorcu 82 neizkušenih in izkušenih odločevalcev nismo ugotovili pomembne povezave med parametri HRV v mirovanju in HRV parametri med procesom odločanja ter nagnjenostjo k tveganju pri odločitvah v razmerah tveganja in v razmerah negotovosti. Opazili pa smo pomembno povezavo med HRV v mirovanju in HRV med samim procesom odločanja (za HRV parametre, ki kažejo na visokofrekvenčno komponento v normaliziranih enotah, angl. high frequency HRV in normalized units – HFnu in za razmerje med nizkofrekvenčno in visokofrekvenčno komponento HRV, angl. ratio between low frequency and high frequency HRV - LF/HF) in nagnjenostjo k tveganju pri odločitvah v razmerah negotovosti. Ugotovili smo, da je i) HFnu v mirovanju pozitivno

povezan z nagnjenostjo k tveganju le, kadar je HFnu med odločanjem v razmerah negotovosti visok, in da je ii) LF/HF v mirovanju negativno povezan z nagnjenostjo k tveganju le, kadar je LF/HF med odločanjem v razmerah negotovosti nizek. Te ugotovitve skupaj kažejo, da je višja modulatorna parasimpatična aktivnost povezana z višjo nagnjenostjo k tveganju pri odločitvah v razmerah negotovosti le, če se modulatorna parasimpatična aktivnost med sprejemanjem odločitev ni zmanjšala ali se je še celo nekoliko povečala. To kaže, da posamezniki, ki kažejo boljšo samoregulacijo in prilagodljivost, sprejemajo bolj tvegane odločitve pri odločitvah v razmerah negotovosti. Ti rezultati so v nasprotju z našimi pričakovanji, vendar jih lahko razložimo s potencialnim modulatornim vplivom motivacijskih dejavnikov (Laborde et al., 2018; Prell et al., 2024).

Namen druge študije je bil raziskati vpliv osebnostnih lastnosti povezanih z vedenjskim sistemom umika in približevanja (nevroticizem-anksioznost, družabnost) na odnos med ravnjo testosterona in nagnjenostjo k tveganju pri odločitvah v razmerah tveganja (GDT) in odločitvah v razmerah negotovosti (BART). Na mešanem vzorcu 100 neizkušenih in izkušenih odločevalcev smo ugotovili, da je bazalna raven testosterona pozitivno povezana z nagnjenostjo k tveganju pri odločitvah v razmerah tveganja pri moških z nizko oceno nevroticizma-anksioznosti, medtem ko je bila pri moških z visoko oceno nevroticizma-anksioznosti negativno povezana z nagnjenostjo k tveganju pri odločitvah v razmerah tveganja. Nismo pa odkrili pomembnih povezav pri i) odločitvah v razmerah negotovosti pri moških, neodvisno od nevroticizma-anksioznosti, ii) odločitvah v razmerah tveganja ali negotovosti pri moških, neodvisno od družabnosti, in iii) odločitvah v razmerah tveganja ali negotovosti pri ženskah, neodvisno od družabnosti in nevroticizma-anksioznosti. Ti rezultati kažejo, da lahko individualne razlike v osebnostnih značilnostih povezanih z vedenjskem sistemom umika, ne pa tudi individualne razlike v osebnostnih značilnostih povezane z vedenjskem sistemu približevanja, vplivajo na razmerje med hormonskim mehanizmom vedenjske disregulacije in nagnjenostjo k tveganju, vendar le pri odločitvah v razmerah tveganja in le pri moških ter tako zagotavljajo dokaze o kompleksnosti tega razmerja.

Naše ugotovitve podpirajo hipotezo, da je sprejemanje odločitev v razmerah tveganja in negotovosti zapleten proces, ki vključuje različne psihološke in nevrobiološke mehanizme. Za konkretnejše sklepe bi si morali pri prihodnjih študijah prizadevati za ponovitev teh ugotovitev na večjih vzorcih in razmisliti o vključitvi scenarijev tveganega odločanja v vsakodnevnem življenju, da bi izboljšali veljavnost rezultatov.

Ključne besede: nagnjenost k tveganju, odločitve v razmerah tveganja, odločitve v razmerah negotovosti, variabilnost srčne frekvence, testosteron, osebnostne značilnosti, nevroticizem-anksioznost, družabnost

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

sl. – Slovene

EV – (sl. pričakovana vrednost); expected value

EU – (sl. pričakovana koristnost); expected utility

WTP – (sl. pripravljenost plačati); willingness to pay

ANS – (sl. avtonomni živčni sistem); autonomic nervous system

CAN – (sl. centralno avtonomno omrežje); central autonomic network

PNS – (sl. parasimpatični živčni sistem); parasympathetic nervous system

SNS – (sl. simpatični živčni sistem); sympathetic nervous system

HRV – (sl. variabilnost srčne frekvence); heart rate variability

SDNN – (sl. standardni odklon NN intervalov); standard deviation of NN intervals

RMSSD – (sl. kvadratni koren povprečne kvadrirane razlike med sosednjima intervaloma NN); root mean square of successive differences

LF – (sl. nizkofrekvenčna komponenta/pas spektra); low frequency component/band

HF – (sl. visokofrekvenčna komponenta/pas spektra); high frequency component/band

HFnu – (sl. visokofrekvenčna komponenta/pas spektra v normaliziranih enotah); high frequency component/band in normalized units

LF/HF – (sl. razmerje med nizkofrekvenčno in visokofrekvenčno komponento/pasom spektra); low frequency and high frequency component/band ratio

SD2/SD1 – (sl. razmerje med standardno deviacijo vzdolž istovetne črte in standardno devicijo pravokotno na istovetnostno črto v Poincaréjevem grafu); ratio between standard deviation along the line-of-identity and standard deviation perpendicular to the line-of-identity in the Poincaré plot

DFA1 – (sl. detrendna fluktuacijska analiza); detrended fluctuation analysis

HPG – (sl. os hipotalamus-hipofiza-gonade); hypothalamic–pituitary–gonadal axis

OFC – (sl. orbitofrontalni korteks); orbitofrontal cortex

PFC – (sl. prefrontalni korteks); prefrontal cortex

CC – (sl. cingulatni korteks); cingulate cortex

INS – (sl. inzula); insula

HT – (sl. hipotalamus); hypothalamus

AMY – (sl. amigdala); amygdala

BS – (sl. možgansko deblo); brainstem

SYM.N – (sl. simpatični živci); sympathetic nerves

PSYM.N – (sl. parasimpatični živci); parasympathetic nerves

NAcc – (sl. nucleus akumbens); nucleus accumbens

VTA – (sl. ventralno tegmentno področje); ventral tegmental area

CEO – (sl. generalni direktor); chief executive officer

BART – (sl. naloga tveganja z baloni); Balloon Analogue Risk Task

GDT – (sl. naloga igre s kockami); Game of Dice Task

ZKPQ – (sl. Zuckerman-Kuhlman vprašalnik osebnostnih značilnosti); Zuckerman-Kuhlman Personality Questionnaire

Sy – (sl. družabnost); sociability

N-Anx – (sl. nevroticizem-anksioznost); neuroticism-anxiety

ELISA – (sl. encimska imunoadsorpcijska preiskava); enzyme-linked immunosorbent assay

T – (sl. testosteron); testosterone

RST – (sl. Grayev psihobiološki model osebnosti); reinforcement sensitivity theory

BAS – (sl. vedenjski sistem približevanja); behavioral approach system

BIS – (sl. vedenjski sistem umika); behavioral inhibition system

FFFS – (sl. sistem boja-bega-zamrznitve); fight-flight-freeze system

PANE – (sl. pristop pozitivne afektivne nevroendokrinologije); positive affective neuroendocrinology approach

1 INTRODUCTION

Decision-making is a multi-phased process that is generally characterized by two main phases: valuation and choice. In the valuation phase, individuals assign subjective values to potential actions based on their internal state and external environment (Rangel et al., 2008). These subjective valuations, which can be governed by habitual or goal-directed systems, are then compared to make a choice. In contrast to the habitual system, the goal-directed system assigns values to actions by computing action-outcome associations and then evaluates different outcomes. If the value of action-outcome association changes based on the changes in the internal state and external environment, then the goal-directed system allows for a flexible adaptation of behavior to meet the new needs (Daw & O'Doherty, 2014).

The subjective values assigned to actions in the goal-directed system are influenced by a number of variables, including the riskiness of the associated outcome (Tobler & Weber, 2014), the temporal delay with which they occur (Kable, 2014) and the social context (Fehr & Camerer, 2007). In the context of financial decision-making, understanding risk and uncertainty, especially from a neuroeconomic point of view is crucial for understanding how individuals assign value to different financial options and ultimately make choices.

Classical economic theories view decision-making as a purely cognitive process, governed by rationality and utility maximization (Bernoulli, 1954). Early models, grounded in the notion of the homo economicus, viewed individuals as perfectly rational agents, making decisions based on their ability to optimize utility through cost-benefit calculations. These models, built around utility functions in the framework of expected utility theory (EU theory), assumed, that individuals had access to perfect information and made consistent, logical choices aimed at maximizing their personal benefit. However, real-world behavior often deviates from these models, as humans frequently make decisions that appear irrational, driven by emotions, biases, and external influences that traditional economic theories struggle to explain.

The emergence of behavioral economics marked a pivotal shift in understanding decision-making (Kahneman & Tversky, 1979). Behavioral economists recognized that human behavior cannot be fully captured by purely rational models and began integrating psychological insights into economic theory. The introduction of dual-process theories of cognition and emotion highlighted the distinction between fast, intuitive, emotionally driven decision-making and slow, deliberate, rational thinking (Evans & Stanovich, 2013). Behavioral economics demonstrated that emotions and cognitive biases significantly shape decisions. This enriched the field by providing more realistic models of human behavior, yet many underlying mechanisms remained poorly understood.

In recent years, the field of neuroeconomics has emerged as a powerful tool for bridging these gaps by applying neuroscientific methods to study the neurobiological mechanisms of decision-making processes. By employing techniques such as functional magnetic resonance imaging**,** electroencephalography, and measuring physiological markers like heart rate variability (HRV) and concentrations of hormones in saliva or blood samples (e.g., testosterone), neuroeconomics try to offer a more objective view of the interplay between the cognitive and emotional systems during decision-making. This interdisciplinary approach integrates insights from economics, neuroscience, and psychology, allowing researchers to observe how different neurobiological mechanisms coordinate the processing of risk, and uncertainty (Camerer et al., 2005).

This dissertation **aims** to contribute to the understanding of how different physiological (HRV, associated with self-regulation and adaptability and hormonal mechanism of behavioral dysregulation[3], as indicated by testosterone levels) and psychological mechanisms (neuroticism-anxiety and sociability personality traits related to behavioral inhibition and approach system, respectively) are associated with risk propensity in two decision-making contexts: under risk and under uncertainty. The **goal** is to conduct two studies that explore the integration of cognition and emotion in decision-making within these contexts. The first study investigates the relationship between self-regulation and adaptability as indicated by HRV and risk propensity in decisions made under conditions of risk and uncertainty. The second study examines the moderating effects of personality traits (specifically neuroticism-anxiety and sociability) on the relationship between hormonal mechanism of behavioral dysregulation as indicated by basal testosterone levels and risk propensity in decisions under both risk and uncertainty.

The dissertation is organized as follows. Chapter 2 presents the theoretical foundation for this research, beginning with an overview of decision-making theories under risk and uncertainty from the perspectives of classical economics, finance, and behavioral economics. This is followed by an introduction to the field of neuroeconomics and a discussion of the theoretical frameworks for examining the relationships between self-regulation and adaptability (as indicated by HRV) and risk propensity in decision-making under risk and uncertainty, as well as the role of hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) and personality traits related to behavioral inhibition and approach systems (neuroticism-anxiety and sociability personality traits, respectively) in these decision-making contexts. Chapter 3 provides a critical review of the literature on both HRV and testosterone in relation to decision-making under risk and under uncertainty. Chapter 4 explains the methodology used in both studies, detailing the procedures, measures, and analyses conducted to test the proposed associations. Chapter 5

[3] Hormones are crucial in regulating behavior and can affect risk-taking, which may be adaptive in some contexts. However, certain hormone levels can also contribute to behavioral dysregulation, leading to maladaptive behaviors like excessive risk-taking. Given that this dissertation does not aim to distinguish between adaptive and maladaptive forms of risk-taking, the term 'behavioral dysregulation' is used more broadly to refer to risk-taking behavior in general.

presents the results of the studies, while Chapter 6 discusses these findings in relation to the existing literature, highlighting both theoretical and practical contributions. Finally, Chapter 7 offers a conclusion, summarizing the key findings and discussing the practical implications of the research.

2 THEORETICAL BACKGROUND

In the following section, the theoretical foundations of this research are presented. This includes an explanation of the theoretical distinction between decision-making under risk and decision-making under uncertainty. The section provides a summary of the theoretical background drawn from classical economics, finance, and behavioral economics to explore the concept of risk propensity in both contexts, decision-making under risk and under uncertainty. Additionally, the section introduces the field of neuroeconomics and provides the theoretical framework for examining the relationship between self-regulation and adaptability (as indicated by HRV) and decision-making under risk and uncertainty, as well as the role of hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) in decision-making in both contexts.

2.1 Risk and uncertainty

Defining risk is a complex task, as it is context-dependent and audience-specific. In everyday language, risk is often associated with potential losses (Oxford Learner's Dictionary, 2024). For example, managers tend to view risk as a function of the magnitude of potential losses (March & Shapira, 1987), whereas medical clinicians perceive risk as either a potential loss or harm to oneself or in relation to others (Furby & Beyth-Marom, 1992). However, in decision theory, risk is typically defined as the sensitivity to the variance of expected outcomes (Markowitz, 1952). This sensitivity is referred to as risk preferences and can vary from risk averse to risk seeking. Thus, risk-taking refers to choosing an option with a higher degree of outcome variability, or in other words, a wider range of possible outcome (Figner & Weber, 2011).

It is important to distinguish between risk and uncertainty, as these terms are often used interchangeably but have distinct meanings in decision theory (Ellsberg, 1961; Knight, 1921). Risk refers to situations with known probability distribution of possible outcomes. Uncertainty, on the other hand, refers to situations in which the likelihood of possible outcomes is unknown to the decision maker (Platt & Huettel, 2008). Both concepts are differentiated by their relative degree of uncertainty, depending on the amount of information about the expected outcome and are positioned on a continuum from complete ignorance, in which not even possible outcomes are known, to certainty, in which only a single outcome is known (Weber & Johnson, 2009).Various theorists have used different terminology to describe these concepts, such as unambiguous versus ambiguous probability (Ellsberg, 1961), risk versus uncertainty (Knight, 1921), and precise or sharp versus vague

probability (Savage, 1954). However, they all essentially refer to the same concepts. Neurobiological research further demonstrates that decision-making under risk and decision-making under uncertainty engage distinct brain circuits (Blankenstein et al., 2017; Huettel et al., 2006; Schultz et al., 2008). It is also possible that risk and uncertainty recruit a common brain mechanism, albeit to different degrees, triggering stronger responses to uncertain or risky choices (De Groot & Thurik, 2018).

In decision theory, decisions under risk and uncertainty are typically studied in the context of monetary payoffs, involving lotteries with known and unknown probabilities, respectively (Harrison & Rustrom, 2008). However, not all studies employ adequate measures of decisions under risk and decisions under uncertainty, which can lead to confusion of the concepts and erroneous conclusions (De Groot & Thurik, 2018).

2.2 The classical economics view

The understanding of valuation and choice, the two main phases of decision making, has evolved over time and across various disciplines (Tobler & Weber, 2014). Initially, economists proposed that decision makers assign values to risky options by calculating the expected value (EV) of an option, which is the product of the potential outcomes and their associated probabilities, as is shown in equation (1). In the subsequent step, when making a choice between several risky options, the decision maker should choose the one with the highest expected value (Tobler & Weber, 2014). Although elegant and simple, this rule does not sufficiently explain decision-making under risk, as evidenced by the St. Petersburg's Paradox. In this paradox, the theoretically infinite expected value of a gamble does not align with typical human behavior, as most people would reject this gamble in favor of a large finite sum (Tobler & Weber, 2014).

$$EV(X) = \sum_x p(x) * x \tag{1}$$

In response to these challenges, classical economists developed the expected utility theory, which considers the subjective value (utility) that individuals assign to outcomes (Bernoulli, 1954). Utility is modeled through functions that vary depending on risk preferences, with concave functions representing risk aversion and convex functions representing risk-seeking behavior. These functions describe how increases in wealth yield diminishing returns in utility for risk averse individuals, a concept known as diminishing marginal utility. For example, an increase of 10,000 EUR from 0 EUR to 10,000 EUR results in a greater increase in utility than an increase in wealth from 20,000 EUR to 30,000 EUR (Tobler & Weber, 2014).

Conversely, risk-seeking preferences result in a convex utility function, which represents increasing marginal utility. This indicates the opposite, that increase in wealth at higher initial levels results in greater utility than the same increase in wealth at lower initial levels. Thus, the exponent of the utility function describes the curvature and serves as an index of

the decision maker's risk preferences. As implied by these utility functions, a risk-averse decision maker would be more inclined to select the certain option in comparison to a risky one, as it would result in greater utility. Conversely, a risk-seeking decision maker would be more likely to select the risky option over a certain one for the same reason (Tobler & Weber, 2014).

In the subsequent phase of the decision-making process, the decision maker continues to adhere to the maximization rule. However, rather than selecting the option with the highest expected value, they select the option with the highest expected utility. As equation (2) shows, the EU of a gamble X is calculated by summing utilities of the outcomes x (u), each weighted by its probability (p). Furthermore, when making a choice, the decision maker adheres to certain choice axioms, including the completeness axiom, transitivity axiom, and the independence axiom, which translates into very rational behavior (Von Neumann & Morgenstern, 1944). These axioms posit, that the decision maker is always capable of ranking preferences between different outcomes, consistently ranking these lotteries, and that their preference ordering of two lotteries in the presence of a new outcome common to both remains unchanged, respectively. These decision rules suggest, that the decision maker is rational, completely informed, and infinitely sensitive when making a choice (Edwards, 1954).

$$EU(X) = \sum_x p(x) * u(x) \tag{2}$$

In contrast to decisions under risk, in decisions under uncertainty, the probabilities assigned to uncertain options are not objectively known; rather, they are subjective and reflect the decision maker's beliefs and perceptions of the likelihood of different outcomes (Savage, 1954). In the context of both types of decision-making, decision makers consistently demonstrate a preference for those options with which they are more familiar, a phenomenon known as ambiguity aversion (Ellsberg, 1961). This phenomenon has been observed in numerous settings, including insurance (Alary et al., 2013) and financial trading (Ju & Miao, 2012; Maenhout, 2004).

In summary, classical economists defined risk propensity in decision making under risk and decision making under uncertainty through the lenses of the utility function and rational choice, which categorizes decision makers as risk-averse, risk-seeking, or risk neutral. This categorization is based on the preference for certain versus uncertain outcomes. While this normative and mathematical approach to modeling decisions under risk and uncertainty is appealing, it systematically violates its fundamental principles in actual decision-making (for a review see Starmer, 2000). For example, it cannot explain why decision makers simultaneously purchase insurance (indicating risk aversion) and lottery tickets (indicating risk-seeking).

2.3 The behavioral economics view

Behavioral economics emerged in response to the descriptive challenges of classical models, integrating psychological insights to better capture decision-making under risk and uncertainty (Glimcher & Fehr, 2014). The most influential behavioral theory of decision-making under risk is the prospect theory (Kahneman & Tversky, 1979). In contrast to classical economists, behavioral economists believe, that the decision-making process does not start with valuation, but with the representation phase in which decision makers identify acts and outcomes that are associated with a particular problem. This phase is typically influenced by framing or other editing operations, such as acceptation, rounding, coding, combining, and cancellation (Kahneman & Tversky, 1979). Framing is a cognitive process that influences representation by involving basic operations to simplify and provide basic context for a choice (McDermott, 2001). In monetary choices, framing typically contributes to decision making by describing potential options in terms of losses and gains and probabilities (Fox & Poldrack, 2014).

The subsequent valuation phase in the prospect theory introduces a value and weighting function that diverges from utility function of the EU theory. First, the value function is reference-dependent, meaning it evaluates gains and losses relative to a reference point, typically the status quo. This reference point typically represents the status quo but, in some cases, it may be determined by the decision maker's goals (Heath et al., 1999) or experiences (Koszegi & Rabin, 2006). Second, the value function is concave for gains, indicating risk aversion, and convex for losses, indicating risk-seeking behavior, with a steeper slope for losses than equivalent gains and thus reflecting loss aversion, the third distinction from utility function in the EU (Fox et al., 2015).

In addition to the value function, behavioral models incorporate a weighting function that captures how decision-makers perceive probabilities. Unlike the objective probabilities used in the EU models, decision weights are subjective and exhibit an inverse-S-shaped curve. This curve suggests that decision-makers overestimate low probabilities, while underestimate high probabilities (Fox & Poldrack, 2014). These patterns can explain paradoxical behavior such as the tendency to purchase lottery tickets and to over-insure against unlikely events (Barseghyan et al., 2013; Boyer & Vorkink, 2014; Wakker, 2001).

An inverse-S-shaped weighting function reinforces the risk preferences implied by the value function for moderate to high probabilities, contributing to risk aversion for gains and risk seeking for losses. Conversely, the weighting function reverses the risk preferences implied by the value function for low probabilities, leading to risk seeking for low-probability gains and risk aversion for low-probability losses (Fox et al., 2015). Thus, it can explain the fourfold pattern of risk preferences observed in empirical studies, including the tendency to purchase lottery tickets and to over-insure against unlikely events (Barseghyan et al., 2013; Boyer & Vorkink, 2014; Wakker, 2001).

In the choice phase, decision makers calculate the value of a prospect (or option) by multiplying the value and decision weight, a process similar to that employed in the EU theory. However, they do not adhere to the maximization rule in a strict manner. Instead, they make decisions based on a combination of principles derived from the behavioral approach to decision making, including framing, reference dependence, loss aversion, overweighting and underweighting of low and high probabilities, respectively (Fox & Poldrack, 2014)

Prospect theory describes decisions under risk. However, it has also been extended to decisions under uncertainty through cumulative prospect theory, which introduces separate weighting functions for gains and losses and adjusts for the cumulative probabilities of different outcomes (Tversky & Kahneman, 1992).

Although prospect theory and cumulative prospect theory successfully explain some known paradoxes and certain real life irrational behaviors (Camerer, 1998; Kahneman et al., 1991), it remains unsatisfactory in some aspects of the descriptive approach to decision making under risk and uncertainty. First, one of the general problems of the prospect theory lies in its broad parameterization. To account for individual differences in risk preferences, weighting functions, loss aversion, and reference points, the theory requires six parameters to describe behavior. This high level of flexibility allows the unrestricted version of prospect theory to predict almost any behavioral pattern, such as the observation that individuals in learning situations often underweight rather than overweight small probabilities (Camerer, 1998). This complexity exceeds that of the models, which prospect theory was intended to replace, and introduces practical difficulties with behavioral fitting, as the parameters are not always independent. For example, choices involving mixed gambles can be explained by varying risk preferences for gains and losses or by loss aversion, leading to overlapping interpretations (Symmonds, 2011).

Second, the prospect theory remains primarily a descriptive model of behavior in specific circumstances, rather than offering a detailed explanation of underlying cognitive or neurobiological mechanisms, which would enhance its ability to predict behavior across varying contexts. The prospect theory does not specify which cognitive processes are involved and how they are implemented in the brain. For example, the prospect theory does not specify how reference points are set (Baillon et al., 2020). Although the neural basis of the prospect theory has been explored and has also successfully demonstrated that the brain does not conform to the predictions of the EU theory (De Martino et al., 2006; Hsu et al., 2009; Tom et al., 2007), these theories have primarily focused on some narrow aspects of the prospect theory (e.g., framing effects, binary mixed gambles, win-lose gambles). Consequently, prospect theory remains an extension of the EU theory (Harrison & Rutström, 2009), highly applicable and effective, but only in specific scenarios (Symmonds, 2011).

Third, prospect theory does not adequately address the role of emotions and affective states in decision-making. Emotional influences can shape how individuals perceive gains and

losses and how they evaluate risks, yet prospect theory largely focuses on cognitive biases and distortions without integrating these emotional factors. This omission limits its explanatory power in emotionally charged decision contexts, such as those under risk and uncertainty. Neuroscience has begun playing a key role in research of decision-making because it allows for direct measurement of structural and functional correlates/surrogates of thoughts and feelings (Camerer et al., 2005). Some of the most influential neural theories of decision-making under risk and uncertainty emphasize the importance of emotions and feelings in the decision-making process (Bechara & Damasio, 2005; Loewenstein et al., 2001). This line of research demonstrates, that emotional responses are not merely secondary to cognitive processes but are, in fact, integral to how people make choices, suggesting that an accurate model of decision-making must incorporate both cognitive and emotional elements.

Finally, the prospect theory is part of the description-based paradigm, which assumes that decision makers are given complete and explicit information about outcome values and probabilities. However, relatively few situations in real life match these characteristics. Real life situations typically align with the experience-based paradigm, in which decision variables are learnt through trial-and-error feedback (Garcia et al., 2021). The translation of descriptive-based decision problems into experience-based decision problems revealed the existence of substantial discrepancies between descriptive and experiential accounts of risk preferences in humans (Hertwig & Erev, 2009; Madan et al., 2019; Wulff et al., 2018). These findings collectively suggest that behavioral economics does not fully capture the nuances of decision making under risk and uncertainty, particularly in learning situations where decision makers must apply newly acquired information to their decision-making process.

2.4 The finance view

An alternative approach to decision making under risk originates from financial theories and is known as the mean-variance model or risk-return model (Markowitz, 1952). In contrast to the EU theory, risky options are not represented as outcome-probability pairs, but as outcome distributions that can be described by their moments. The first moment is represented by the mean of the outcome distribution, while the second moment is represented by the variance of the outcome distribution. As equation (3) shows, willingness to pay (WTP) for a risky option X is calculated as the difference between its mean return (V) and risk (R). Individual differences in risk attitude are captured in the model parameter b, which indicates whether an individual is risk-averse (positive values) or risk-seeking (negative values). In accordance with the risk-return model, decision-makers evaluate risky options as a trade-off between expected returns and associated risk. When making a choice, they aim to minimize the level of risk for a given level of expected return (Tobler & Weber, 2014).

$$WTP(X) = V(X) - bR(X) \tag{3}$$

The mean-variance model is a normative model of decision making under risk, which received its descriptive versions following the development of behavioral paradigm (Sarin & Weber, 1993; Weber, 1997; Weber & Hsee, 1998). In descriptive versions, risk and return are defined as psychological constructs (Figner & Weber, 2011). Risk, in particular, is defined as perceived risk, which can vary between individuals and depends on the content and context of decision making (Weber & Hsee, 1998). The main contribution of these models is that risk attitude is not a stable trait, but it differs across domains based on differences in risk perceptions (Cooper et al., 1988; Weber et al., 2002).

Risk-return models offer several advantages over EU models. Primarily, they can be generalized to accommodate any outcome distribution. Additionally, complex scenarios involving multiple probabilities and outcomes can be distilled into a few descriptive parameters, making these models computationally attractive, conducive to learning, and neurobiologically appealing. Nevertheless, the observation of behavior alone is insufficient to distinguish between EU and risk-return models, as under certain assumptions, such as a quadratic utility function or normally distributed returns, the EU and the risk-return models coincide (Fox et al., 2015). Moreover, risk-return models do not specifically distinguish between decisions under risk and decisions under uncertainty.

As summarized in Table 1, distinct theoretical perspectives offer different approaches to decision-making under risk and uncertainty. Classical economics relies on the expected utility theory, where risk preferences are defined by utility curves and choices are made by maximizing objective outcomes (Bernoulli, 1954; Von Neumann & Morgenstern, 1944). Behavioral economics, on the other hand, introduces prospect theory, where subjective value is relative to a reference point, reflecting loss aversion and probability weighting (Kahneman & Tversky, 1979). Choices are made by maximizing subjective value. However, these choices are not completely rational as they are influenced by heuristics and biases. In finance, risk is conceptualized as the variance of outcome distributions, guiding decisions that minimize risk for a given expected return (Markowitz, 1952). Finally, behavioral finance highlights the role of perceived risk, which is context-dependent and subjective, influencing how individuals balance expected benefits against perceived risks (Sarin & Weber, 1993; Weber & Hsee, 1998).

Table 1: Summary of distinct views on decision-making under risk and uncertainty

	Decisions under	**Theory**	**Reference**	**Definition of risk propensity**	**Valuation phase**	**Choice phase**
Classical Economics	Risk	Expected Utility Theory	Bernouli (1954), Von Neumann & Morgenstern (1994)	Utility curve	Assess objective probabilities and associated outcomes.	Maximization rule
	Uncertainty	Subjective Expected Utility Theory	Savage (1954)	Utility curve	Assess subjective probabilities and associated outcomes.	
Behavioral Economics	Risk	Prospect Theory	Kahneman & Tversky (1979)	Combination of the valuation and weighting function	Value is relative to a reference point. Value function is concave for gains, convex for losses and steeper for losses (loss aversion). Each outcome is weighted by an individual probability function.	Maximization rule (including biases and heuristics)
	Uncertainty	Cumulative Prospect Theory	Tversky & Kahneman (1992)		Values for gains and losses have separate weighting functions. Each outcome is weighted by the cumulated probabilities separated for gains and losses.	

To be continued

Table 1: Summary of distinct views on decision-making under risk and uncertainty (cont.)

Field	**Decisions under**	**Theory**	**References**	**Definition of risk propensity**	**Valuation phase**	**Choice phase**
Finance	Risk and uncertainty*	Risk-return framework	Markowitz (1952)	Risk is the variance of outcome distribution.	Trade-off between risk (variance of outcome distribution) and expected return (mean of the outcome distribution).	Minimize risk for a given expected return
Behavioral Finance	Risk and uncertainty*	Psychological variations of risk-return framework	Sarin & Weber (1993), Weber & Hsee (1998), Weber & Milliman (1997)	Perceived risk is a psychological construct dependent on content and context.	Evaluate expected benefits and risks.	Trading off expected benefits and perceived risks based on the content and context.

*Notes. *no clear distinction.*

Source: own work.

2.5 The neuroeconomics view

An interdisciplinary field of research emerged in response to limitations of classical and behavioral economics in explaining decision making under risk and under uncertainty. As we discussed in the prior sections, traditional economic theories viewed decision-making under risk and under uncertainty through the lenses of rational cost-benefit analysis. Neuroeconomics, also known as decision neuroscience, is one of the domains of cognitive and behavioral neuroscience (Bashir et al., 2023). Its primary objective is to understand the human decision-making process through the biological micro-foundations of economic cognition and behavior (Camerer et al., 2015). Neuroeconomics is a discipline that integrates various pieces of information from diverse sources, including knowledge from the structure and organization of the nervous system, the relationship between brain structures and functions, and the association between the nervous and endocrine systems. This integration aims to inform the decision-making process (Bashir et al., 2023).

The primary goal of neuroeconomics is to integrate knowledge from neuroscience, psychology, and sociology, in order to provide a more comprehensive understanding of economic behavior. In many ways, neuroeconomics has succeeded in its initial goal: it has identified and explained several neural mechanisms that underlie decision-making processes, particularly in contexts involving risk and uncertainty. This is a significant achievement, as it has provided empirical insights into how the brain processes risks, rewards and uncertainty. However, the next, and perhaps more difficult challenge, lies in systematically integrating this diverse knowledge into a unified framework that would enable a systematical explanation of economic behavior on multiple levels of analysis i.e., neural, psychological, and sociological. One potential issue with such a unified integration of neuroeconomic knowledge in multiple layers is that the methods and findings from these disciplines operate on different scales and paradigms. For instance, neuroscience typically focuses on neural circuits, neurotransmitters, and brain regions involved in decision-making, often relying on experimental tasks that are highly controlled but do not always capture all the aspects of real-world economic behaviors. This limitation is partly due to the controlled nature of the experiments and also to the technical constraints of the measuring equipment used in neuroscience. In contrast, psychology often emphasizes cognitive and emotional processes, such as decision biases or motivational drives, which are shaped by individual experiences. Meanwhile, sociology takes a broader perspective, considering how social norms, cultural context, and structural inequalities influence economic behavior. Integrating these perspectives is challenging because each field offers its own explanations and methodologies that do not always translate seamlessly across levels.

Another critical challenge is ensuring ecological validity – the extent to which laboratory-based findings translate to real-world decision-making. In experimental settings, variables can be tightly controlled, but real-world decision-making often involves layers of complexity, uncertainty, and social influence that are difficult to replicate in experimental

environments. For neuroeconomic research to have greater applicability, it will be essential to develop methodologies that reflect the complexity of everyday decision-making, ensuring that experimental tasks mirror real-world scenarios more accurately. One potential solution for this issue for future studies might involve field studies, real-time behavior tracking, or the inclusion of real-life economic contexts to better understand how individuals make decisions outside the laboratory.

Another key challenge for neuroeconomics is the difficulty of establishing causal links between neurobiological processes and decision-making. Most of the data in neuroeconomics is correlational, meaning that while brain activity can be associated with certain decision-making patterns, it remains unclear whether the observed neural processes are directly driving these behaviors or merely reflecting them. This limitation is partly due to the complexity of the brain and neurobiological systems itself, but it is also influenced by ethical constraints. Many of the more invasive methods that could allow researchers to directly manipulate brain activity for example, can raise ethical concerns, especially when used in healthy individuals. Consequently, researchers are often limited to non-invasive methods, which are primarily correlational in nature.

Despite these challenges, there are experimental approaches that can help bridge the gap between correlation and causation. For example, transcranial magnetic stimulation allows for the temporary disruption or stimulation of specific brain regions, providing insights into how those areas contribute to decision-making processes. Similarly, methods like pharmacological manipulation or lesion studies in clinical populations offer another pathway for exploring causal relationships. However, these methods must be used carefully, as they come with ethical implications related to participants' safety, potential long-term effects, and the broader question of whether it is appropriate to alter brain function for experimental purposes. As neuroeconomics continues to evolve, finding a balance between exploring causal relationships and adhering to strict ethical standards, will be critical for advancing the field responsibly.

Thus, while neuroeconomics faces these challenges, it has, in our opinion nonetheless made significant progress in achieving its initial goal: identifying neural mechanisms that underlie decision-making processes, and explaining how they function, particularly in contexts involving risk and uncertainty. Despite advances in mapping the brain regions and neural circuits involved in decision-making, one of the fundamental questions remain to be answered: who or what is ultimately making the decision? Is it the brain, the mind, or the people? While neuroeconomics has contributed to the objective measurement of neurobiological processes in decision-making, it has yet to provide a definitive answer to this question.

We now understand that decisions are not purely the result of rational, cognitive processes. Instead, they emerge from the dynamic interplay between two primary systems: the cognitive system, which engages in analytical, logical reasoning, and the emotional system, which

processes feelings, values, and subjective experiences. The interaction between these systems is crucial for understanding decision-making, particularly in uncertain and risky situations.

According to the dual process theory, humans make both strategic decisions with rational-analytical processing and intuitive decisions with intuitive-experiential processing (Epstein et al., 1996). If uncertainty is high, i.e., if the decision situation does not provide suitable cues for a strategic decision, the intuitive–experiential system may play a greater role compared to the rational–analytical system (Starcke & Brand, 2012). It is assumed that the cognitive and emotional states during decision making correspond to certain somatic states, depending on the adaptability to the risky and uncertain conditions, which in turn influence the current decision making (Dunn et al., 2006; Starcke & Brand, 2012; Thayer & Lane, 2009). A central role in this integration between cognitive and emotional states is ascribed to the autonomic nervous system (ANS) and the endocrine system.

In the following chapters, a detailed explanation of the biological foundations of each system will be provided, highlighting how the ANS and endocrine system are associated with decision-making under risk and under uncertainty.

2.5.1 The autonomic nervous system

The nervous system is responsible for managing the selection of appropriate responses and the coordination of bodily systems that interact, when a certain response is required according to sensory inputs. It can be generally divided into the somatic nervous system and the ANS (Kandel & Shandlen, 2021). The somatic nervous system controls voluntary movement of the skeletal muscles, which enables humans to speak, move and behave in certain ways. The ANS is crucial for homeostasis and regulates involuntary physiological processes, including heart rate, blood pressure, respiration, digestion, and sexual arousal. It plays a pivotal role in the regulation of visceral, cardiovascular, neuroendocrine, and behavioral processes which are essential for the survival of the organism and the species (Lowell et al., 2021).

The neurovisceral integration model (Thayer & Lane, 2000, 2009) identified a flexible neural network associated with self-regulation and adaptability that offers a unified framework for understanding the wide range of responses observed across different domains (Thayer & Lane, 2000, 2009). This neural network is controlled by the ANS and is composed of central and peripheral components. The central part of the ANS is represented by the central autonomic network (CAN), which involves several brain structures including the anterior cingulate, insular, orbitofrontal, and ventromedial prefrontal cortices, the central nucleus of the amygdala, the paraventricular and related nuclei of the hypothalamus, the periaqueductal gray matter, the parabrachial nucleus, the nucleus of the solitary tract, the nucleus ambiguus, the ventrolateral medulla, the ventromedial medulla, and the medullary tegmental field (Thayer et al., 2009). Functionally, this network regulates the bidirectional

flow of information between subcortical (lower levels) and cortical structures (higher levels) of the nervous system and is an integral component of an internal regulation system through which the nervous system regulates visceromotor, neuroendocrine, pain and behavioral responses that are essential for survival, such as goal-directed behavior and adaptability (Benarroch, 1993; Laborde et al., 2018).

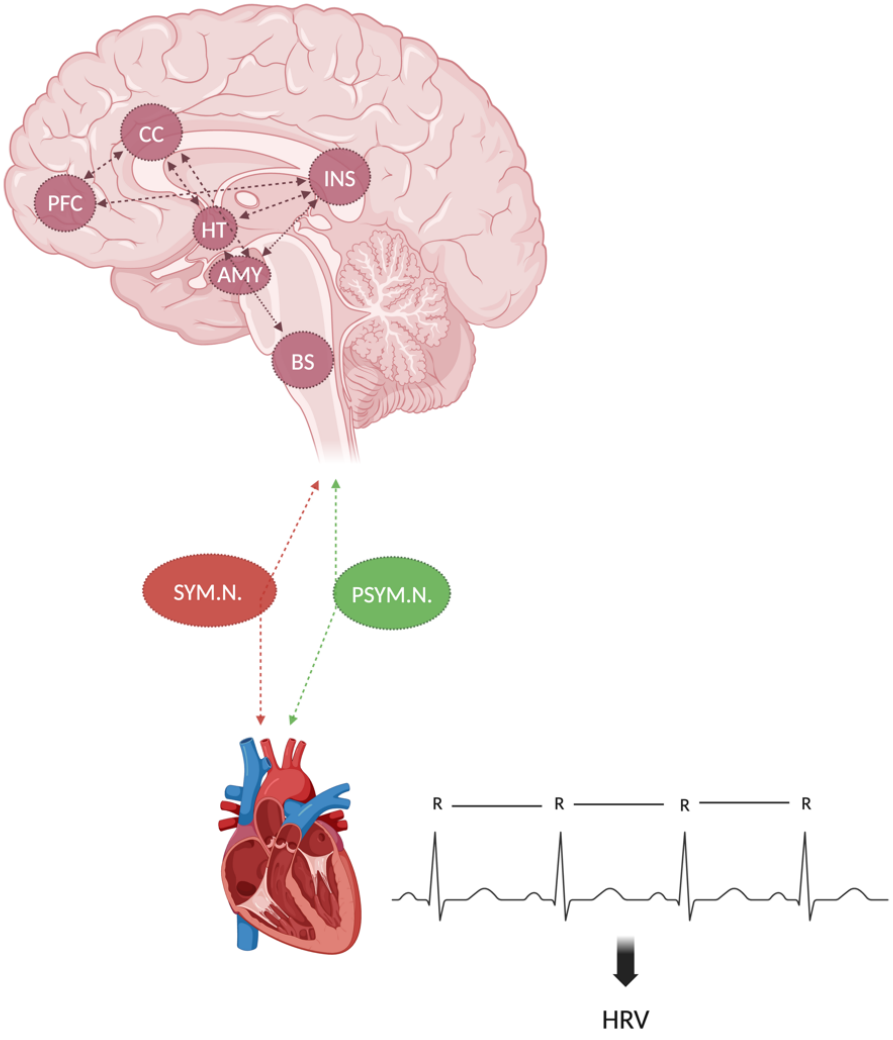
These common inhibitory cortico-subcortical neural circuits serve as the structural link between psychological processes like emotion and cognition (Thayer & Lane, 2009). Subcortical structures, such as the amygdala, are involved in generating bottom-up autonomic responses to emotional and physiological stimuli, playing a key role in initiating immediate autonomic responses to stress, fear, or reward. Broadly, they can be considered as emotional responses. On the other hand, cortical structures, such as the PFC, are primarily responsible for the top-down regulation of emotional and autonomic processes, integrating cognitive and emotional information to modulate physiological responses. The key mechanism of cortical functioning is inhibition, which represents the ability to inhibit impulsive and reflective responses. These inhibitory influences of PFC on the subcortical structures thus allow the organism to flexibly regulate its behavior in response to changing environmental demands (Thayer, 2006).

The CAN communicates with the body's visceral organs and skin by transmitting and receiving information through the efferent nerve fibers of the peripheral autonomic nervous system (ANS). These nerves belong to the two anatomically and functionally distinct branches of the ANS, the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS). These branches typically have opposing effects on a given tissue, allowing for rapid and precise control of bodily functions by balancing their activity. Both systems are constantly tonically active, and the overall response is determined by a dynamic shift in balance between the two. An increase in the activity of one branch results in a decrease in the activity of the other branch (McCorry, 2007). As a result, tissue activity may be either enhanced or inhibited. Each system is dominant under certain conditions. The SNS predominates during an emergency "fight-or-flight" response and during exercise, whereas the PNS predominates during quiet, resting conditions, which promote restorative processes.

The heart is, as the majority of tissues and organs, innervated by both, sympathetic and parasympathetic nerves, allowing for flexible responses depending on the environmental demands. When the SNS dominates, the heart rate increases, whereas when the PNS prevails, the heart rate decreases (Waxenbaum et al., 2021). In a state of rest, the tonic activity of the PNS to the heart is dominant, while the tonic activity of the SNS is barely observed (Mendelowitz, 1996). However, when the body is required to respond to internal and external stimuli, the ANS exhibits phasic activity, which is responsible for creating and fine-tuning appropriate responses (Laborde et al., 2018). Although the heart is innervated with sympathetic and parasympathetic nerve fibers, the main influence on the heart is exerted by the PNS via the vagus nerve. This is because the sympathetic influence on the heart is too slow to produce beat-to-beat changes (Jose & Collison, 1970). Consequently, the heart is

predominantly subject to the parasympathetic inhibitory influence, which is often referred to as the cardiac vagal control, as it can either inhibit or release the sympathetic influence on the heart (Laborde et al., 2018). These alterations in the phasic activity of the ANS are referred to as the modulatory activity of the SNS and PNS and can be evaluated non-invasively through the use of heart rate variability (HRV). Figure 1 presents a simplified schematic representation of the interconnected regions within the central and peripheral nervous systems that regulate autonomic functions.

Figure 1: Schematic representation of the neurovisceral integration model (Thayer & Lane, 2000) involving regions in the central and peripheral nervous system



Notes. PFC = prefrontal cortex, CC = cingulate cortex, INS = insula, HT = hypothalamus, AMY = amygdala, BS = brainstem, SYM.N = sympathetic nerves, PSYM.N = parasympathetic nerves, HRV = heart rate variability. Created with BioRender.com.

Source: adopted from Thayer and Sternberg (2006).

When the fast vagal modulation of cardiac function is diminished, the organism is less capable of tracking the rapid alternations in environmental demands and less able to organize an appropriate response (Thayer & Lane, 2009). Thus, HRV is a marker of the functional integrity and flexibility of the CAN, which reflects the capacity for self-regulation and adaptability, cognitive flexibility, emotional control, and autonomic adaptability. High parasympathetic modulation signifies better overall health, cognitive functioning, emotional regulation and decision-making, whereas low parasympathetic modulation is associated with worse cognitive and emotional regulation (Forte et al., 2019, 2022; Williams et al., 2015).

2.5.1.1 Heart rate variability

HRV is the time variability (in milliseconds) measured between two consecutive heartbeats. This variability is primarily a result of the dynamic interaction between the parasympathetic and sympathetic inputs via the stellate ganglia and the vagus nerve, respectively to the heart through the sinoatrial node (Forte et al., 2022).

HRV is evaluated from an electrocardiogram recording using the distance between the two consecutive R peaks, which is referred to as the RR interval. HRV analysis can be conducted in the time domain, frequency domain, and by using non-linear analysis (Malik, 1996). The time analysis of the HRV signal employs diverse statistical methods to calculate various HRV parameters, including SDNN (standard deviation of the NN intervals), which represents the total HRV, and RMSSD (root mean square of successive differences), which reflects the parasympathetic modulation of the heart rate (Forte et al., 2022). Frequency analysis estimates the distribution of absolute or relative power into four frequency bands (Malik, 1996). The most relevant for this dissertation is the high frequency HRV (HF; 0.15-0.40 Hz) and high frequency HRV in normalized units (HFnu), which reflect the parasympathetic modulation of the heart rate (Forte et al., 2022). Some studies also employ the low frequency HRV (LF, 0.04-0.15 Hz), which is thought to reflect a mix of sympathetic and parasympathetic influences. However, opinions are divided on this matter (Berntson et al., 1997; Malik, 1996). Finally, the low frequency – high frequency ratio (LF/HF ratio) has been considered as an index of sympatho-vagal balance. There are several other HRV parameters obtained by various methods of RR interval analysis (Sassi et al., 2015), but in this dissertation we will limit ourselves to the HRV parameters presented above.

HRV is a physiological phenomenon that is affected by numerous other factors, including age (Natarajan et al., 2020), body mass index (Koenig et al., 2014), circadian rhythm (Boudreau et al., 2012), physical activity (Danieli et al., 2014), sex (Natarajan et al., 2020), and meditation (Tung & Hsieh, 2019).

In the context of decision-making under risk and uncertainty, a higher parasympathetic modulation indicates a more balanced ANS, which is associated with enhanced cognitive flexibility and emotional regulation (Forte et al., 2021). These attributes are crucial in

financial decision-making, where individuals must carefully evaluate potential returns and associated risks.

When an individual's parasympathetic modulation is high, it reflects an effective capacity for self-regulation and adaptability, with a predominance of parasympathetic activity (Thayer & Lane, 2009). This physiological state is characterized by a sense of calmness and alertness, allowing the individual to inhibit impulsive, reflexive tendencies to pursue immediate rewards. Instead, the person is able to engage in more deliberate and composed reasoning, weighing the trade-offs between risk and reward more effectively. As a result, the higher parasympathetic modulation facilitates a better decision-making by enabling the individual to avoid rash or overly aggressive risk-taking (Bhatt et al., 2015).

Conversely, when parasympathetic modulation is low, it indicates a dominant sympathetic activity, which is often associated with heightened stress and impaired emotional regulation (Williams et al., 2015). In this state, individuals may experience reduced cognitive clarity and increased impulsive behavior. This diminished capacity for self-regulation and adaptability can lead to an increased likelihood of making riskier decisions, as the individual may be less able to resist the temptation of high rewards, without adequately considering the potential downsides. Therefore, low parasympathetic modulation can be linked to a predisposition toward excessive risk-taking, driven by heightened emotional reactivity and a reduced ability to engage in reflective decision-making processes.

In summary, HRV serves as a physiological marker of self-regulation and adaptability in decision-making under risk and uncertainty. Individuals with a higher parasympathetic modulation are better equipped to remain calm, process information clearly, and make well-reasoned decisions, while those with lower parasympathetic modulation may struggle to regulate their impulses and emotions, leading to increased risk-taking.

The purpose of this dissertation is to study how baseline HRV, which correlates with self-regulation and adaptability, is associated with risk propensity in decisions under risk and with decisions under uncertainty. Therefore, to study the possible association between HRV and risk propensity in decisions under risk and under uncertainty, we proposed the next hypothesis:

H1: A higher resting modulatory parasympathetic activity is associated with lower risk propensity in decisions under risk and under uncertainty.

2.5.2 The endocrine system

The capacity to produce an adaptive response to environmental challenges is not solely within the domain of the nervous system. However, the nervous system interacts with other bodily systems to organize and manage appropriate responses (Breedlove & Watson, 2020). One such system is the endocrine system, which has evolved as one of the body’s

communication systems using hormones to send messages throughout the body (Neave, 2008). In accordance with the prevailing understanding, hormones are defined as "chemicals secreted by a group of cells in one part of the body and carried through the bloodstream to other parts of the body, where they act on specific target tissues to produce specific physiological effects" (Breedlove & Watson, 2020, p. 138). Hormones are secreted from distinct endocrine glands and regulate the internal metabolism, reproduction, growth, development, response to injury, stress, and environmental factors. In its most basic form of hormone regulation, an endocrine gland releases a hormone that acts on a target cell. However, the same hormone also feeds back to inhibit the gland that released it. More complex endocrine systems typically include the hypothalamus, a brain region involved in the controlling hormone secretion. The hypothalamus also represents the interaction between the nervous and the endocrine systems (Breedlove & Watson, 2020).

Hormones exert their effects on cells that possess corresponding receptor proteins, which recognize the hormones and alter the cell function. Thus, hormones bind to their specific receptors to produce the specific physiological effect (Breedlove & Watson, 2020). Because neurons producing hormone receptors are found only in a limited number of brain regions, it is possible to study how hormones affect behavior by identifying those brain sites and investigating the effects of the hormones that bind on the appropriate site. Some hormones produced at the periphery, can easily pass the brain-blood barrier and bind to receptors within the brain. Consequently, they exert effects on the brain which can influence our behavior. For example, testosterone is a steroid hormone, that can bind to receptors located in subcortical brain structures, such as the ventral tegmental area and nucleus accumbens, which influence emotional processing through the dopaminergic system (Welker et al., 2015). This subcortical network is closely linked to the PFC, which is often regarded as the brain's cognitive center, highlighting how testosterone impacts the integration of cognition and emotion. However, it is essential to recognize that hormones do not cause behavior, they merely increase the probability of certain behavior occurring in the right physiological, psychological, social and other environmental contexts (Neave, 2008). The reciprocal connection between hormones and behavior makes it challenging to determine whether hormones influence behavior by directly affecting neural responses or whether behaving in a particular manner influences hormone production (Breedlove & Watson, 2020).

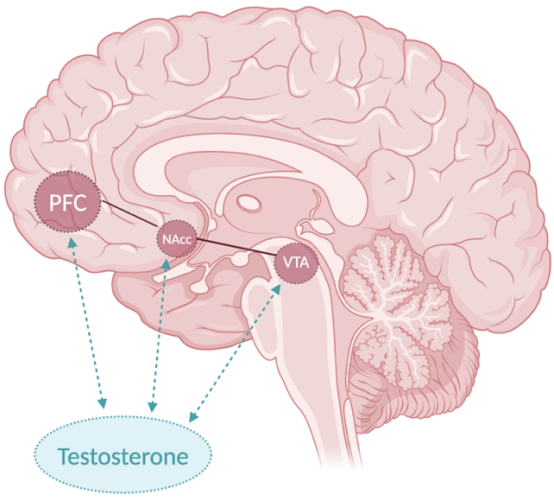
2.5.2.1 Testosterone

Testosterone is a steroid hormone that is regulated by the hypothalamic-pituitary-gonadal axis (HPG axis). It is best known for its role in reproduction (Breedlove & Watson, 2020). In males, testosterone is produced in the testes, while in females, it is produced in the ovaries and in the adrenal cortex, albeit in much smaller quantities (Nelson, 2005). This results in males having significantly higher baseline levels of testosterone (Van Anders et al., 2015).

Researchers often distinguish between two types of testosterone effects: organizational and activational effects (Neave, 2008). However, in this dissertation, we will limit ourselves to the study of the activational effects of testosterone. The activational effects are temporary, non-developmental moment-to-moment effects of testosterone that modulate affect, cognition, and behavior upon administration or release of testosterone, especially after puberty (Sapienza et al., 2009). They are typically assessed using salivary measures, which are relatively easy to collect, store and analyze (Dabbs, 1993). The hormonal concentration in saliva reflects the biologically active or "free" fraction of the hormone in circulation. Unlike the "bound" hormones that circulate in the blood, this fraction is able to cross the blood-brain barrier and influence the central nervous system, thus affecting human behavior (Neave, 2008). Testosterone exhibits a diurnal cycle, with the highest concentrations observed upon waking and subsequent decline across the day, with a flattening in the afternoon (Dabbs, 1990). However, testosterone concentrations remain relatively stable when measured at the same time of day (Liening et al., 2010). Consequently, baseline testosterone can be considered a trait-like index of the effects of the activational effects of testosterone.

Testosterone is related to decision making, yet similarly to HRV, it is challenging to clearly distinguish which phase of decision making is affected, the valuation or the choice. The effects of testosterone on the valuation phase can be explained within the positive affective neuroendocrinology (PANE) perspective (Welker et al., 2015). This theoretical framework holds that testosterone represents a hormonal mechanism of behavioral dysregulation as it affects risk-taking behavior by enhancing reward sensitivity through the modulation of dopaminergic pathways in reward-related brain regions (see Figure 2), which increase the likelihood of behavioral dysregulation (e.g., risk-taking behavior). The reward system of the brain utilizes several key dopamine-linked structures, such as the ventral tegmental area and nucleus accumbes, which project their output to higher level brain structures such as the prefrontal cortex. Testosterone modulates the activity in these brain regions in a way where it stimulates reward-seeking behavior, making rewards more appealing and overshadowing potential risks associated with them, which contributes to behavioral dysregulation and indicates increased risk-taking behavior (Hermans et al., 2010; Van Honk et al., 2004).

Figure 2: Schematic representation of brain regions presumably associated with testosterone's effects on reward processing



Notes. PFC = prefrontal cortex, NAcc = nucleus accumbens, VTA = ventral tegmental area. Created with BioRender.com.

Source: adopted by Welker et al. (2015).

The PANE perspective assumes the relationship between testosterone levels and risk-taking as not linear, thus acknowledging the importance of several potential modulators such as sex, age, cortisol and individual differences in reward processing. Initial work on sex differences in testosterone are thought to account for sex differences in risk-taking (Sapienza et al., 2009). However, these differences could also be explained by other characteristics such as decreased sensitivity to androgens and variability in testosterone levels in women (Wood & Newman, 1999; Yellon et al., 1989). The second potential modulator is age, because post-adolescent aging coincides with decreases in testosterone levels, neural reward-related function and risk-taking behavior (Peper et al., 2018). Another potential modulator is cortisol – a glucocorticoid steroid hormone released as the end-product of the hypothalamic-pituitary-adrenal axis. Cortisol downregulates androgen receptors, inhibits HPG activity and the effects of testosterone on specific tissues. This interaction is referred to as the dual hormone hypothesis, which has demonstrated that testosterone levels are positively associated with risk-taking, only when cortisol levels are low and not high (Mehta et al., 2015).

Finally, individual differences in reward processing and motivation might also modulate the relationship between testosterone and risk-taking, although the research so far is scarce and preliminary. To explain the potential moderating effects of individual differences in reward processing, the knowledge from reinforcement sensitivity theory is incorporated (RST - Gray & McNaughton, 1982, 2000). RST explains individual differences based on the conceptual nervous system that is comprised of the behavioral approach system (BAS), the

behavioral inhibition system (BIS) and the fight-flight-freeze system (FFFS). Each system is activated in response to specific stimuli i.e., the approach system responds to reward cues, the inhibition system responds to conflicting stimuli, and the fight-flight-freeze system responds to threats. Neurobiologically, BAS is linked to the dopaminergic system, BIS primarily to the septo-hippocampal system and the amygdala, and FFFS to the amygdala, hypothalamus, and periaqueductal grey. Individuals with a highly sensitive BAS are generally more motivated to seek rewards, while those with a highly sensitive BIS are linked with anxiety and the inhibition of behavior to avoid negative outcomes. Both systems contain core elements of emotion and motivation related to specific personality traits. BAS reflects the cause of individual differences in approach-related personality traits such as extraversion and impulsiveness, whereas BIS reflects individual differences in avoidance-related personality traits such as neuroticism. Therefore, for an increased risk-taking behavior, one's approach system should be 'high' and the inhibition system 'low', which in terms of personality traits translates to extraverted, sociable individuals, who are not very neurotic and anxious. There have been discussions which personality trait best captures individual differences in BAS, extraversion or impulsiveness (see Smilie et al., 2006 for more detailed discussion). However, there appears to be more evidence in support of the extraversion personality trait in relation to BAS (Krupić & Corr, 2017).

The purpose of this dissertation was to study the possible moderating effects of individual differences in reward processing related to the behavioral approach and inhibition system (as indicated by sociability and neuroticism-anxiety personality traits, respectively), on the relationship between hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) and risk propensity in decisions under risk and with decisions under uncertainty. Therefore, we proposed the next hypotheses:

H2: Basal testosterone levels are positively related to risk propensity in decisions under risk and under uncertainty only in individuals low in the neuroticism-anxiety personality trait.

H3: Basal testosterone levels are positively related to risk propensity in decisions under risk and under uncertainty only in individuals high in the sociability personality trait.

Table 2 summarizes an overview of the theoretical frameworks, constructs, and variables used in this dissertation to explore the relationship between psychological and physiological traits and risk propensity in decisions under risk and uncertainty.

Table 2: Overview of theoretical frameworks, main constructs, and variables for studying risk propensity

<table>
<tr><td>Research question</td><td colspan="2">How are psychological and physiological traits associated with risk propensity in decisions under risk and under uncertainty?</td></tr>
<tr><td>Theoretical framework</td><td>The neurovisceral integration model (Thayer, 2000) posits that HRV, as a marker of parasympathetic modulation, reflects the functional connectivity of the CAN, linking cognitive, emotional, and physiological regulation. A higher HRV indicates a better self-regulation and adaptability by enhancing brain-body communication, leading to improved emotional control, stress management, and decision-making.</td><td>The PANE perspective (Welker et al., 2015) holds that testosterone promotes increased risk-taking behavior by enhancing neural activity in brain regions associated with reward processing.</td></tr>
<tr><td>Main hypotheses</td><td>Higher parasympathetic modulation is associated with lower risk propensity.</td><td>Individual differences in reward processing moderate the relationship between testosterone and risk propensity.</td></tr>
<tr><td rowspan="5">Construct (variable)</td><td>Self-regulation and adaptability (HRV)</td><td>Hormonal mechanism of behavioral dysregulation (testosterone)</td></tr>
<tr><td>Risk propensity in decisions under risk (GDT score)</td><td>Individual differences in reward processing related to BAS (sociability personality trait)</td></tr>
<tr><td rowspan="3">Risk propensity in decisions under uncertainty (BART score)</td><td>Individual differences in reward processing related to BIS (neuroticism-anxiety personality trait)</td></tr>
<tr><td>Risk propensity in decisions under risk (GDT score)</td></tr>
<tr><td>Risk propensity in decisions under uncertainty (BART score)</td></tr>
</table>

Notes. PANE = positive affective neuroendocrinological perspective, HRV = heart rate variability, GDT score = Game of Dice Task score, BART score = Balloon Analogue Risk Task score, BAS = behavioral approach system, BIS = behavioral inhibition system.

Source: own work.

The effects of testosterone on the choice phase may be explained via its effects on the orbitofrontal cortex (OFC) (Mehta & Beer, 2010). OFC is a brain region involved in comparison of different options (Padoa-Schioppa & Conen, 2017). Receptors for androgens such as testosterone are also found in the OFC, which means that testosterone can affect behavior via the OFC (Finley & Kritzer, 1999). Testosterone administration can decouple the OFC from subcortically generated threat reactivity, leading to an increase in impulsive and goal-directed behavior (Heany et al., 2018). Additionally, a more recent study indicates that testosterone shifts an individuals' salience and focus from long-term to short-term goals (White et al., 2020). Collectively, these findings indicate that testosterone can influence the choice phase of decision making by prompting the adoption of more impulsive and also riskier decisions via its effects on the OFC (Peper et al., 2013). Finally, higher baseline testosterone levels are associated with greater risk-taking in competitive environments (Nofsinger et al., 2018; Zilioli & Watson, 2014), indicating that social contexts modulate the relationship between baseline testosterone levels and decision making.

2.6 Theoretical contributions

In this dissertation, a few theoretical contributions are made. The first contribution is to the neurovisceral integration model (Thayer & Lane, 2000) by extending its application to the study of decision-making under conditions of risk and uncertainty. By investigating the association between resting HRV and risk propensity in different decision contexts, this study enhances our understanding of how autonomic regulation affects decision-making processes in uncertain and risky environments. Specifically, this research expands the model to show that self-regulation and adaptability (as indicated by HRV) are involved in managing the trade-offs between risk and reward in decision-making under risk and under uncertainty.

Second, the role of HRV in decision-making under risk (where probabilities are known) versus uncertainty (where probabilities are unknown) is distinguished, following the economic distinction between these two types of decisions (Knight, 1921). Research suggests that HRV might differentially impact decision-making in these contexts, with a higher parasympathetic modulation indicating greater emotional and cognitive control, which is especially important when navigating the ambiguity inherent in uncertain situations (Prell et al., 2024). This distinction adds depth to the neurovisceral integration model by showing that the self-regulation and adaptability reflected by HRV may affect different decision-making strategies depending on the nature of the decision environment.

In terms of the second study, a theoretical contribution is made to the PANE perspective (Welker et al., 2015) by investigating how individual differences in reward processing, particularly in relation to the BAS and BIS, moderate the relationship between the hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) and risk propensity in decision-making under risk and uncertainty. The PANE perspective postulates that testosterone affects reward-seeking behavior by enhancing the activity in reward-related

brain regions (Welker et al., 2015). The current study contributes to this perspective by incorporating the moderating roles of personality traits related to individual differences in reward processing, offering a more nuanced understanding of testosterone's impact on decision-making.

A key contribution of this study to the PANE perspective lies in integrating the individual differences in reward processing related to BIS, which is typically associated with sensitivity to punishment and avoidance behaviors (DeYoung & Blain, 2020). The present research examines how neuroticism-anxiety personality traits might modulate the relationship between testosterone and risk propensity. Individuals with a high BIS may be less likely to engage in testosterone-driven risk-taking, especially under uncertain and risky conditions, where anxiety is heightened. This introduces the idea that the effect of the hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) on decision-making under risk and under uncertainty could be moderated by an individual's tendency to avoid risk due to underlying anxiety or fear of negative outcomes, which is captured by neuroticism-anxiety, a personality correlate of the behavioral inhibition system.

Furthermore, this study contributes to the PANE perspective by exploring the role of individual differences in reward processing related to BAS, which is linked to personality traits such as extraversion and sociability (DeYoung & Blain, 2020). By examining how individual differences in sociability moderate the relationship between testosterone and risk propensity, this research highlights the importance of personality traits in shaping how testosterone affects decision-making under risk and uncertainty. Individuals with a high BAS may be more sensitive to the reward-enhancing effects of testosterone, leading to increased risk-taking. This suggests that the effect of hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) on risk propensity is not uniform, but varies depending on individual differences in the behavioral approach system, as measured with the personality correlate sociability.

By incorporating the individual differences in reward processing into the analysis, this study advances the PANE perspective by proposing that personality traits related to individual differences in approach and inhibition systems (sociability, and neuroticism-anxiety, respectively) interact with hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) to shape decision-making behavior. This extends the framework beyond the traditional view of testosterone as a direct driver of risk-taking behavior, suggesting that the effects of testosterone are dependent on individual differences in reward processing. This insight helps explain the variability in how testosterone affects risk behavior, providing a more comprehensive model of how biological and psychological factors jointly regulate decision-making under risk and uncertainty.

Another significant contribution lies in the differentiation of decision-making under risk versus uncertainty, following the economic distinction (Knight, 1921). This research investigates whether individual differences in behvaioral approach and inhibition systems

related to sociability and neuroticism-anxiety personality traits, respectively differentially moderate testosterone's effects in known risk contexts versus uncertain environments. This distinction adds to the PANE perspective by suggesting that the impact of testosterone on decision-making is context-dependent, with personality traits playing a crucial role in determining whether testosterone enhances risk-taking in risky or uncertain situations. Understanding these nuances enriches the theoretical framework by incorporating contextual sensitivity into the interaction between testosterone, personality traits, and decision-making under risk and uncertainty.

2.7 A neuroeconomic multi-level approach to studying decision-making under risk and uncertainty

To test the second and the third hypothesis, we adopted a multi-level approach to investigate the factors associated with risk propensity in decisions under risk and uncertainty, integrating insights from both neurobiological and psychological perspectives. This approach allows for a comprehensive investigation of how neurobiological mechanisms and individual differences interact in predicting risk propensity in decisions under risk and under uncertainty.

The evaluation of the association between testosterone levels and risk propensity is conducted on a neurobiological level, representing the hormonal mechanism of behavioral dysregulation (e.g., risk-taking). Testosterone serves as a biological marker reflecting sub-personal processes, such as hormonal regulation and its effects on brain activity, which operate at a subconscious level (Welker et al., 2015). By examining testosterone, the study addresses biological influences that may affect decision-making under risk and under uncertainty.

In contrast, the investigation of the potential moderating effects of individual differences in reward processing is carried out at a psychological level. Here, personality traits linked to the behavioral approach system and behavioral inhibition system, such as sociability and neuroticism-anxiety, respectively, are assessed through self-report questionnaires (DeYoung & Blain, 2020). These measures capture conscious experiences and subjective perceptions of personality traits that are correlated to risk and reward sensitivity (Corr, 2004; DeYoung & Blain, 2020; Gray & McNaughton, 2000). Thus, self-report measures are used to explore the psychological moderators that may affect the relationship between neurobiological processes (as indicated by testosterone) and risk propensity.

One might argue, that this approach represents a risk of theoretical multicollinearity, given the potential overlap in underlying neurobiological mechanisms of constructs in the study. However, it is important to recognize that in a human organism, all systems are interconnected, and hormonal, neural, and psychological processes continuously interact (e.g., Bechara & Damasio, 2005; Gray & McNaughton, 2000; Thayer & Lane, 2000); thus, it is impossible to fully separate the underlying mechanisms without considering their

inherent overlap. Nonetheless, the risk of theoretical multicollinearity is minimized in the current study because the conceptual and methodological distinctions between the levels of analaysis are carefully maintained. Testosterone is used as a measure of hormonal mechanism of behavioral dysregulation, affecting risk-taking behavior by increasing neural activity in brain regions involved in reward processing such as the ventral tegmental area and nucleus accumbens (Welker et al., 2015). These brain regions involved in reward processing, together with the amygdala form the neurobiological foundations for conceptual nervous systems of the behavioral approach and inhibition system, respectively (Gray & McNaughton, 2000).

The functioning of both behavioral systems is observable in certain personality traits such as sociability and neuroticism-anxiety (DeYoung & Blain, 2020), which are self-reported and measured at a psychological level in this study. In contrast, the hormonal mechanism of behavioral dysregulation (as indicated by testosterone) is examined at the neurobiological level, providing a distinct perspective on how biological processes are associated to decision-making. By focusing on testosterone as a biological predictor, the study addresses how hormonal influences affect decision-making processes, while personality traits are treated as moderators, providing insight into whether the relationship between testosterone and risk propensity varies at different levels of these traits.

This approach avoids redundancy, as it does not assume that hormonal and psychological factors represent the same underlying construct, but rather that they interact across levels of analysis. The neurobiological and psychological levels are kept conceptually distinct, with the former reflecting biological mechanisms linked to risk-taking behavior and the latter capturing individual differences that might alter how these processes manifest in behavior.

In summary, the second study of this dissertation adopts a multi-level framework to investigate how testosterone (at the neurobiological level) and personality traits (at the psychological level) interact to shape risk propensity in decision-making under risk and under uncertainty. This integration of different levels of analysis helps to ensure a conceptually coherent approach, addressing both biological mechanisms and self-reported psychological processes.

3 LITERATURE REVIEW

In the following section, a brief review of the literature on decision-making and self-regulation and adaptability (as indicated by HRV), as well as decision-making and hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels), is provided. It includes a critical evaluation of the existing research in the field of neuroeconomics, identifying key findings, methodological strengths and limitations, and gaps in the current understanding that warrant further investigation.

3.1 Decision making and HRV

HRV can be associated with both valuation and choice, but the effect on the valuation phase is considered more pronounced. However, due to methodological issues in behavioral decision-making paradigms, it is challenging to distinguish whether the exerted influence targets the valuation or the choice phase (De Groot, 2020; Schonberg et al., 2011). Nevertheless, it is hypothesized that HRV is associated with the valuation phase, as the same brain structures involved in parasympathetic modulation of the heart rate support goal-directed behavior and adaptability (Benarroch, 1993). It should be noted that goal-directed behavior represents one way of assigning subjective values to action-outcome associations and is modulated by the riskiness of the associated outcomes (Rangel et al., 2008). In decisions under risk and uncertainty, it is crucial for a decision maker to possess the ability to inhibit prepotent and reflexive responses. This enables them to achieve long-term goals and prevents them from making irrational mistakes (Thayer, 2006). The parasympathetic modulation of the heart rate is associated with inhibitory prefrontal structures, which can assist in inhibiting riskiness before it takes an excessive toll and thus results in less negative outcomes (Bhatt et al., 2015).

In the last decade, researchers have investigated the possible relationship between HRV and risk propensity in decision-making under risk and under uncertainty, and their results are mixed (Forte et al., 2022). In decisions under uncertainty, a couple of studies found a negative association between risk propensity and resting HF and RMMSD, reflecting the parasympathetic modulatory activity (Bhatt et al., 2015; Forte et al., 2021). One study found a negative correlation between resting HF and risk propensity in decisions under uncertainty, but only in highly anxious individuals (Ramírez et al., 2015). In addition, another study found a negative relationship between resting LF, which represents the sympathetic influences, and risk propensity (Drucaroff et al., 2011). Another study found a positive association between ambiguity avoidance and resting SDNN, which reflects the sympatho-vagal influences (Jiryis et al., 2022). These discrepancies may be due to differences in task designs, sample sizes, and population characteristics.

In contrast to decisions under uncertainty, the relationship between HRV and risk propensity in decisions under risk has been studied less. Three studies found no significant relationship between different HRV metrics, reflecting parasympathetic modulation or sympatho-vagal balance, and risk propensity (Drucaroff et al., 2011; Jiryis et al., 2022; Prell et al., 2024). Furthermore, only one study has explicitly acknowledged the difference between decision-making under risk and under uncertainty and investigated its relationship with HRV and found no significant associations between resting HRV and risk propensity in decisions under risk and under uncertainty (Prell et al., 2024).

Moreover, while some studies have examined HRV reactivity (i.e., HRV during specific decision-making tasks) (Forte et al., 2021; Prell et al., 2024), most research has focused on resting HRV, potentially overlooking the dynamic nature of autonomic regulation during

decision-making. As risk-taking behavior is inherently linked to emotional and cognitive responses, a more nuanced approach that incorporates HRV reactivity and its potential moderating effects is necessary. By addressing these methodological limitations and focusing on baseline HRV and HRV reactivity (during decision-making), the field could move toward a more comprehensive understanding of the relationship between autonomic regulation and risk propensity in decisions under risk and under uncertainty.

Only two studies have examined the associations between risk propensity and HRV reactivity so far, and found that during decisions under uncertainty, HF reactivity was higher in subjects who take fewer risks than in subjects who take more risks (Forte et al., 2021). The other study found contradictory associations in decisions under risk and uncertainty, only in the analysis of different HRV parameters (DFA1, and LF/HF, SD2/SD1, respectively) (Prell et al., 2024). However, Prell et al. (2024) evaluated the change in HRV by calculating the difference between HRV reactivity and resting HRV levels. While this approach may provide insight, we believe it presents potential challenges, as it may not clearly indicate whether the direction of the effect is consistent across all participants. It could be that some participants show an increase in HRV parameters, whereas some show a decrease. In such cases, simply calculating the difference score may hide individual variations in the magnitude and direction of HRV dynamics, leading to potentially misleading conclusions about the overall relationship between HRV reactivity and decision-making. A more nuanced methodological approach would involve analyzing within-subject variability and considering an individual's dynamic in parasympathetic modulation.

3.2 Decision making and testosterone[4]

In general, empirical findings indicate that individuals with higher baseline testosterone levels tend to make riskier financial decisions in a laboratory and in real life (Apicella et al., 2008; Coates & Herbert, 2008; Cueva et al., 2015; Nofsinger et al., 2018; Stanton, Liening & Schultheiss, 2011). However, the results of studies are not consistent for both sexes and for all risk measures of decisions under risk and under uncertainty (see Apicella et al., 2015 for a review). For example, some studies have reported that testosterone is positively associated with risk-taking behavior in gain domain only and in men only (Schipper, 2023). Another study has found that higher testosterone levels correlate with higher risk-taking in women but not in men (Sapienza et al., 2009). Moreover, a more recent multi-study and multi-method investigation observed no significant relationship between baseline testosterone levels and various risk-taking measures in men (Stanton et al., 2021). Furthermore, in one study, individuals with both lower and higher levels were more likely to make risky decisions (Stanton, Mullete-Gillman, et al., 2011). Taken together, these

[4] Some paragraphs in this chapter were published in co-authorship in: Ferjančič, U., Bajrović, F., & Valentinčič, A. (2024). Effects of Neuroticism–Anxiety and Sociability Personality Traits on the Relationship Between Testosterone and Risk Propensity in Finance. *Economic and Business Review, 26*(3), 184-195. *https://doi.org/10.15458/2335-4216.1341*.

observations suggest a more complex relationship between testosterone and financial risk-taking that is dependent on other neurobiological systems including hypothalamic-pituitary-adrenal axis (Mehta et al., 2015), sex (Sapienza et al., 2009), age (Rolison et al., 2014), social context, such as competition (Nofsinger et al., 2018; Zilioli & Watson, 2014), optimism (Cueva et al., 2015) and individual differences related to reward processing (Welker et al., 2015).

Risk-taking behavior has been shown to be related to personality traits such as sensation-seeking, aggression, power motivation, sociability, and social contexts such as interpersonal competition (Welker et al., 2019; Zilioli & Watson, 2014; Zuckerman & Kuhlman, 2000). In finance, CEOs who are higher in extraversion and lower in conscientiousness are less likely to reduce their firm's strategic risk-taking when the value of their stock options increases (Benischke et al., 2019). Individuals high in risk-taking are often characterized by high extraversion and low neuroticism, agreeableness and conscientiousness traits (Nicholson et al., 2005). Extraversion and neuroticism reflect the underlying neuropsychological mechanisms of behavioral approach and inhibition systems, which are related to reward processing (Corr, 2004; DeYoung & Blain, 2020; Welker et al., 2015) and are bidirectionally linked to testosterone levels (El Ahdab et al., 2023; Enter et al., 2014). It is therefore possible that the relationship between testosterone and risk-taking is affected by extraversion and neuroticism. However, we are not aware of any study that addresses the possible effects of particular personality traits, on the relationship between testosterone and decision-making.

Despite these insights, the role of individual differences in reward processing captured by personality traits as moderators of the testosterone-risk relationship remains poorly explored. To date, no study has systematically examined how traits such as extraversion and neuroticism interact with testosterone to affect decision-making under risk or uncertainty. This gap is particularly significant given the theoretical background that individual differences in reward processing (as evaluated by personality traits) may be key to understanding the variability in testosterone's effects on risk-taking behavior (Welker et al., 2015). Given the clear links between personality traits and decision-making under risk and uncertainty, addressing this gap would represent a crucial advance in the field.

The lack of clarity regarding the relationship between testosterone and risk propensity reflects broader challenges within the field of neuroeconomics. One of the main issues is that the dynamic and context-dependent nature of hormone effects is often neglected in favor of more simplistic, one-dimensional approaches. However, there are some studies that have considered the complexity of testosterone functioning and demonstrated that it depends on other neurobiological systems such as the hypothalamic-pituitary-adrenal axis (Mehta et al., 2015) and the mesolimbic dopaminergic system (Welker et al., 2015), social context such as interpersonal competition (Zilioli & Watson, 2014) and psychological constructs such as self-construal (Welker et al., 2019), and optimism about future price changes (Cueva et al., 2015). As neuroeconomics aims to develop comprehensive models that capture the

biological and psychological foundations of economic behavior, it is essential to account for the interactive effects of hormones like testosterone and other potential modulators such as personality traits related to individual differences in reward processing.

In this context, our research aims to fill these gaps by investigating how individual differences in reward processing related to behavioral approach and inhibition systems (as measured by sociability and neuroticism-anxiety personality traits) moderate the relationship between testosterone and risk propensity in decisions under risk and uncertainty. By adopting a more nuanced approach that accounts for the role of personality in modulating hormonal effects, this research aims to offer a more complete picture of how testosterone affects decision-making under risk and uncertainty. In doing so, it advances the field of neuroeconomics by highlighting the importance of contextual and individual differences in shaping hormonal effects on behavior.

4 METHODOLOGY[5]

In the following section, the methodology is explained, including information about the participants, the study protocol, the measures used to assess the constructs, and the data analysis procedures employed.

4.1 Participants

Participants were recruited through the university and its alumni base. Participants with previous or current psychiatric diagnoses, medical conditions affecting autonomic nervous system (e.g., alcohol or drug abuse, diabetes, neurological disease and arterial hypertension), professional athletes and those who violated study instructions (e.g., had breakfast before testing) were excluded from the analysis of the relationship between HRV and risk propensity in decisions under risk and under uncertainty. Exclusion criteria for the analysis of interactional effects between basal testosterone levels and personality traits on risk propensity in decisions under risk and under uncertainty were alcohol or drug abuse, eating, drinking, smoking, chewing or flossing their teeth, taking medicine or engaging in physical activity within 30 minutes before providing saliva samples. Participants were required to provide a signed informed consent form before participating in the study. The research design and all related procedures were approved by the Committee for Ethics and Research at the School of Economics and Business of the University of Ljubljana and by the National Medical Ethics Committee of the Republic of Slovenia.

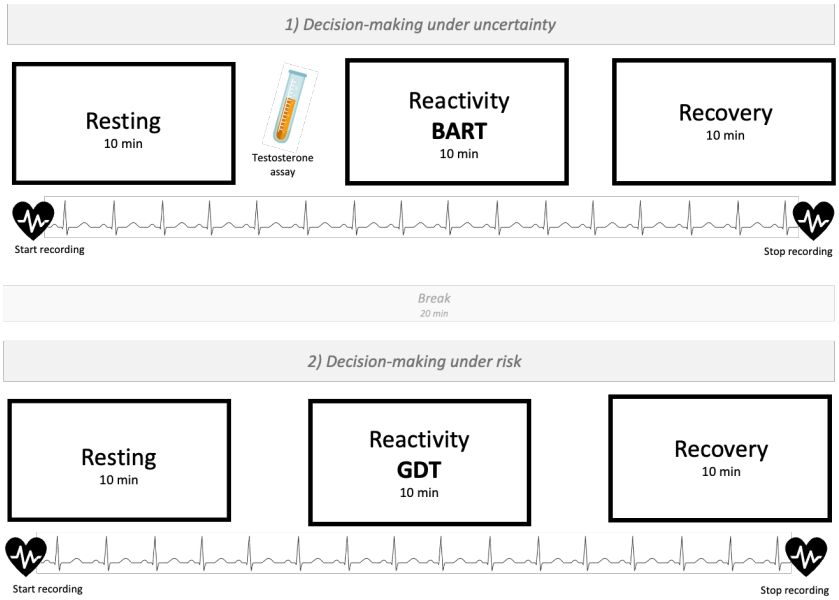
[5] Some paragraphs in this chapter were published in co-authorship in: Ferjančič, U., Bajrović, F., & Valentinčič, A. (2024). Effects of Neuroticism–Anxiety and Sociability Personality Traits on the Relationship Between Testosterone and Risk Propensity in Finance. *Economic and Business Review, 26*(3), 184-195. *https://doi.org/10.15458/2335-4216.1341*.

4.2 Study protocol

The tests were conducted in several sessions from April 2022 to September 2022 in the same time slots from around 7:30 to 9:30 in the morning. Once the participant entered the laboratory, Polar watches and sensor straps were placed around their chests and they were seated. The experiment was conducted in two parts, with a 20-minute break in between (see Figure 3). Each part consisted of a resting, reactivity and recovery phase, each lasting ten minutes. HRV was recorded throughout the experiment. HRV in the resting and recovery phases was recorded for ten minutes while the participants sat with knees at a 90° angle, both feet flat on the floor and hands on their thighs, according to the guidelines (Malik, 1996). Immediately after the first ten-minute resting phase, saliva samples were collected for the hormone assay, which took an average of four minutes each time.

After the initial resting phase, participants completed either the Balloon Analogue Risk Task (BART) (Lejuez et al., 2002) or the Game of Dice Task (GDT) (Brand et al., 2004). The order of experimental tasks assigned to participants was randomized. After the first part of the experiment, the participants took a 20-minute break. Participants then completed the second part of the experiment, but with a different task. At the end of the experiment, participants completed a general questionnaire regarding their age, education, physical activity, and medical history. They also completed the Zuckerman-Kuhlman Personality Questionnaire (ZKPQ) (Zuckerman, 2002) for the assessment of neuroticism-anxiety and sociability personality traits. To stimulate real-life behavior in both tasks, one randomly selected participant from each test group received a voucher for a sports shop equal to their total earnings in BART. Participants were informed in advance about the possibility of receiving a financial reward in the amount of their total earnings in BART.

Figure 3: Study protocol



Source: own work.

4.3 Instruments and measures

4.3.1 Decisions under risk

Decision-making under risk was assessed using the GDT, in which participants are asked to increase their imaginary starting capital (1,000 EUR) within 18 throws of a single virtual dice. Before each throw, the subjects had to guess which number or combination of numbers (2, 3, or 4 numbers) would be thrown. Each choice was associated with certain gains and losses depending on the probability of occurrence of choice (a single number with a winning probability of 1:6 = 1,000 EUR gain/loss; combination of two numbers with winning probability of 2:6 = 500 EUR gain/loss; combination of three numbers with winning probability of 3:6 = 200 EUR gain/loss; combination of four numbers with winning probability of 4:6 = 100 EUR gain/loss). The gains and losses were explicitly described in the test instructions. This allowed the participants to calculate the expected returns and the associated risks. The outcome of the throws was pseudorandomized to ensure that each of the six possible numbers occured three times during the task performance, but in a balanced order. The maximum outcome was 19,000 EUR (if the subject chose a single number and was successful in each throw). The maximum deficit was -17,000 EUR (if the subject chose a single number and was unsuccessful in each throw). To analyze the decisions, choices of one or two numbers (probability of winning was less than 50% and high gains but also high penalties) were classified as “disadvantageous” or risky choices. Conversely, the choices of three or four numbers (probability of winning was 50% or higher, low gains, but also low penalties) were classified as “advantageous” or safe choices. In the GDT, the net score (GDT score) is commonly used as a measure of performance and as a dependent variable for risk propensity in decisions under risk. It was calculated by subtracting the number of risky choices from the number of safe choices. The net score was a quantitative indicator of risk propensity, with a more negative score indicating a higher risk propensity in decisions under risk.

4.3.2 Decisions under uncertainty

Decision-making under uncertainty was assessed using the BART, in which participants inflated 30 balloons in a row and earned virtual five cents for each successful inflation. Each balloon could explode at any time during the process, representing the risk of losing the accumulated gains. Participants were not informed about the probability of an explosion, which was determined via a random selection of numbers between 1 and 128. The selection of the number “1” indicated an explosion. Based on this algorithm, the average “explosion point” for each balloon was 64 pumps. To model excessive risk leading to decreased gains and increased threats, each additional pump increased the potential loss and decreased the relative gain of additional pumps. The average number of pumps on the balloons that did not explode (BART score) was used as the dependent variable in decisions under uncertainty,

conceptualized as the risk propensity in decisions under uncertainty. A higher adjusted average number of pumps indicated a higher risk propensity in decisions under uncertainty.

4.3.3 Heart rate variability

The heart rate signal was recorded using a Polar H10 sensor strap attached to the participants' chests together with a Polar V800 watch. From the RR intervals, the selected time domain parameters, i.e., SDNN, as a function of parasympathetic and sympathetic influences, and RMSSD, a marker of parasympathetic modulation, were obtained. In the frequency domain, LF and LF/HF, reflecting sympathetic-parasympathetic modulation and sympatho-vagal balance, respectively, and HF in absolute and normalized units (HFnu), markers of parasympathetic modulation were obtained (Malik, 1996). Following international guidelines (Malik, 1996) and findings from a recent methodological study on within session stability and reliability of standard HRV parameters (Žunkovič et al., 2023), all three phases consisted of ten-minutes recordings, and only the second five-minute recordings of each phase were used for the analysis.

4.3.4 Testosterone assay

Basal testosterone levels were determined via saliva samples collected after a ten-minute resting period prior to BART or GDT testing. Samples were analyzed according to standard procedures (Tecan, 2019). The certified laboratory used enzyme-linked immunosorbent assay (ELISA) kits to test for free testosterone. The intra-assay coefficient of variation averaged at 5.6%, and the inter-assay coefficient of variation averaged at 8.7%.

4.3.5 Personality traits

Personality traits were assessed using the ZKPQ, which is based on the assumption that personality traits have a strong biological-evolutionary basis and distinguishes between five personality traits: activity, aggression-hostility, impulsive sensation-seeking, neuroticism-anxiety (N-Anx), and sociability (Sy) (see Appendix 2 - Zuckerman, 2002). N-Anx and Sy are correlated with neuroticism and extraversion from the Big Five (DeYoung & Blain, 2020) and are used to measure individual differences in reward processing based on the underlying neuropsychological mechanisms of behavioral inhibition and approach systems, respectively (DeYoung et al., 2021). N-Anx describes being emotionally agitated, anxious, tense or worried, compulsively indecisive, lacking self-confidence, and sensitive to criticism. Sy includes the number of friends one has, and the time one spends with them, outgoingness at parties, and preference for being with others rather than being alone or pursuing solitary activities, thus measuring extraversion (Aluja et al., 2002). Each participant can score between 0 and 10 on each personality trait scale. Higher scores on the N-Anx and Sy scales indicate higher levels of neuroticism-anxiety and sociability, respectively.

4.3.6 Sociodemographic data

A semi-structured sociodemographic questionnaire (see Appendix 3) was used to obtain information on sex, age, decision-making experience (status: student or employed, short description of work tasks and job title), education, daily habits, including alcohol consumption (number of drinks per week), smoking (number of cigarettes smoked per day), sport activity (how often they practiced aerobic or anaerobic sports, when they were last physically active and what kind of activity they did, whether they are they professional sportsmen), coffee consumption (coffee consumption on the testing day) and sleep schedule on the day of testing (hours of sleep, wake up and bedtime). The information collected in this questionnaire was used for exclusion criteria in the study (drinking, eating, smoking, taking medicine or engaging in a physical activity within 30 minutes before providing the saliva samples) and for determining the participants' general health status.

4.3.7 Anthropometric data

A Tanita RD-953 professional digital balance, calibrated in kg, was used to measure participants' weight and other anthropometric data such as body mass index (BMI). The height of each participant was self-reported.

4.4 Data analysis

The following section describes the data analysis procedures for both studies. The first study evaluated the relationship between HRV and risk propensity in decisions under risk and under uncertainty (hypothesis 1). The second study evaluated the potential effects of neuroticism-anxiety and sociability personality traits on the relationship between basal testosterone levels and risk propensity in decisions under risk and under uncertainty (hypothesis 2 and 3).

4.4.1 First study: Association of HRV and risk propensity

The 45-minute recordings of beat-to-beat RR intervals were imported into a software program (Kubios HRV version 3.5.0, Department of Physics, University of Kuopio, Finland). The raw RR interval tachograms were visually inspected to assess the quality of signal acquisition. Artifacts were automatically corrected with a very low, low or medium correction in Kubios, depending on the signal quality of each individual recording. The 45-minute RR interval recording was divided into three ten-minute segments (resting, reactivity, and recovery), and the last five minutes of each segment were analyzed for time- and frequency-domain parameters according to the current standards for short-term HRV recordings guidelines (Malik, 1996). The calculated statistical HRV parameters were the SDNN, RMSSD (in ms) LF and HF (in ms^2), HFnu (in normalized units), and LF/HF ratio in resting, reactivity, and recovery phase. All HRV values, BART score, and GDT score

were skewed and therefore transformed using the natural logarithm (ln). However, all log-transformed variables are given without the prefix *ln*, except in the tables.

Three multiple regression models were analyzed to test the first hypothesis (H1: a higher resting modulatory parasympathetic activity is associated with lower risk propensity in decisions under risk and under uncertainty) and to evaluate the association between HRV and risk propensity in decisions under risk and under uncertainty, including potential confounding variables (sex, decision-making experience). The first model included the following independent variables: resting HRV, sex and decision-making experience. The second model included the following independent variables: HRV reactivity (during each decision-making task), sex and decision-making experience. The final model included the following independent variables: sex, decision-making experience, resting HRV, HRV reactivity, and interaction term between resting HRV and HRV reactivity. All three models were tested for two dependent variables: risk propensity in decisions under risk (GDT score) and risk propensity in decisions under uncertainty (BART score). The assumptions for multiple regression analysis were inspected. To avoid potential problems with high multicollinearity affecting the interaction term, we mean-centered the HRV parameters in the resting and reactivity phase and created an interaction term between both predictors (Hayes, 2022). To interpret a significant interaction, we computed simple slopes using the PROCESS macro (Hayes, 2022). Statistical analyses were performed using SPSS software (version 29.0.2.0 - 20). The level of significance was set at $p < .05$ and corrected for multiple parameters applying the Bonferroni correction ($\alpha = 0.05 / 6$).

4.4.2 Second study: Effects of neuroticism-anxiety/sociability on the association between testosterone and risk propensity

Testosterone levels were standardized separately for men and women using z-scores (Mehta & Josephs, 2010). High testosterone levels in an individual indicate a high value relative to other individuals of the same sex. Personality correlates of the inhibition and approach systems, N-Anx and Sy, as well as the GDT and BART scores were transformed using the natural logarithm (ln) to better approximate the normal distributions. However, all log-transformed variables are given without the prefix *ln*, except in the tables.

The second hypothesis (H2: basal testosterone levels are positively related to risk propensity in decisions under risk and under uncertainty only in individuals low in the neuroticism-anxiety personality trait) was analyzed using a moderated multiple regression model (Hayes, 2022). The dependent variables, GDT score and BART score were used for the risk propensity in decisions under risk and under uncertainty, respectively. Each model included the following independent variables: sex, decision-making experience, basal testosterone levels, neuroticism-anxiety score, and the interaction term between basal testosterone levels and the neuroticism-anxiety score. To avoid potential problems with high multicollinearity affecting the interaction term, the independent variable and the moderator were mean-

centered and an interaction term between standardized testosterone levels within sexes and N-Anx scores (Hayes, 2022) was created. To interpret a significant interaction, a simple slope analysis with the PROCESS macro for R software was used (Hayes, 2022).

To test the third hypothesis (H3: basal testosterone levels are positively related to risk propensity in decisions under risk and under uncertainty only in individuals high in the sociability personality trait), a similar approach was applied. Each model included the following independent variables: sex, decision-making experience, basal testosterone levels, sociability score, and the interaction term between basal testosterone levels and sociability score. Both predictors (standardized testosterone levels within sexes and Sy) were mean-centered to avoid potential problems with high multicollinearity associated with the interaction term. To interpret the significant interaction, a simple slope analysis with the PROCESS macro for R software was used (Hayes, 2022).

The data analysis procedure (testing H2 and H3) was repeated separately for female and male participants. In these additional analyses, the testosterone levels were log-transformed with a natural logarithm to better approximate a normal distribution. The multiple regression model for testing the second hypothesis included the following independent variables: basal testosterone levels, neuroticism-anxiety score, and the interaction term between basal testosterone levels and neuroticism-anxiety score. The multiple regression model for testing the third hypothesis included the following independent variables: basal testosterone levels, sociability score, and the interaction term between basal testosterone levels and sociability score. The level of significance for all analyses was set at $p < .05$.

5 RESULTS

The following section presents the results of both studies. The first part presents the findings of the study of the relationship between HRV and risk propensity in decisions under risk and under uncertainty. The second part presents the results of study of the effects of neuroticism-anxiety and sociability personality traits on the relationship between baseline testosterone levels and risk propensity in decisions under risk and under uncertainty.

5.1 First study: Association between HRV and risk propensity

The data were collected from 104 participants. Fifteen participants were excluded from the analysis because HRV data or data from behavioral tests were missing due to technical issues. Two participants were excluded because they were professional athletes. Three participants were excluded because they were considered outliers. One participant was excluded because of reported allergies and one participant was excluded because of reported mental or neurological disorder. The final sample[6] included 82 participants (mean age =

[6] The final sample that demonstrated a significant interaction effect between resting HFnu and HFnu reactivity, and resting LF/HF and LF/HF reactivity.

28.07 +/- 7.38, range 21 – 49; 50 females), who were tested in two experimental conditions: decisions under risk and decisions under uncertainty. The participants could be divided into two groups based on their decision-making experiences: inexperienced decision-makers (n = 54, mean age = 23.76 +/- 2.27, range 21 – 33; 36 females) and experienced decision-makers (n = 28, mean age = 36.39 +/- 6.65, range 23 – 49; 14 females). The demographic characteristics of the subjects are shown in Table 3.

Table 3: Descriptive statistics for demographic variables, risk propensity scores, and HRV parameters

Variable	**N**	**Min**	**Max**	**Mean**	**SD**
Age	89	21.00	49.00	28.79	7.64
BMI	89	17.50	36.40	23.15	3.39
Smoking (cigarettes per week)	89	0.00	140.00	8.62	25.62
Alcohol (units per week)	81	0.00	18.00	3.06	3.57
Height (in cm)	88	158.00	197.00	173.53	9.43
Weight (in kg)	89	47.05	123.30	69.85	14.30
ln(SDNN) - resting	88	2.86	4.65	3.82	0.33
ln(SDNN) - reactivity	85	3.02	4.48	3.84	0.33
ln(SDNN) - recovery	87	3.18	4.54	3.89	0.34
ln(RMSSD) - resting	88	2.74	4.61	3.64	0.43
ln(RMSSD) - reactivity	85	2.69	4.57	3.71	0.43
ln(RMSSD) - recovery	87	2.87	4.56	3.68	0.41
ln(LF) - resting	88	4.64	9.05	7.00	0.72
ln(LF) - reactivity	85	5.47	8.51	7.01	0.71
ln(LF) - recovery	87	5.16	8.73	7.14	0.76
ln(HF) - resting	88	4.67	8.64	6.31	0.86
ln(HF) - reactivity	85	4.54	8.42	6.36	0.90
ln(HF) - recovery	87	4.72	8.46	6.35	0.86
ln(HFnu) - resting	88	2.01	4.24	3.45	0.50
ln(HFnu) - reactivity	85	2.23	4.41	3.47	0.49
ln(HFnu) - recovery	87	2.46	4.35	3.40	0.43

To be continued

Table 3: Descriptive statistics for demographic variables and HRV parameters for the entire sample of subjects (cont.)

Variable	N	Min	Max	Mean	SD
ln(LF/HF) - resting	88	-0.81	2.52	0.69	0.74
ln(LF/HF) - reactivity	85	-1.52	2.28	0.65	0.77
ln(LF/HF) - recovery	87	-1.22	2.02	0.79	0.65
Mean HR - resting	88	49.57	96.26	68.60	10.60
Mean HR - reactivity	85	50.38	97.72	68.19	10.12
Mean HR - recovery	87	50.28	93.15	68.35	10.33
BART score	87	5.75	79.15	38.62	17.40
GDT score	87	-18.00	18.00	5.45	11.95

Notes. BMI = body mass index, BART score = Ballon Analogue Risk Task score, GDT score = Game of Dice Task score. The discrepancies between the numbers of observations for some variables and the total number of participants included in the analyses (82) are due to missing data because of technical issues.

Source: own work.

5.1.1 Hypothesis 1

A multiple regression model was applied to examine the potential associations between resting HRV parameters and risk propensity in decisions under risk and under uncertainty. We found no significant effects of the resting HRV parameters (SDNN, RMSSD, LF, HF, HFnu, LF/HF) or decision-making experience on risk propensity in decisions under risk (GDT score) and under uncertainty (BART score). However, the effect of sex on risk propensity in decisions under uncertainty was significant in the models including SDNN (b = -0.23, p = .047), RMSSD (b = -0.23, p = .047), LF (b = -0.23, p = .048), HF (b = -0.23, p = .046), HFnu (b = -0.23, p = .045) and LF/HF (b = -0.23, p = .045). When the Bonferroni correction is applied, these results were not significant (Bonferroni threshold = .008).

5.1.1.1 Additional analysis (reactivity)

A multiple regression model was applied to examine the potential associations between HRV reactivity (during decision-making) and risk propensity in decisions under risk and under uncertainty. We found no significant effects of the HRV parameters in the reactivity phase (SDNN, RMSSD, LF, HF, HFnu, LF/HF) or potential confounding variables (sex, decision-making experience) on risk propensity in decisions under risk (GDT score) and under uncertainty (BART score).

5.1.1.2 Additional analysis (resting x reactivity)

A multiple regression model using the interaction term was applied to examine whether resting HRV parameters depend on the HRV reactivity parameters (during decision-making) when predicting risk propensity in decisions under risk (GDT score) and under uncertainty (BART score). We found significant interactions for two HRV parameters i.e., the HFnu and LF/HF ratio. For the significant interaction between resting HFnu and HFnu reactivity, the overall model, in which the dependent variable was the BART score was significant, $F(5, 76) = 2.49$, $p = .038$, and explained 14% of the variance in BART score. As is shown in Table 4, we found a significant interaction between resting HFnu and HFnu reactivity phase on BART scores ($b = 0.45$, $p = .009$), indicating that the effect of resting HFnu on the BART score varied depending on the level of HFnu reactivity. When the Bonferroni correction is applied, the result is only marginally significant (Bonferroni threshold = .008).

Table 4: Multiple regression model predicting BART scores using resting HFnu, HFnu reactivity, their interaction and control variables

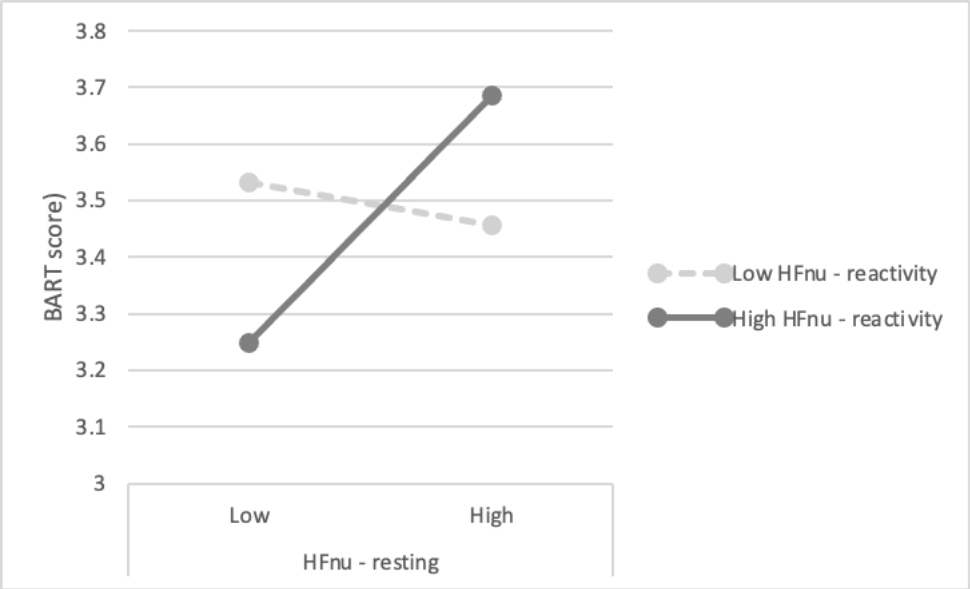
Dependent variable: BART score	b	SE	t	p	95% CI	
					LL	UL
Constant	3.62	0.10	35.05	0.000	3.42	3.83
ln(HFnu) resting	0.17	0.13	1.35	0.182	-0.08	0.42
ln(HFnu) reactivity	-0.02	0.13	-0.18	0.855	-0.29	0.24
ln(HFnu) resting * ln(HFnu) reactivity [a]	**0.45**	**0.17**	**2.68**	**0.009***	**0.12**	**0.79**
Sex[b]	-0.22	0.11	-1.88	0.063	-0.44	0.01
Decision-making experience [c]	-0.03	0.12	-0.27	0.788	-0.26	0.20
Model summary N = 82, $R^2 = 0.14$, F(5, 76) = 2.49, p = 0.038						

Notes. BART score = Balloon Analogue Risk Task score; [a] predictors are mean-centered; [b] 0 = males, 1 = females; [c] 0 = inexperienced decision-makers, 1 = experienced decision-makers. Significance is displayed at p < .05 (*) and p < .01 (**).

Source: own work.

The simple slope analysis revealed that the resting HFnu was associated with BART scores only in subjects with high HFnu in the reactivity phase ($b = 0.41$, $p = .018$, see Figure 4, solid line), but not in subjects with low HFnu in the reactivity phase ($b = -0.07$, $p = .610$, see Figure 4, dashed line).

Figure 4: Risk propensity in decisions under uncertainty (BART score) as a function of HFnu in resting and reactivity phases



Notes. Plotted points represent conditional low and high values (+/- 1 SDs) of resting HFnu and HFnu reactivity. BART score, resting HFnu and HFnu reactivity are log-transformed using a natural logarithm.

Source: own work.

Detailed results of the simple slope analysis are presented in Table 5.

Table 5: Simple slope analysis (HFnu)

Variable	b	SE	t	p	95% CI	
					LL	UL
Low ln(HFnu) reactivity	-0.07	0.14	-0.51	0.610	-0.35	0.20
Mean ln(HFnu) reactivity	0.17	0.13	1.35	0.182	-0.08	0.42
High ln(HFnu) reactivity	**0.41**	**0.17**	**2.42**	**0.018***	**0.07**	**0.75**

Notes. Low ln(HFnu) reactivity = mean - 1 SD; mean ln(HFnu) reactivity = mean value; high ln(HFnu) reactivity = mean + 1 SD. Significance is displayed at p < .05 (*) and p < .01 (**).

Source: own work.

For the second significant interaction between resting HRV and HRV reactivity (LF/HF), the overall model, in which the dependent variable was the BART score, was significant, $F(5, 76) = 2.76$, $p = .024$, and explained 15% of the variance in the BART score. As is shown in Table 6, we found a significant effect of the interaction between resting LF/HF and LF/HF reactivity on BART scores ($b = 0.24$, $p = .005$). The interaction effect is significant with and without applying the Bonferroni correction (Bonferroni threshold = .005).

Table 6: Multiple regression model predicting BART scores using resting LF/HF, LF/HF reactivity, their interaction and control variables

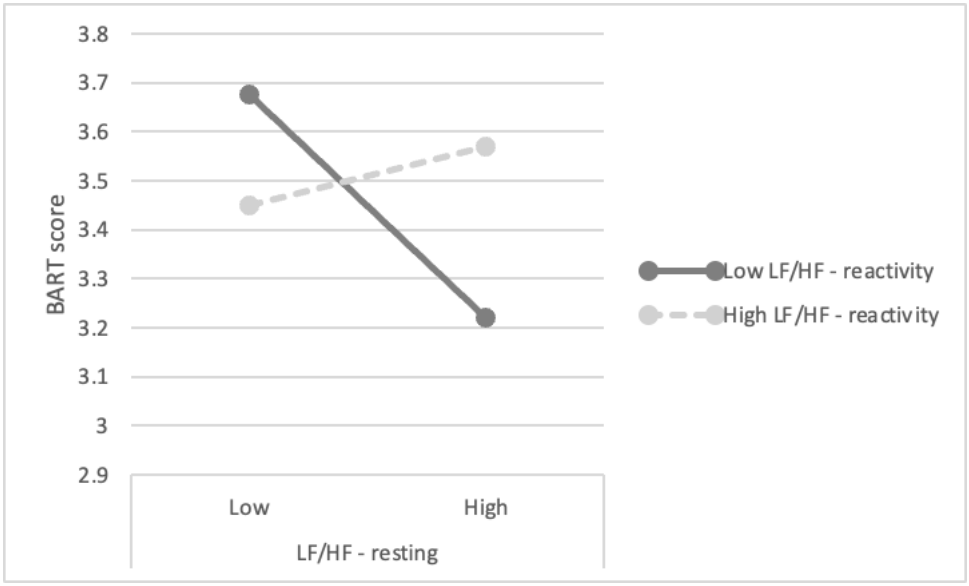
Dependent variable: BART score	b	SE	t	p	95% CI	
					LL	UL
Constant	3.63	0.10	35.73	0.000	0.34	3.83
ln(LF/HF) resting	-0.11	0.08	-1.33	0.189	-0.27	0.05
ln(LF/HF) reactivity	0.04	0.09	0.47	0.640	-0.13	0.21
ln(LF/HF) resting * ln(LF/HF) reactivity[a]	**0.24**	**0.08**	**2.89**	**0.005***	**0.07**	**0.40**
Sex[b]	-0.22	0.11	-1.93	0.057	-0.44	0.01
Decision-making experience[c]	-0.05	0.12	-0.40	0.689	-0.27	0.02
Model summary N = 82, R^2 = 0.15, F(5, 76) = 2.76, p = 0.024						

Notes. BART score = Balloon Analogue Risk Task score; [a] predictors are mean-centered; [b] 0 = males, 1 = females; [c] 0 = inexperienced decision-makers, 1 = experienced decision-makers. Significance is displayed at p < .05 (*) and p < .01 (**).

Source: own work.

The simple slope analysis revealed a significant association between the resting LF/HF and BART scores only in subjects with a low LF/HF in the reactivity phase (b = -0.29, p = .010, see Figure 5, solid line), but not in subjects with a high LF/HF in the reactivity phase (b = 0.08, p = .429, see Figure 5, dashed line).

Figure 5: Risk propensity in decisions under uncertainty (BART score) as a function of LF/HF in resting and reactivity phases



Notes. Plotted points represent conditional low and high values (+/- 1 SDs) of resting LF/HF and LF/HF reactivity. BART score, resting LF/HF and LF/HF reactivity are log-transformed using a natural logarithm.

Source: own work.

Detailed results of the simple slope analysis are presented in Table 7. We found no other significant effects of HRV parameters in the resting and reactivity phases, their interactions or potential confounding variables (sex, decision-making experience) on BART scores.

Table 7: Simple slope analysis (LF/HF)

Variable	b	SE	t	p	95% CI	
					LL	UL
Low ln(LF/HF)	**-0.29**	**0.11**	**-2.64**	**0.010***	**-0.51**	**-0.07**
Mean ln(LF/HF)	-0.11	0.08	-1.33	0.189	-0.27	0.05
High ln(LF/HF)	0.08	0.10	0.80	0.429	-0.11	0.03

Notes. Low ln(LF/HF) = mean - 1 SD; mean ln(LF/HF) = mean value; high ln(LF/HF) = mean + 1 SD. Significance is displayed at p < .05 (*) and p < .01 (**).

Source: own work.

In decisions under risk, no significant effects of the HRV parameters (SDNN, RMSSD, LF, HF, HFnu, LF/HF) in the resting phase, the reactivity phase, their interaction or potential confounding variables (sex, decision-making experience) on the risk propensity were observed.

5.2 Second study: Effects of neuroticism-anxiety/sociability on the association between testosterone and risk propensity[7]

The data were collected from 104 participants. Four participants were excluded from the analysis because testosterone data was missing due to technical issues. The final sample included 100 participants (mean age = 28.94 +/- 7.77, range 21 – 49; 58 females), who were tested under two conditions: decisions made under risk and under uncertainty. Participants were further divided into two groups, inexperienced (n = 59, mean age = 23.59 +/- 1.98, range 21 - 33; 38 females) and experienced decision-makers (n = 41, mean age = 36.63 +/- 6.38, range 23 - 49; 20 females), based on their decision-making experience.

Basic demographics, basal testosterone levels, and risk propensity scores in decisions under risk and under uncertainty by sex are shown in Table 8. Independent samples t-tests were conducted to compare risk propensities in decisions under risk and under uncertainty, personality traits, and basal testosterone levels between females and males. No significant differences were found in Sy scores and in BART and GDT scores between females and males, although males appeared to have higher BART scores, and GDT scores compared to

[7] Some paragraphs in this chapter were published in co-authorship in: Ferjančič, U., Bajrović, F., & Valentinčič, A. (2024). Effects of Neuroticism–Anxiety and Sociability Personality Traits on the Relationship Between Testosterone and Risk Propensity in Finance. *Economic and Business Review, 26*(3), 184-195. *https://doi.org/10.15458/2335-4216.1341*.

females. Compared to females, males had higher basal testosterone levels ($p < .001$) and lower N-Anx scores ($p = .017$). Pearson correlations are presented in Appendix 4.

Table 8: Descriptive statistics by sex

	Male			Female				
Variable	N	M	SD	N	M	SD	t (98)	p	d
Age (years)	42	29.69	7.89	58	28.34	7.67	0.86	0.394	0.17
ln(N-Anx score)	42	1.09	0.81	58	1.41	0.70	-2.15	0.017	-0.44
ln(Sy score)	42	1.50	0.71	58	1.45	0.63	0.35	0.728	0.07
Testosterone (pmol/L)	42	275.82	110.51	58	90.30	58.84	9.91	0.000	2.20
ln(BART score)	42	3.62	0.44	58	3.47	0.53	1.42	0.122	0.29
ln(GDT score)	42	3.11	0.93	58	2.86	1.00	1.27	0.104	0.26

Notes. N = sample size, M = mean, SD = standard deviation, t = t-test statistic with degrees of freedom in the brackets, p = p-value, d = Cohen's effect size, N-Anx = neuroticism-anxiety, Sy = sociability, BART score = Balloon Analogue Risk Task score, GDT score = Game of Dice Task score.

Source: own work.

5.2.1 Hypothesis 2

A moderation analysis was conducted using multiple regression to examine whether the neuroticism-anxiety personality trait moderated the relationship between baseline testosterone levels and risk propensity in decisions under risk (GDT score) and under uncertainty (BART score). The overall model, in which the dependent variable was the GDT score, was not significant, $F(5, 94) = 1.69$, $p = .145$, and explained 8% of the variance in the GDT score. As is shown in Table 9, for the entire sample of subjects in decisions under risk, a significant interaction effect was found between testosterone levels and N-Anx scores ($b = 0.35$, $p = .017$).

Table 9: Moderated multiple regression model predicting GDT scores using testosterone levels, neuroticism-anxiety, their interaction and control variables for the entire sample of subjects

Dependent variable: GDT score	b	SE	t	p	95% CI	
					LL	UL
Constant	3.26	0.18	17.95	0.000	2.90	3.62
T	-0.06	0.10	-0.63	0.528	-0.26	0.13
ln(N-Anx)	0.01	0.14	0.43	0.665	-0.22	0.34
T * ln(N-Anx)[a]	**0.35**	**0.14**	**2.43**	**0.017***	**0.04**	**0.64**

To be continued

Table 9: Moderated multiple regression model predicting GDT scores using testosterone levels, neuroticism-anxiety, their interaction and control variables for the entire sample of subjects (cont.)

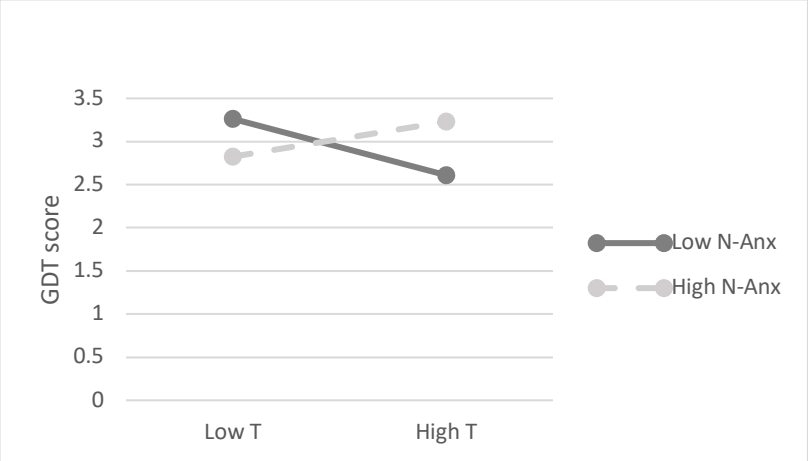
Dependent variable: GDT score	b	SE	t	p	95% CI	
					LL	UL
Sex[b]	-0.03	0.20	-1.67	0.099	-0.73	0.06
Decision-making experience[c]	-0.21	0.21	-0.96	0.340	-0.63	0.22
Model summary N = 100, R^2 = 0.08, F(5, 94) = 1.69, p = 0.145						

Notes. GDT score = Game of Dice Task score, T = testosterone, N-Anx = neuroticism-anxiety; [a] predictors are mean-centered; [b] 0 = males, 1 = females; [c] 0 = inexperienced decision-makers, 1 = experienced decision-makers. Significance is displayed at p < .05 (*) and p < .01 (**).

Source: own work.

The simple slope analysis revealed a significant association between testosterone levels and GDT scores only in subjects with low N-Anx scores (b = -0.33, p = .032, see Figure 6, solid line) and that testosterone levels and GDT scores were not associated in subjects with high N-Anx scores (b = 0.20, p = .156, see Figure 6, dashed line).

Figure 6: Risk propensity in decisions under risk (GDT score) as a function of testosterone and neuroticism-anxiety for the entire sample of subjects



Notes. Plotted points represent conditional low and high values (+/- 1 SDs) of T levels, standardized within sexes, and N-Anx scores. GDT scores and N-Anx scores are log-transformed using a natural logarithm.

Source: own work.

Detailed results of the simple slope analysis are presented in Table 10.

Table 10: Simple slope analysis (N-Anx) for the entire sample of subjects

Variable	b	SE	t	p	95% CI	
					LL	UL
Low N-Anx	**-0.33**	**0.15**	**-2.17**	**0.032***	**-0.63**	**-0.03**
Mean N-Anx	-0.06	0.10	-0.63	0.528	-0.26	0.13
High N-Anx	0.20	0.14	1.43	0.156	-0.08	0.49

Notes. N-Anx = neuroticism-anxiety. Low N-Anx = mean - 1 SD; mean N-Anx = mean value; high N-Anx = mean + 1 SD. Significance is displayed at p < .05 (*) and p < .01 (**).

Source: own work.

Further analysis of the male and female subsample revealed, that the overall model for the male subsample, in which the dependent variable was the GDT score, was significant, $F(3, 38) = 3.33$, $p = .030$, and explained 21% of the variance in GDT score. As is shown in Table 11, we found a significant effect of the N-Anx score on the association between testosterone levels and GDT scores only in males ($b = 1.22$, $p = .004$).

Table 11: Moderated multiple regression model predicting GDT scores using testosterone levels, neuroticism-anxiety, their interaction and control variables for the male subsample

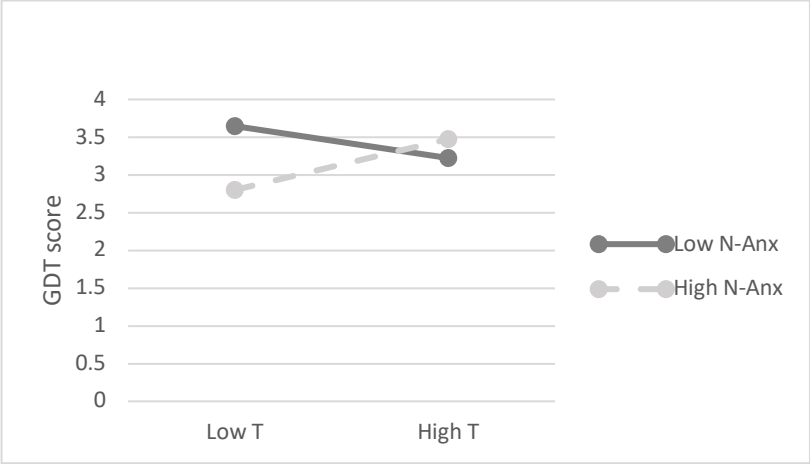
Dependent variable: GDT score	b	SE	t	p	95% CI	
					LL	UL
Constant	3.15	0.13	23.56	0.000	2.88	3.42
ln(T)	-0.01	0.31	-0.04	0.972	0.64	0.62
ln(N-Anx)	0.03	0.17	0.19	0.854	-0.31	0.37
T * ln(N-Anx)[a]	**1.22**	**0.39**	**3.10**	**0.004***	**0.42**	**2.01**
Model summary N = 42, $R^2 = 0.21$, F(3, 38) = 3.33, p = 0.030						

Notes. GDT score = Game of Dice Task score, T = testosterone, N-Anx: = neuroticism-anxiety; [a] predictors are mean-centered. Significance is displayed at p < .05 (*) and p < .01 (**).

Source: own work.

The simple slope analysis revealed that testosterone levels were negatively related to GDT scores in males with low N-Anx scores ($b = -0.99$, $p = .019$) and positively related in males with high N-Anx scores ($b = 0.97$, $p = .050$), as is shown in Figure 7.

Figure 7: Risk propensity in decisions under risk (GDT scores) as a function of testosterone and neuroticism-anxiety for males



Notes. Plotted points represent conditional low and high values (+/- 1 SDs) of T levels, and N-Anx scores. GDT scores, T levels and N-Anx scores are log-transformed using a natural logarithm.

Source: own work.

Detailed results of the simple slope analysis are presented in Table 12. No significant effects were observed in the female subsample.

Table 12: Simple slope analysis (N-Anx) for the male subsample

Variable	b	SE	t	p	95% CI	
					LL	UL
Low N-Anx	**-0.99**	**0.40**	**-2.46**	**0.019***	**-1.81**	**-0.18**
Mean N-Anx	-0.01	0.31	-0.04	0.097	-0.64	0.62
High N-Anx	**0.97**	**0.48**	**2.03**	**0.050***	**0.00**	**1.95**

Notes. N-Anx = neuroticism-anxiety. Low N-Anx = mean - 1 SD; mean N-Anx = mean value; high N-Anx = mean + 1 SD. Significance is displayed at p < .05 (*) and p < .01 (**).

Source: own work.

In decisions under uncertainty, we found no significant main effects of testosterone levels and N-Anx scores on BART score. The effects of the control variables (sex and decision-making experience) and the interaction between the two predictors (testosterone levels and N-Anx scores) were not significant. Furthermore, when analyzing female and male subsamples, no significant main effects of testosterone levels and N-Anx scores or the interaction between them were observed.

5.2.2 Hypothesis 3

A moderation analysis was conducted using multiple regression to examine whether sociability personality trait moderated the relationship between baseline testosterone levels and risk propensity in decisions under risk (GDT score) and under uncertainty (BART score). In the first model, the dependent variable was the GDT score (risk propensity in decisions under risk). No significant main effects of testosterone levels or Sy scores or interaction between them were observed in decisions under risk. No significant main effects of testosterone levels and Sy scores or the interaction between them were observed when analyzing female and male subsamples in decisions under risk.

In the second model, the dependent variable was the BART score (risk propensity in decisions under uncertainty). Neither testosterone levels nor Sy scores had a significant effect on risk propensity when the other predictor was conditioned on its mean. No significant interaction was found in decisions under uncertainty. Control variables for sex and decision-making experience were included in both the risk and uncertainty models, and the effects were not significant. No significant main effects of testosterone levels and Sy scores or the interaction between them were observed when analyzing female and male subsamples in decisions under uncertainty.

6 DISCUSSION

The following chapter discusses the results of the two studies in two parts. The first part of the discussion is related to the study investigating the relationship between self-regulation and adaptability (as indicated by HRV) and risk propensity in decisions under risk and under uncertainty. The second part of the discussion is related to the study of the effects of the individual differences in reward processing, related to behavioral approach and inhibition systems (sociability and neuroticism-anxiety personality traits, respectively) on the relationship between hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) and risk propensity in decisions under risk and under uncertainty.

6.1 First study: Association between HRV and risk propensity

In this study, we investigated the relationship between baseline capacity for self-regulation and adaptability (as indicated by resting HRV) and risk propensity in decisions under risk and under uncertainty. We found no associations between any of the examined resting or reactivity HRV parameters (SDNN, RMSSD, LF, HF, HFnu, LF/HF) and risk propensity in either condition. However, we found a positive association between resting HFnu and risk propensity in decisions under uncertainty for subjects with high HFnu in reactivity. In addition, we found a negative association between the resting LF/HF ratio and risk propensity in decisions under uncertainty, in subjects with a low LF/HF ratio in reactivity, and not in decisions under risk. These findings indicate, that a higher parasympathetic

modulatory activity and a lower sympatho-vagal balance at rest are associated with increased risk propensity in decisions under uncertainty, but only when the parasympathetic modulatory activity remained high and the sympatho-vagal balance remained low during decision-making, respectively. Taken together, these findings indicate that i) the baseline capacity for self-regulation and adaptability depends on the capacity for self-regulation and adaptability during decision-making when predicting risk propensity in decisions under uncertainty, and ii) that individuals with a greater baseline capacity for self-regulation and adaptability, which also remained high during decision-making, make riskier decisions in the context of uncertainty.

Based on the neurovisceral integration model (Thayer & Lane, 2000, 2009), we hypothesized that a higher baseline capacity for self-regulation and adaptability (indicated by greater parasympathetic modulation) would be associated with a lower risk propensity in both decision-making contexts. The model suggests that a higher parasympathetic modulation reflects better self-regulation and adaptability, as it is associated with a stronger inhibitory control exerted by the PFC over subcortical structures, allowing for the inhibition of impulsive and reflective responses. In decision-making under risk and under uncertainty, this suggests that individuals with a higher resting parasympathetic modulation make less risky decisions because they are better able to inhibit the initial response to reward cues, leading to less risky decisions. Contrary to our hypothesis, the results showed no significant associations between resting HRV parameters and risk propensity in decisions under either risk or uncertainty.

Prior studies on the association between resting HRV and risk propensity in decisions under uncertainty provide inconsistent results. Our results are in line with a recent study that found no significant correlation between a number of resting HRV parameters and risk propensity (Prell et al., 2024), which suggest there is no significant association between baseline capacity for self-regulation and adaptability and risk propensity in decisions under uncertainty. However, other studies have reported mixed results, with some showing positive associations between HRV parameters that reflect parasympathetic modulation and risk propensity (Ramirez et al., 2015), while others found that a higher resting parasympathetic modulation was associated with lower risk-taking behavior (Forte et al., 2021). These discrepancies may be due to differences in task designs, sample sizes, and population characteristics.

The lack of significant findings for resting HRV could be explained by the fact that resting HRV primarily reflects a tonic regulatory capacity, which is considered a value at a specific point in time and may not be sufficient to predict behavior in dynamic, real-time decision-making contexts. Based on the neurovisceral integration model (Thayer & Lane, 2000, 2009), a higher resting parasympathetic modulation indicates a greater baseline capacity for self-regulation, adaptability and emotional control, which should theoretically lead to more cautious or risk averse behavior. However, resting HRV parameters primarily capture an individual's tonic level regulation capacity, reflecting their general automatic balance, rather

than how they respond to specific situational demands. It is possible, that decisions under risk and under uncertainty are affected by phasic parasympathetic modulation activity, which requires a dynamic regulation of emotions and cognitive processing during the decision-making task itself and is considered as interaction between resting HRV and HRV reactivity (during decision-making) in this study. As such, it is possible that resting HRV does not fully capture the real-time processes that drive risk-taking behavior in decisions under risk and under uncertainty.

According to the vagal tank theory (Laborde et al., 2018), the ability to adaptively modulate HRV in response to task demands (i.e., HRV reactivity) may be a stronger predictor of risk-taking behavior. In this sense, the interaction between a resting HRV and HRV reactivity could provide a more nuanced understanding of how autonomic regulation affects decisions under risk and uncertainty. Prior studies show that certain phenomena are revealed only when considering parasympathetic modulation during reactivity (Calkins et al., 2007; Yaroslavsky et al., 2013). For example, one study found that while resting parasympathetic modulation and parasympathetic modulation during reactivity were not independently associated with depression, their interaction significantly predicted levels of latent depression (Yaroslavsky et al., 2013).

In light of these insights, we also tested the potential interaction between resting HRV and HRV reactivity, to assess the interaction between self-regulation and adaptability at rest and during the decision-making process. A significant interaction between resting HRV parameters that reflects parasympathetic modulation (HFnu) and sympatho-vagal balance (LF/HF ratio) and risk propensity in decision-making under uncertainty was found only when these HRV parameters were considered during the decision-making task (HRV reactivity). More specifically, the present findings indicate, that a higher resting HFnu was associated with greater risk propensity only in subjects with high HFnu during decision-making (reactivity). Additionally, we found that a lower resting LF/HF ratio was associated with greater risk only in subjects with a low LF/HF ratio during decision-making (reactivity). These findings suggest that a high parasympathetic modulation and a low sympatho-vagal balance at rest are associated with greater risk propensity during decisions under uncertainty only in conjunction with a high parasympathetic modulation and a low sympatho-vagal balance, respectively.

Taken together, these findings indicate that individuals with a better baseline capacity for self-regulation and adaptability, which also remained high during decision-making, make riskier decisions in the context of uncertainty. To date, only two studies have examined the possibility of an association between HRV reactivity and risk propensity in decisions under uncertainty. One study found that individuals who take fewer risks have a higher HF reactivity during decisions under uncertainty, compared to individuals who take more risks (Forte et al., 2021). In contrast, results of the second study suggest that parasympathetic modulation (measured with % change in SD2/SD1 and DFA1) was lower in men who take fewer risks during decision-making under uncertainty (Prell et al., 2024). The discrepancies

within the results of the two studies might be due to different study protocols used. In Prell et al. (2024), participants had to complete two behavioral tasks with only a one minute break in between, which might have led to a carry-over effect (Geng et al., 2022) and influenced the HRV parameters during each behavioral task.

While these observations are not fully comparable, they are in line with the proposal that adaptability, and thus HRV reactivity, is crucial in decision-making under uncertainty (Laborde et al., 2018; Porges, 2007). High resting parasympathetic modulation is associated with better emotional regulation, cognitive flexibility and stress resilience, enabling individuals to remain calm, composed and effective in dynamic and uncertain environments (Forte et al., 2019). During cognitive tasks that require mental effort, such as making decisions under risk and uncertainty, both an increase and a decrease in HRV could be considered adaptive. A slight increase in parasympathetic modulation during the task would suggest that reduced energy demands in the periphery allowed more resources to be allocated to the metabolic costs of mental effort, which is controlled by prefrontal functioning, in order to promote calm reflection and lower the risk propensity (Porges, 2007). However, a decrease in parasympathetic modulation during the cognitive task is also possible in response to a stressful event leading to higher risk propensity (Laborde et al., 2018). In a subset of subjects with high resting HRV parameters (indicating high parasympathetic modulation), a lack of decrease or even an increase in these parameters was associated with higher risk propensity, which could also be considered as an adaptive response. As suggested by Prell et al. (2024), higher risk propensity in individuals with higher parasympathetic modulation could be explained by the potential moderating effects of motivational processes. The absence of real monetary consequences when losing money in a laboratory task might cause decreased motivation, leading to increased risk-taking behavior (Steingroever et al., 2013). For example, motivation can affect parasympathetic modulation, with reduced motivation for cognitive effort resulting in a diminished physiological capacity to respond to increased cognitive demands (Laborde et al., 2018; Westbrook et al., 2023). In this study, the lack of substantial monetary rewards may have resulted in a lower task motivation and potentially moderated the parasympathetic modulation and thus the capacity for self-regulation and adaptability in the context of decision-making under uncertainty.

In decisions under risk, we find no significant associations between baseline capacity for self-regulation and adaptability (as indicated by HRV) and risk propensity. Our results are in line with the three studies that find no significant association between several resting HRV parameters (RMSSD, SDNN, LF, HF, VLF, LF/HF) and risk propensity, as measured by the GDT (Drucaroff et al., 2011; Prell et al., 2024) and by another behavioral task (Jiryis et al., 2022). However, one study (Fooken et al., 2016) observed a positive association between the LF/HF ratio and risk propensity as measured by the AH method (Andreoni & Harbaugh, 2009), suggesting that a lower physiological response is associated with higher risk propensity. The inconsistency in the results between these studies might be due to the use of the lottery task by Andreoni and Hartbough (2009) in the study by Fooken et al. (2016),

which is not typically used in decision-making literature to evaluate risk propensity in decisions under risk. Second, this study did not investigate the relationship between risk propensity and other HRV parameters such as RMSSD, SDNN, and HF, which are typically reported in other studies. Finally, the study protocol differed as the resting phase lasted only five minutes and not ten as it was done in other studies (e.g., Drucaroff et al., 2011; Prell et al., 2024), including the present study.

In contrast to decisions under uncertainty, no significant associations between risk propensity in decisions under risk and resting HRV parameters were found, not even when HRV during decision-making was considered. A recent study found that in decisions under risk, as measured by the GDT, the vagally mediated HRV increased (Prell et al., 2024), which indicates an adaptive response to cognitive load during the task. However, the results of our study and the results of Prell et al. (2024) are not entirely comparable because of the study design and different data analysis procedure. In Prell et al. (2024) participants had only a one-minute break in between both tasks, which might have led to a more significant carry-over effect (Geng et al., 2022) and influenced the HRV parameters during each behavioral task. Moreover, they analyzed the percentage change in HRV parameters between reactivity and resting phase and not the absolute values. Taken together, the present findings indicate that a baseline capacity for self-regulation and adaptability are not associated with risk propensity in decisions under risk.

The discrepancies in results in decisions under uncertainty and decisions under risk could be due to differences in the activation of the autonomic nervous system during decisions under risk and decisions under uncertainty. Risk has been shown to recruit the orbitofrontal cortex, the striatum, the insula and the (posterior) parietal cortex, whereas uncertainty recruits the amygdala and parts of the frontal cortex such as the inferior frontal gyrus, and the (dorsal) lateral prefrontal cortex (Hsu et al., 2005; Levy et al., 2010; Platt & Huettel, 2008; Schultz et al., 2008). It is also possible that risk and uncertainty recruit a common brain mechanism, albeit to different degrees, triggering stronger responses to uncertain or risky choices (De Groot & Thurik, 2018). These findings could also be explained by the fact that capacity for self-regulation and adaptability (as indicated by HRV) plays a more significant role in managing decision strategies that involve emotional reactivity, which is more typical in decisions under uncertainty than those that require calculation i.e., decisions under risk (Starcke & Brand, 2012).

We found a significant correlation between sex and risk propensity in decisions under uncertainty. This result suggests that, on average, women exhibit lower risk propensity than men, which is in line with the existing literature on financial decisions (Byrnes et al., 1999; Weber et al., 2002) and could be explained by potential differences in the perception of risk across genders (Figner & Weber, 2011).

6.2 Second study: Effects of neuroticism-anxiety/sociability on the association between testosterone and risk propensity[8]

In this study, we evaluated the possible effects of individual differences in reward processing related to behavioral approach and inhibition systems (sociability and neuroticism-anxiety personality traits, respectively), on the relationship between hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) and risk propensity under two conditions: decisions under risk and decisions under uncertainty. Based on the PANE perspective (Welker et al., 2015), a positive relationship between baseline testosterone levels and risk propensity in both decision-making contexts was predicted, because testosterone affects brain regions involved in reward processing by increasing the reward sensitivity and decreasing the sensitivity to risks. However, this association could be moderated by individual differences in reward processing related to behavioral approach and inhibition systems, which are reflected by sociability and neuroticism-anxiety personality traits, respectively (Corr, 2004; DeYoung & Blain, 2020; Welker et al., 2015). It was thus hypothesized, integrating the PANE perspective (Welker et al., 2015) and reinforcement sensitivity theory (Gray & McNaughton, 2000), that baseline testosterone levels are positively associated with risk propensity in decisions under risk and under uncertainty only when individuals are low in neuroticism-anxiety and high in the sociability personality trait.

We found that basal testosterone levels were positively correlated with risk propensity in decisions under risk in males with low neuroticism-anxiety scores, whereas they were negatively correlated with risk propensity in decisions under risk in males with a high neuroticism-anxiety score. We found no effect of sociability on the relationship between testosterone and risk propensity in decisions under risk for males. In decisions under uncertainty, no effect of neuroticism-anxiety or sociability on the relationship between testosterone and risk propensity for males was observed. We found no significant effects for females in either condition (decisions under risk and under uncertainty), regardless of the neuroticism-anxiety or sociability personality trait considered. These findings contribute to the PANE perspective, which highlights the role of individual differences in personality traits related to behavioral approach and inhibition system in moderating the relationship between testosterone and behavioral dysregulation (e.g., risk-taking behavior). Specifically, our results demonstrate that individual differences related to the behavioral inhibition system, particularly the neuroticism-anxiety personality trait, moderates the relationship between basal testosterone levels and risk propensity in decisions under risk in males, but not under uncertainty and not in females.

[8] Some paragraphs in this chapter were published in co-authorship in: Ferjančič, U., Bajrović, F., & Valentinčič, A. (2024). Effects of Neuroticism–Anxiety and Sociability Personality Traits on the Relationship Between Testosterone and Risk Propensity in Finance. *Economic and Business Review, 26*(3), 184-195. *https://doi.org/10.15458/2335-4216.1341*.

According to the PANE perspective, testosterone generally increases neural activity in reward-related brain regions, such as the ventral tegmental area and the nucleus accumbens. These regions are central to the behavioral approach system and are sensitive to potential rewards (El Ahdab et al., 2023; Gray & McNaughton, 2000). Animal studies demonstrate that testosterone enhances sensitivity to rewards by promoting dopaminergic activity, particularly within these reward-related circuits (Purves-Tyson et al., 2014). The expectation is, that a heightened sensitivity to rewards would lead to greater risk-taking behaviors, especially when potential rewards are present. Additionally, there is another potential neurobiological mechanism that may help explain testosterone's effects on risk propensity. The ventral tegmental area also sends dopaminergic projections to other brain regions, including the amygdala, which is crucial for emotional processing and the evaluation of threats and risks (Šimić et al., 2021; Welker et al., 2015). Together with the septo-hippocampal system they represent the neurobiological foundation of the behavioral inhibition system (Gray & McNaughton, 2000). Research indicates that highly anxious and neurotic individuals have a heightened amygdala activity, which contributes to their increased sensitivity to perceived threats and potential negative outcomes (Everaerd et al., 2015). This hyperactivity of the amygdala underlies their stronger behavioral inhibition system, which makes them more prone to anxiety and avoidance behaviors in risky situations. When testosterone interacts with this heightened amygdala activity in individuals high in neuroticism-anxiety, it may fail to reduce their threat sensitivity, rather amplify it, which would lead to a lower risk propensity and more risk-averse behavior. In contrast, individuals with low neuroticism-anxiety who have a lower baseline amygdala activity and reduced sensitivity to threats, would more likely exhibit a higher risk propensity and greater risk-taking behavior.

Moreover, testosterone has been negatively associated with avoidant personality traits such as neuroticism (Peper et al., 2018). Since basal testosterone levels were negatively correlated with neuroticism-anxiety scores in the present study (see Appendix 4), it would be possible that basal testosterone levels were positively correlated with risk propensity in decisions under risk in males with low neuroticism-anxiety scores only because of the higher basal testosterone levels. However, this possibility is not supported by the negative correlation of basal testosterone levels with risk propensity in decisions under risk in males with high neuroticism-anxiety scores. Therefore, the mechanism thorugh which neuroticism-anxiety has an effect on the relationship between basal testosterone levels and risk propensity in decisions under risk must be more complex. To sum up, the findings of the present study partially support the second hypothesis suggesting that testosterone is related to risk propensity in decisions under risk by decreasing the sensitivity to threats through the inhibition system.

Interestingly, we did not find significant moderating effects of the behavioral approach system on the relationship between testosterone and risk propensity and thus can not support the third hypothesis. This suggests that the testosterone-risk relationship may be more

strongly governed by threat-related mechanisms (behavioral inhibition system) rather than by reward-seeking mechanisms (behavioral approach system). In individuals with lower neuroticism-anxiety, testosterone may effectively suppress the behavioral inhibition activity, leading to greater risk-taking due to a diminished threat sensitivity. Conversely, in highly anxious and neurotic individuals, testosterone may have less impact on reward sensitivity and instead reinforce the existing threat sensitivity, resulting in decreased risk propensity. Taken together, these findings highlight the nuanced role that testosterone plays in risk-related decision-making, operating through inhibition pathways depending on individual differences in personality traits.

To the best of our knowledge, no other studies have examined the moderating role of individual differences in reward processing on the association between testosterone levels and risk propensity in decisions under risk and under uncertainty. Consequently, we can only partially compare our findings with the existing literature. Prior results on the associations between testosterone levels and risk propensity in decisions under risk (Goudriaan et al., 2010; Nofsinger et al., 2018; Schipper, 2023) and under uncertainty (Goudriaan et al., 2010; Stanton et al., 2021; Stanton, Liening & Schultheiss, 2011), and studies on the associations between personality traits and risk propensity in both contexts (Buelow & Cayton, 2020; Peper et al., 2018) are generally mixed, which could be mostly due to different methodology and study populations used. However, more recent studies on the relationship between testosterone levels and risk propensity in decision-making under risk and under uncertainty, together with the results of the present study, support the hypothesis that this relationship is not linear and far more complex and depended on other neurobiological systems such as hypothalamic-pituitary-adrenal axis (Mehta et al., 2015) and mesolimbic dopaminergic system (Welker et al., 2015), social context such as interpersonal competition (Zilioli & Watson, 2014) and psychological constructs such as self-construal (Welker et al., 2019), optimism about future price changes (Cueva et al., 2015), and personality traits related to behavioral inhibition system, especially neuroticism-anxiety trait, as is evident in the present study.

Moreover, no significant associations between testosterone levels and neuroticism-anxiety score were found when predicting risk propensity in decisions under uncertainty in female and male subsamples. The differences in the effect of neuroticism-anxiety on the possible relationship between basal testosterone levels and risk propensity between decisions under risk and decisions under uncertainty could be explained by the neurobiological differences in risk and uncertainty (De Groot & Thurik, 2018). One hypothesis suggests, that uncertainty could activate distinct brain systems than risk. Risk has been shown to activate the orbitofrontal cortex, the striatum, the insula, and the (posterior) parietal cortex, while uncertainty engages the amygdala and parts of the frontal cortex such as the inferior frontal gyrus and the (dorsal) lateral prefrontal cortex (Bach et al., 2009; Huettel et al., 2006; Krain et al., 2006; Platt & Huettel, 2008; Schultz et al., 2008). Another hypothesis suggests that risk and uncertainty activate a common brain mechanism, albeit to different degrees, with

stronger responses to decisions under risk or uncertainty. Activity in the orbitofrontal cortex and amygdala has been shown to be positively correlated with the uncertainty task, while activity in the striatal system is negatively correlated such task (Hsu et al., 2005; Levy et al., 2010; Platt & Huettel, 2008; Schultz et al., 2008).

In an additional analysis of a subsample of only female participants, no significant effects of the neuroticism-anxiety trait on the relationship between basal testosterone levels and risk propensity in decisions under risk was found. We are not aware of any study comparing the effects of neuroticism-anxiety on the relationship between basal testosterone levels and risk propensity in decisions under risk between the sexes. The few studies that examined the relationship between basal testosterone levels and risk propensities in decisions under risk in both sexes have provided inconsistent results. One study found that basal testosterone levels are positively associated with risk propensity in decisions under risk only in females (Sapienza et al., 2009), while another study found a significant positive association between the two for males and for gains only (Schipper, 2023). Yet, another study found a nonlinear relationship between basal testosterone levels and risk propensity in decisions under risk for both sexes (Stanton, Mullete-Gillman, et al., 2011). The divergence in the results of these studies could be possibly explained by findings from animal studies, which have shown that females are less responsive to androgens (e.g., testosterone) than males in terms of the neuroendocrine function and sexual behavior (Yellon et al., 1989). Additionally, females produce significantly less testosterone in their bodies compared to males and exhibit less variability in testosterone levels (Wood & Newman, 1999), which was also observed in our sample (see Table 1). Furthermore, smaller variability of testosterone levels in females may reduce the statistical power to detect the psychological and behavioral effects of testosterone in females (Cohen, 1988). Given that testosterone is predominantly considered a male sex hormone, female sex hormones such as estrogen and progesterone may have a more significant impact on risk propensity in decisions under risk and under uncertainty in females than testosterone. Both estrogen and progesterone, like testosterone, affect the reward processing in the brain, which could affect risk-taking behavior (Dreher et al., 2007). Although some studies have investigated these effects, the findings remain mixed (Derntl et al., 2014; Diekhof, 2018; Zethraeus et al., 2009). Taken together, these observations suggest that sex differences in hormonal responsiveness and testosterone levels may account for the inconsistent findings regarding the effect of neuroticism-anxiety trait on the relationship between testosterone levels and risk propensity in decisions under risk and uncertainty.

6.3 Limitations[9]

To our knowledge this is only the second study to explore the potential effects of HRV parameters on risk propensity in decisions under risk and under uncertainty and the first

[9] Some paragraphs in this chapter were published in co-authorship in: Ferjančič, U., Bajrović, F., & Valentinčič, A. (2024). Effects of Neuroticism–Anxiety and Sociability Personality Traits on the Relationship Between

study examining the effects of personality traits, specifically neuroticism-anxiety and sociability, on the relationship between basal testosterone levels and risk propensity in decisions under risk and decisions under uncertainty. There is at least a couple of strengths of this study that should be emphasized. First, we adequately distinguished between decisions under risk and decisions under uncertainty, following the distinction in economics (Knight, 1921) and consequently, appropriate methods were employed to evaluate risk propensity in each context. That is often inadequately executed in the existing literature (for more details see De Groot & Thurik, 2018). We employed the GDT to measure risk propensity in decisions under risk and BART to evaluate risk propensity in decisions under uncertainty. The GDT allows participants to calculate expected returns based on associated probabilities, making it an appropriate measure of risk propensity in decision-making under risk. In contrast, in BART, participants can not predict when each balloon will explode and are thus unable to calculate expected returns based on the associated probabilities. This makes BART an appropriate measure of risk propensity in decisions under uncertainty.

Second, we examined the effects of certain personality traits on the relationship between basal testosterone levels and risk propensity in decisions under risk and uncertainty, which has not been done before, although there are theory-driven reasons for doing so (Welker et al., 2015). Finally, prior studies investigating the relationship between decision-making under risk and uncertainty and resting HRV have mainly employed samples of students, which can impact the ecological validity of the results. We have employed a sample of graduate students, who we consider inexperienced decision-makers and individuals who already have at least a few years of working experience in decision-making positions in various business sectors. This enhances the generalizability of our findings, as it includes participants who are more representative of the population typically engaged in real-world decision-making processes. A similar argument can be made regarding the second study. In contrast to prior research on the relationship between basal testosterone levels and risk propensity in decisions under risk and uncertainty, which has predominantly used samples of undergraduate students (Stanton, Liening & Schultheiss, 2011) or exclusively male samples (Apicella et al., 2008), we used a mixed-sex sample of inexperienced and experienced decision makers to ensure better generalizability and validity for both sexes.

Nonetheless, our study is subject to some limitations. First, due to financial constraints, we were not able to offer participants real monetary rewards equivalent to the amounts simulated in the BART and GDT. This limitation impacts the ecological validity of our findings, as the simulated monetary rewards may not accurately reflect the participants' real-life decision-making process under risk and under uncertainty in the financial context. Consequently, the generalizability of our results is restricted to laboratory settings and may not translate to real-life financial contexts. To address this limitation, future research should aim to externally validate BART and GDT by using real monetary incentives that mirror actual financial

Testosterone and Risk Propensity in Finance. *Economic and Business Review, 26*(3), 184-195. https://doi.org/10.15458/2335-4216.1341.

stakes. This approach would improve the applicability of these measures to real-life financial decision-making and provide a more robust understanding of how individuals assess and respond to risk and uncertainty in financial contexts.

Moreover, it might be that the stimulus of both behavioral tasks was too weak to elicit a sufficient neurobiological response, that could be detected as a significant change in HRV parameters in the first study. Another limitation and potential explanation for the non-significant results of the first study concerning the association between resting HRV parameters and risk propensity in decisions under risk and under uncertainty might be the carry-over effect (Geng et al., 2022). The tasks in our study were administered in a randomized order, with a 20-minute break between each part of the experiment. However, it is possible that despite this break the effects of the first task carried over to the second resting phase, influencing the resting HRV measured before the second task. For more firm conclusions, future studies are needed to address this issue. Finally, the relatively small sample size might have contributed to the non-significant results. HRV parameters are highly variable, which requires sufficient sample sizes to detect significant correlations and differences between groups (Žunkovič et al., 2023). According to Žunković et al. (2023), the minimum sample size for detecting significant changes in RMSSD is 50, and a larger sample size (more than 100 participants) is required for detecting changes in frequency domain measures (such as HF). Therefore, it is expected that in our study with a sample of 82, the results for the frequency domain measures, but not the time domain measures would be limited by the sample size. Future studies should aim to replicate these findings in larger sample sizes.

The second study tested only the associations between endogenous testosterone levels, personality traits and risk propensity. We were therefore unable to draw any conclusions about causality. Future studies should examine the effects of exogenously administered testosterone to determine causality. Moreover, the study was limited to examining the effects of a single hormone, testosterone. However, it is possible that estradiol could play a role in risk-taking in women (Bröder & Hohmann, 2003; Peper et al., 2018). Finally, the sample size was relatively small, which may have contributed to the non-significant results. Future studies should aim to replicate these findings in larger sample sizes. Nonetheless, we were able to partially confirm the first hypothesis and show that the neuroticism-anxiety trait affects the relationship between basal testosterone levels and risk propensity in decisions under risk, supporting the hypothesis that decision-making under risk is a complex process, that depends on neurobiological and psychological systems (Mehta et al., 2015; Welker et al., 2015, 2019).

7 CONCLUSION

Classical economic theory assumes decision-making is a rational, logical process, driven by objective calculations (Bernoulli, 1954). However, real-world decision-making often

deviates from these ideals, as emotional and psychological factors frequently come into play. In response to these challenges, neuroeconomics has emerged and revealed that decision-making involves a dynamic integration of both cognitive and emotional processes (Bechara & Damasio, 2005; Thayer & Lane, 2000, 2009). The purpose of this dissertation is to answer the main research question of how different physiological (self-regulation and adaptability as indicated by HRV and hormonal mechanism of behavioral dysregulation as indicated by testosterone levels) and psychological mechanisms (neuroticism-anxiety and sociability personality traits related to behavioral inhibition and approach system, respectively) are associated with risk propensity in decisions under risk and decisions under uncertainty.

Decision-making is a complex process involving many psychological and neurobiological mechanisms. Taken together, our findings support the role of psychology and neurobiology in decision-making under risk and uncertainty. According to the neurovisceral integration model, it would be expected that the relationship between the baseline capacity for self-regulation and adaptability (as indicated by HRV) is negatively related to risk propensity in decision-making under risk and uncertainty (Thayer & Lane, 2000, 2009). In other words, individuals with a higher baseline parasympathetic modulation, which reflects greater parasympathetic control and a stronger capacity for self-regulation and adaptability, are expected to be more capable of inhibiting impulsive responses to immediate rewards. This would likely result in more cautious and less risky decisions, as they are better equipped to evaluate potential outcomes and trade-offs, particularly in situations involving uncertainty or risk. In contrast, individuals with a lower baseline parasympathetic modulation may exhibit higher risk propensity due to reduced autonomic regulation and greater difficulty controlling impulsive or emotionally driven decision-making. However, the results of our study show that i) the baseline capacity for self-regulation and adaptability depends on self-regulation and adaptability during decision-making when predicting risk propensity in decisions under uncertainty, and ii) that individuals with a better baseline capacity for self-regulation and adaptability, which also remained high during decision-making, make riskier decisions in the context of uncertainty. Thus, our results contrast with our expectations, suggesting the existence of a segment of individuals who are better at inhibiting impulsive responses yet still make riskier choices in decisions under uncertainty. These results could be explained with the modulating role of motivational processes (Laborde et al., 2018; Prell et al., 2024). Furthermore, our findings suggest that the association between self-regulation and adaptability and risk propensity is context-dependent, as we found a significant association only in decision-making under uncertainty and not in decision-making under risk.

The practical contribution of these results is an increased understanding of the relationship between self-regulation and adaptability (as indicated by HRV) and risk propensity in situations of risk and uncertainty. This new knowledge can be applied in the context of financial decision-making under risk and uncertainty. Our findings suggest that there is a subset of individuals who demonstrate strong self-regulation and adaptability (e.g., the

ability to inhibit impulsive responses) yet still engage in higher risk-taking when faced with decisions under uncertainty. Further investigations are needed to establish this relationship with decision-making under uncertainty more firmly.

In the second part of the study, we examined the effects of certain personality traits such as neuroticism-anxiety and sociability on the relationship between basal testosterone levels and risk propensity in decision-making under risk and uncertainty. Based on the PANE perspective, the association between hormonal mechanism of behavioral dysregulation (as indicated by testosterone levels) and risk propensity is not linear but could instead be affected by several modulators. It was accordingly hypothesized that basal testosterone levels are positively associated with risk propensity in decision-making under risk and under uncertainty only in those individuals, who are low in neuroticism-anxiety and high in the sociability personality trait. This hypothesis is also partly supported by our results, which show that the relationship between basal testosterone levels and risk propensity in decision-making is affected by the neuroticism-anxiety personality trait, but not by sociability, and only in men. Specifically, the present study showed that higher basal testosterone levels are associated with a higher risk propensity in decisions under risk only in men who are not excessively neurotic and anxious. Whereas in more neurotic and anxious men, the relationship is reversed, i.e. higher testosterone levels are associated with a lower propensity to take risks in decisions under risk. Taken together, these findings suggest that the relationship between the hormonal mechanism of behavioral dysregulation and risk propensity in decisions under risk is modulated by the neuroticism-anxiety personality trait that is related to the behavioral inhibition system in males. Additionally, our results also suggest the importance of context, as the effect of the neuroticism-anxiety personality trait in men, on the association between hormonal mechanism of behavioral dysregulation and risk propensity is significant only in decisions under risk, but not in decisions under uncertainty.

These results offer some practical contributions, suggesting that neurotic and anxious men with high basal testosterone levels are more inclined to engage in risky behaviors when making decisions under risk. This can be applied to financial contexts, whereby neurotic and anxious men with higher basal testosterone levels should not be placed in risk-taking situations as decision-makers, if one wants to avoid risky decision-making. However, it is essential to be mindful of the limitations of the research and, consequently, of the relevant applicability of the research in practice.

In this context, it should be pointed out that both studies were limited to examining the effects of physiological and psychological factors on risk propensity in decisions under risk and uncertainty in a laboratory setting, and to the use of behavioral methods to assess risk propensity. In order to draw more robust conclusions that can be directly applied to financial decision-making under risk and uncertainty, future studies should assess the relationship between risk propensity and performance outside the laboratory and use measures that better replicate real-life decision-making. Despite its limitations, our study contributes to the

existing literature on decision-making under risk and uncertainty by providing insights into the complex interplay of psychological and neurobiological mechanisms in different decision-making contexts.

REFERENCE LIST

1. Alary, D., Gollier, C., & Treich, N. (2013). The Effect of Ambiguity Aversion on Insurance and Self-protection. *The Economic Journal*, *123*(573), 1188–1202. https://doi.org/10.1111/ecoj.12035

2. Aluja, A., García, Ó., & García, L. F. (2002). A comparative study of Zuckerman's three structural models for personality through the NEO-PI-R, ZKPQ-III-R, EPQ-RS and Goldberg's 50-bipolar adjectives. *Personality and Individual Differences*, *33*(5), 713–725. https://doi.org/10.1016/S0191-8869(01)00186-6

3. Andreoni, J., & Harbaugh, W. T. (2009). *Unexpected Utility: Experimental Tests of Five Key Questions about Preferences over Risk*. Working Paper.

4. Apicella, C. L., Carré, J. M., & Dreber, A. (2015). Testosterone and Economic Risk Taking: A Review. *Adaptive Human Behavior and Physiology*, *1*(3), 358–385. https://doi.org/10.1007/s40750-014-0020-2

5. Apicella, C. L., Dreber, A., Campbell, B., Gray, P. B., Hoffman, M., & Little, A. C. (2008). Testosterone and financial risk preferences. *Evolution and Human Behavior*, *29*(6), 384–390. https://doi.org/10.1016/j.evolhumbehav.2008.07.001

6. Bach, D. R., Seymour, B., & Dolan, R. J. (2009). Neural activity associated with the passive prediction of ambiguity and risk for aversive events. *Journal of Neuroscience*, *29*(6), 1648–1656. https://doi.org/10.1523/JNEUROSCI.4578-08.2009

7. Baillon, A., Bleichrodt, H., & Spinu, V. (2020). Searching for the reference point. *Management Science*, *66*(1), 93–112. https://doi.org/10.1287/mnsc.2018.3224

8. Barseghyan, B. L., Molinari, F., Donoghue, T. O., & Teitelbaum, J. C. (2013). The Nature of Risk Preferences : Evidence from Insurance Choices. *American Economic Review*, *103*(6), 2499–2529. https://doi.org/10.1257/aer.103.6.2499

9. Bashir, S., Mir, A., Altwaijri, N., Uzair, M., Khalil, A., Albesher, R., Khallaf, R., Alshahrani, S., & Abualait, T. (2023). Neuroeconomics of decision-making during COVID-19 pandemic. *Heliyon*, *9*, e13252. https://doi.org/10.1016/j.heliyon.2023.e13252

10. Bechara, A., & Damasio, A. R. (2005). The somatic marker hypothesis: A neural theory of economic decision. *Games and Economic Behavior*, *52*(2), 336–372. https://doi.org/10.1016/j.geb.2004.06.010

11. Benarroch, E. E. (1993). The central autonomic network: functional organization, dysfunction, and perspective. *Mayo Clinical Proceedings*, *68*(10), 988–1001. https://doi.org/10.1016/s0025-6196(12)62272-1

12. Benischke, M. H., Martin, G. P., & Glaser, L. (2019). CEO equity risk bearing and strategic risk taking: The moderating effect of CEO personality. *Strategic Management Journal*, *40*(1), 153–177. https://doi.org/10.1002/smj.2974

13. Bernoulli, D. (1954). Exposition of a New Theory on the Measurement of Risk. *Econometrica*, *22*(1), 23–36. https://doi.org/10.2307/1909829

14. Berntson, G. G., Bigger Jr, J. T., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., Nagaraja, H. N., Porges, S. W., Saul, J. P., Stone, P. H., & van der Molen, M. W. (1997). Heart rate variability: Origins, methods, and interpretive caveats. *Psychophysiology*, *34*, 623–648. https://doi.org/10.1111/j.1469-8986.1997.tb02140.x

15. Bhatt, R. R., Williams, D. P., Koenig, J., & Thayer, J. F. (2015). Heart rate variability predicts the outcome of risk taking behavior in judgment and decision-making. *73rd Annual Meeting of the American Psychosomatic Society, Savannah, Georgia*.

16. Blankenstein, N. E., Peper, J. S., Crone, E. A., & van Duijvenvoorde, A. C. K. (2017). Neural Mechanisms Underlying Risk and Ambiguity Attitudes. *Journal of Cognitive Neuroscience*, *29*(11), 1–15. https://doi.org/10.1162/jocn

17. Boudreau, P., Yeh, W. H., Dumont, G. A., & Boivin, D. B. (2012). A circadian rhythm in heart rate variability contributes to the increased cardiac sympathovagal response to awakening in the morning. *Chronobiology International*, *29*(6), 757–768. https://doi.org/10.3109/07420528.2012.674592

18. Boyer, B. H., & Vorkink, K. (2014). Stock options as lotteries. *Journal of Finance*, *69*(4), 1485–1527. https://doi.org/10.1111/jofi.12152

19. Brand, M., Labudda, K., Kalbe, E., Hilker, R., Emmans, D., Fuchs, G., Kessler, J., & Markowitsch, H. J. (2004). Decision-making impairments in patients with Parkinson's disease. *Behavioral Neurology*, *15*, 77–85. https://doi.org/10.1155/2004/578354

20. Breedlove, S. M., & Watson, N. V. (2020). Hormones and the brain. In *Behavioral Neuroscience* (9th edition, pp. 137–164). Oxford University Press. https://doi.org/10.1016/0013-4694(81)90111-5

21. Bröder, A., & Hohmann, N. (2003). Variations in risk taking behavior over the menstrual cycle. An improved replication. *Evolution and Human Behavior*, *24*(6), 391–398. https://doi.org/10.1016/S1090-5138(03)00055-2

22. Buelow, M. T., & Cayton, C. (2020). Relationships between the big five personality characteristics and performance on behavioral decision making tasks. *Personality and Individual Differences*, *160*, 109931. https://doi.org/10.1016/j.paid.2020.109931

23. Byrnes, J. P., Miller, D. C., & Schafer, W. D. (1999). Gender differences in risk taking: A meta-analysis. *Psychological Bulletin*, *125*(3), 367–383. https://doi.org/10.1037/0033-2909.125.3.367

24. Calkins, S. D., Graziano, P. A., & Keane, S. P. (2007). Cardiac vagal regulation differentiates among children at risk for behavior problems. *Biological Psychology*, *74*(2), 144–153. https://doi.org/10.1016/j.biopsycho.2006.09.005

25. Camerer, C. F. (1998). Prospect theory in the wild: evidence from the field. In C. F. Camerer, G. Loewenstein, & M. Rabin (Eds.), *Advances in behavioral economics* (pp. 148–161). Princeton University Press.

26. Camerer, C. F., Cohen, J. D., Fehr, E., Glimcher, P. W., & Laibson, D. (2015). Neuroeconomics. In J. H. Kagel & A. E. Roth (Eds.), *The Handbook of Experimental Economics, Vol. 2* (pp. 153–216). Princeton University Press.

27. Camerer, C. F., Loewenstein, G., & Prelec, D. (2005). Neuroeconomics: How neuroscience can inform economics. *Journal of Economic Literature*, *43*(1), 9–64. https://doi.org/10.1257/0022051053737843

28. Coates, J. M., & Herbert, J. (2008). Endogenous steroids and financial risk taking on a London trading floor. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(16), 6167–6172. https://doi.org/10.1073/pnas.0704025105

29. Cohen, J. (1988). *Statistical Power Analysis for Behavioral Sciences* (2nd Edition). Routledge. https://doi.org/https://doi.org/10.4324/9780203771587

30. Cooper, A. C., Woo, C. Y., & Dunkelberg, W. C. (1988). Entrepreneurs' perceived chances for success. *Journal of Business Venturing*, *3*, 97–108.

31. Corr, P. J. (2004). Reinforcement sensitivity theory and personality. *Neuroscience and Biobehavioral Reviews*, *28*(3), 317–332. https://doi.org/10.1016/j.neubiorev.2004.01.005

32. Cueva, C., Roberts, R. E., Spencer, T., Rani, N., Tempest, M., Tobler, P. N., Herbert, J., & Rustichini, A. (2015). Cortisol and testosterone increase financial risk taking and may destabilize markets. *Scientific Reports*, *5*, 11206. https://doi.org/10.1038/srep11206

33. Dabbs, J. M. (1990). Salivary testosterone measurements: Reliability across hours, days, and weeks. *Psychology & Behavior*, *48*(1), 83–86. https://doi.org/ 10.1016/0031-9384(90)90265-6

34. Dabbs, J. M. (1993). Salivary testosterone measurements in behavioral studies. *Annals of the New York Academy Science*, *20*(694), 117–183. https://doi.org/10.1111/j.1749-6632.1993.tb18351.x

35. Danieli, A., Lusa, L., Potočnik, N., Meglič, B., Grad, A., & Bajrović, F. F. (2014). Resting heart rate variability and heart rate recovery after submaximal exercise. *Clinical Autonomic Research*, *24*(2), 53–61. https://doi.org/10.1007/s10286-014-0225-2

36. Daw, N. D., & O'Doherty, J. P. (2014). Multiple Systems for Value Learning. In P. W. Glimcher & E. Fehr (Eds.), *Neuroeconomics: Decision-Making and the Brain* (pp. 393–410). Elsevier Academic Press.

37. De Groot, K. (2020). Burst Beliefs – Methodological Problems in the Balloon Analogue Risk Task and Implications for Its Use. *Journal of Trial and Error*, *1*(1), 43–51. https://doi.org/10.36850/mr1

38. De Groot, K., & Thurik, R. (2018). Disentangling risk and uncertainty: When risk-taking measures are not about risk. *Frontiers in Psychology*, *9*, 1–7. https://doi.org/10.3389/fpsyg.2018.02194

39. De Martino, B., Kumaran, D., Seymour, B., & Dolan, R. J. (2006). Frames, biases and rational decision-making in the human brain. *Science*, *313*(5787), 684–687. https://doi.org/10.1126/science.1128356

40. Derntl, B., Pintzinger, N., Kryspin-Exner, I., & Schöpf, V. (2014). The impact of sex hormone concentrations on decision-making in females and males. *Frontiers in Neuroscience*, *8*(352), 1–11. https://doi.org/10.3389/fnins.2014.00352

41. DeYoung, C. G., & Blain, S. D. (2020). Personality Neuroscience. In P. J. Corr & G. Matthews (Eds.), *The Cambridge Handbook of Personality Psychology* (pp. 273–294). Cambridge University Press. https://doi.org/10.1017/9781108264822.026

42. DeYoung, C. G., Grazioplene, R. G., & Allen, T. A. (2021). The neurobiology of personality. In O. P. John & R. W. Robins (Eds.), *Handbook of Personality: Theory and Research* (4th ed., pp. 193–216). Guilford Press.

43. Diekhof, E. K. (2018). Estradiol and the reward system in humans. *Current Opinion in Behavioral Sciences*, *23*, 58–64. https://doi.org/10.1016/j.cobeha.2018.03.010

44. Dreher, J.-C., Schmidt, P. J., Kohn, P., Furman, D., Rubinow, D., Berman, K. F., & Performed, K. F. B. (2007). Menstrual cycle phase modulates reward-related neural function in women. *Biological Sciences*, *104*(7), 2465–2470. https://doi.org/10.1073/pnas.0605569104

45. Drucaroff, L. J., Kievit, R., Guinjoan, S. M., Gerschcovich, E. R., Cerquetti, D., Leiguarda, R., Cardinali, D. P., & Vigo, D. E. (2011). Higher autonomic activation predicts better performance in Iowa Gambling Task. *Cognitive and Behavioral Neurology*, *24*(2), 93–98. https://doi.org/10.1097/WNN.0b013e3182239308

46. Dunn, B. D., Dalgleish, T., & Lawrence, A. D. (2006). The somatic marker hypothesis: A critical evaluation. *Neuroscience and Biobehavioral Reviews*, *30*(2), 239–271. https://doi.org/10.1016/j.neubiorev.2005.07.001

47. Edwards, W. (1954). The theory of decision making. *Psychological Bulletin*, *51*(4), 380–417. https://doi.org/10.1037/h0053870

48. El Ahdab, J., Khachan, M. J., Richa, S., & Raad, G. (2023). A comprehensive review on the role of testosterone on the neurobehavioral systems implicated in the reinforcement sensitivity theory of personality. *Encephale*, *49*(2), 174–184. https://doi.org/10.1016/j.encep.2022.08.020

49. Ellsberg, D. (1961). Risk, Ambiguity, and the Savage Axioms. *Quarterly Journal Of Economics*, *75*(4), 643–669.

50. Enter, D., Spinhoven, P., & Roelofs, K. (2014). Alleviating social avoidance: Effects of single dose testosterone administration on approach-avoidance action. *Hormones and Behavior*, *65*(4), 351–354. https://doi.org/10.1016/j.yhbeh.2014.02.001

51. Epstein, S., Pacini, R., Denes-Raj, V., & Heier, H. (1996). Individual differences in intuitive–experiential and analytical–rational thinking styles. *Journal of Personality and Social Psychology*, *71*(2), 390–405. https://doi.org/10.1037/0022-3514.71.2.390

52. Evans, J. S. B. T., & Stanovich, K. E. (2013). Dual-Process Theories of Higher Cognition: Advancing the Debate. *Perspectives on Psychological Science*, *8*(3), 223–241. https://doi.org/10.1177/1745691612460685

53. Everaerd, D., Klumpers, F., van Wingen, G., Tendolkar, I., & Fernández, G. (2015). Association between neuroticism and amygdala responsivity emerges under stressful conditions. *NeuroImage*, *112*, 218–224. https://doi.org/10.1016/j.neuroimage.2015.03.014

54. Fehr, E., & Camerer, C. F. (2007). Social neuroeconomics: the neural circuitry of social preferences. *Trends in Cognitive Sciences*, *11*(10), 419–427. https://doi.org/10.1016/j.tics.2007.09.002

55. Figner, B., & Weber, E. U. (2011). Who takes risks when and why: Determinants of changes in investor risk taking. *Current Directions in Psychological Science*, *20*(4), 211–216. https://doi.org/10.1093/rof/rfs024

56. Finley, S. K., & Kritzer, M. F. (1999). Immunoreactivity for intracellular androgen receptors in identified subpopulations of neurons, astrocytes and oligodendrocytes in primate prefrontal cortex. *Journal of Neurobiology*, *15*(40), 446–457.

57. Fooken, J., & Schaffner, M. (2016). The role of psychological and physiological factors in decision making under risk and in a dilemma. *Frontiers in Behavioral Neuroscience*, *10*, 1–10. https://doi.org/10.3389/fnbeh.2016.00002

58. Forte, G., Favieri, F., & Casagrande, M. (2019). Heart rate variability and cognitive function: A systematic review. *Frontiers in Neuroscience*, *13*. https://doi.org/10.3389/fnins.2019.00710

59. Forte, G., Morelli, M., & Casagrande, M. (2021). Heart rate variability and decision-making: Autonomic responses in making decisions. *Brain Sciences*, *11*(2), 1–12. https://doi.org/10.3390/brainsci11020243

60. Forte, G., Morelli, M., Grässler, B., & Casagrande, M. (2022). Decision making and heart rate variability: A systematic review. *Applied Cognitive Psychology*, *36*(1), 100–110. https://doi.org/10.1002/acp.3901

61. Fox, C. R., Erner, C., & Walter, D. J. (2015). Decision Under Risk: From the Field to the Laboratory and Back. In *The Wiley Blackwell Handbook of Judgment and Decision Making* (pp. 43–88). Wiley Blackwell. https://doi.org/10.1002/9781118468333

62. Fox, C. R., & Poldrack, R. A. (2014). Prospect Theory and the Brain. In P. W. Glimcher & E. Fehr (Eds.), *Neuroeconomics: Decision-Making and the Brain* (pp. 533–567). Elsevier.

63. Furby, L., & Beyth-Marom, R. (1992). Risk taking in adolescence: A decision-making perspective. *Developmental Review*, *12*(1), 1–44. https://doi.org/ 10.1016/0273-2297(92)90002-J

64. Garcia, B., Cerrotti, F., & Palminteri, S. (2021). The description-experience gap: A challenge for the neuroeconomics of decision-making under uncertainty. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *376*(20190665). https://doi.org/10.1098/rstb.2019.0665

65. Geng, D., Liu, X., Wang, Y., & Wang, J. (2022). The effect of transcutaneous auricular vagus nerve stimulation on HRV in healthy young people. *Plos One*, *17*(2), 1–17. https://doi.org/10.1371/journal.pone.0263833

66. Glimcher, P. W., & Fehr, E. (2014). Introduction: A Brief History of Neuroeconomics. In *Neuroeconomics: Decision-Making and the Brain* (pp. 16–28). Elsevier Academic Press.

67. Goudriaan, A. E., Lapauw, B., Ruige, J., Feyen, E., Kaufman, J. M., Brand, M., & Vingerhoets, G. (2010). The influence of high-normal testosterone levels on risk-taking in healthy males in a 1-week letrozole administration study. *Psychoneuroendocrinology*, *35*(9), 1416–1421. https://doi.org/10.1016/j.psyneuen.2010.04.005

68. Gray, J. A., & McNaughton, N. (1982). *The neuropsychology of anxiety: An enquiry into the functions of the septo-hippocampal system*. Oxford Psychology Series. Oxford University Press.

69. Gray, J. A., & McNaughton, N. (2000). *The Neuropsychology of Anxiety: An Enquiry into the Functions of the Septohippocampal System*. Oxford University Press.

70. Harrison, G. W., & Rustrom, E. E. (2008). Risk Aversion in the Laboratory. In J. C. Cox & G. W. Harrison (Eds.), *Risk Aversion in Experiments (Research in Experimental Economics, 12)* (pp. 41–196). Emerald Publishing Limited.

71. Harrison, G. W., & Rutström, E. E. (2009). Expected utility theory and prospect theory: One wedding and a decent funeral. *Experimental Economics*, *12*(2), 133–158. https://doi.org/10.1007/s10683-008-9203-7

72. Hayes, A. F. (2022). *Introduction to Mediation, Moderation, and Conditional Process analysis: A Regression-Based Approach* (3rd ed.). The Guilford Publications.

73. Heany, S. J., Bethlehem, R. A. I., van Honk, J., Bos, P. A., Stein, D. J., & Terburg, D. (2018). Effects of testosterone administration on threat and escape anticipation in the orbitofrontal cortex. *Psychoneuroendocrinology*, *96*, 42–51. https://doi.org/10.1016/j.psyneuen.2018.05.038

74. Heath, C., Larrick, R. P., & Wu, G. (1999). Goals as reference points. *Cognitive Psychology*, *38*(1), 79–109.

75. Herbert, J. (2018). Testosterone, cortisol and financial risk-taking. *Frontiers in Behavioral Neuroscience*, *12*, 1–17. https://doi.org/10.3389/fnbeh.2018.00101

76. Hermans, E. J., Bos, P. A., Ossewaarde, L., Ramsey, N. F., Fernández, G., & van Honk, J. (2010). Effects of exogenous testosterone on the ventral striatal BOLD response during reward anticipation in healthy women. *NeuroImage*, *52*(1), 277–283. https://doi.org/10.1016/j.neuroimage.2010.04.019

77. Hertwig, R., & Erev, I. (2009). The description-experience gap in risky choice. *Trends in Cognitive Sciences*, *13*(12), 517–523. https://doi.org/10.1016/j.tics.2009.09.004

78. Hsu, M., Bhatt, M., Adolphs, R., Tranel, D., & Camerer, C. F. (2005). Neuroscience: Neural systems responding to degrees of uncertainty in human decision-making. *Science*, *310*(5754), 1680–1683. https://doi.org/10.1126/science.1115327

79. Hsu, M., Krajbich, I., Zhao, C., & Camerer, C. F. (2009). Neural response to reward anticipation under risk is nonlinear in probabilities. *Journal of Neuroscience*, *29*(7), 2231–2237. https://doi.org/10.1523/JNEUROSCI.5296-08.2009

80. Huettel, S. A., Stowe, C. J., Gordon, E. M., Warner, B. T., & Platt, M. L. (2006). Neural signatures of economic preferences for risk and ambiguity. *Neuron*, *49*(5), 765–775. https://doi.org/10.1016/j.neuron.2006.01.024

81. Jiryis, T., Magal, N., Fructher, E., Hertz, U., & Admon, R. (2022). Resting-state heart rate variability (HRV) mediates the association between perceived chronic stress and ambiguity avoidance. *Scientific Reports*, *12*(1), 1–10. https://doi.org/10.1038/s41598-022-22584-4

82. Jose, A. D., & Collison, D. (1970). The normal range and determinants of the intrinsic heart rate in men. *Cardiovascular Research*, *4*(2), 160–167. https://doi.org/10.1093/cvr/4.2.160

83. Ju, N., & Miao, J. (2012). Ambiguity, Learning and Asset Returns. *Econometrica*, *80*(2), 559–591.

84. Kable, J. W. (2014). Valuation, Intertemporal Choice, and Self-Control. In P. W. Glimcher & E. Fehr (Eds.), *Neuroeconomics: Decision-Making and the Brain* (pp. 173–192). Elsevier Academic Press.

85. Kahneman, D., Knetsch, J. L., & Thaler, R. H. (1991). Anomalies: The endowment effect, loss aversion, and status quo bias. *Journal of Economic Perspectives*, *5*(1), 193–206. https://doi.org/10.1017/CBO9780511803475.009

86. Kahneman, D., & Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. *Econometrica*, *47*(2), 263–291. https://doi.org/10.15957/j.cnki.jjdl.2009.07.004

87. Kandel, E. R., & Shandlen, M. N. (2021). The Brain and Behavior. In E. R. Kandel, J. D. Koester, S. M. Mack, & S. A. Sielgelbaum (Eds.), *The Principles of Neural Science* (6th ed., pp. 7–25). McGraw-Hill Education.

88. Knight, F. H. (1921). *Risk, Uncertainty and Profit*. Houghton Mifflin Company. https://doi.org/10.2307/1884757

89. Koenig, J., Jarczok, M. N., Warth, M., Ellis, R. J., Bach, C., Hillecke, T. K., & Thayer, J. F. (2014). Body mass index is related to autonomic nervous system activity as measured by heart rate variability - A replication using short term measurements. *Journal of Nutrition, Health and Aging*, *18*(3), 300–302. https://doi.org/10.1007/s12603-014-0022-6

90. Koszegi, B., & Rabin, M. (2006). A model of reference-dependent preferences. *Quarterly Journal Of Economics*, *121*(4), 1113–1165. https://doi.org/10.1093/qje/121.4.1133

91. Krain, A. L., Wilson, A. M., Arbuckle, R., Castellanos, F. X., & Milhama, M. P. (2006). Distinct neural mechanisms of risk and ambiguity: A meta-analysis of decision-making. *NeuroImage*, *32*(1), 477–484. https://doi.org/10.1016/j.neuroimage.2006.02.047

92. Krupić, D., & Corr, P. J. (2017). Moving forward with the BAS: Towards a neurobiology of multidimensional model of approach motivation. *Psychological Topics*, *26*(1), 25–45. https://doi.org/10.31820/pt.26.1.2

93. Laborde, S., Mosley, E., & Mertgen, A. (2018). Vagal Tank theory: The three Rs of cardiac vagal control functioning - resting, reactivity, and recovery. *Frontiers in Neuroscience*, *12*, 1–14. https://doi.org/10.3389/fnins.2018.00458

94. Lejuez, C. W., Richards, J. B., Read, J. P., Kahler, C. W., Ramsey, S. E., Stuart, G. L., Strong, D. R., & Brown, R. A. (2002). Evaluation of a behavioral measure of risk taking: The balloon analogue risk task (BART). *Journal of Experimental Psychology: Applied*, *8*(2), 75–84. https://doi.org/10.1037/1076-898X.8.2.75

95. Levy, I., Snell, J., Nelson, A. J., Rustichini, A., & Glimcher, P. W. (2010). Neural representation of subjective value under risk and ambiguity. *Journal of Neurophysiology*, *103*(2), 1036–1047. https://doi.org/10.1152/jn.00853.2009

96. Liening, S. H., Stanton, S. J., Saini, E. K., & Schultheiss, O. C. (2010). Salivary testosterone, cortisol, and progesterone: Two-week stability, interhormone correlations, and effects of time of day, menstrual cycle, and oral contraceptive use on steroid hormone levels. *Physiology and Behavior*, *99*(1), 8–16. https://doi.org/10.1016/j.physbeh.2009.10.001

97. Loewenstein, G., Weber, E. U., Hsee, C. K., & Welch, N. (2001). Risk as feelings. *Psychological Bulletin*, *127*(2), 267–286. https://doi.org/10.1037/0033-2909.127.2.267

98. Lowell, B. B., Swanson, L. W., & Horn, J. P. (2021). The Hypothalamus: Autonomic, Hormonal, and Behavioral Control of Survival. In E. R. Kandel, J. D. Koester, S. H. Mack, & S. A. Siegelbaum (Eds.), *The Principles of Neural Science* (6th ed., pp. 1010–1044). McGraw-Hill Education.

99. Madan, C. R., Ludvig, E. A., & Spetch, M. L. (2019). Comparative inspiration: From puzzles with pigeons to novel discoveries with humans in risky choice. *Behavioural Processes*, *160*, 10–19. https://doi.org/10.1016/j.beproc.2018.12.009

100. Maenhout, P. J. (2004). Robust Portfolio Rules and Asset Pricing. *The Review of Financial Studies*, *17*(4), 951–983. https://doi.org/10.1093/rfs/hhh003

101. Malik, M. (1996). Heart rate variability: Standards of Measurement, Physiological Interpretation and Clinical Use: Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. *Annals of Noninvasive Electrocardiology*, *17*, 151–181. https://doi.org/10.4324/9781315372921

102. March, J. G., & Shapira, Z. (1987). Managerial Perspectives on Risk and Risk Taking. *Management Science*, *33*(11), 1404–1418. https://doi.org/10.1287/mnsc.33.11.1404

103. Markowitz, H. (1952). Portfolio Selection. *The Journal of Finance*, *7*(1), 77–91. https://doi.org/10.1111/j.1540-6261.1952.tb01525.x

104. McCorry, L. K. (2007). Physiology of the Autonomic Nervous System. *American Journal of Pharmaceutical Education*, *71*(4), 1–11. https://doi.org/10.1111/j.1399-6576.1964.tb00252.x

105. McDermott, R. (2001). Prospect theory. In *Risk Taking in International Policies* (pp. 15–44). The University of Michigan Press. https://doi.org/10.4337/9781788974912.P.85

106. Mehta, P. H., & Beer, J. (2010). Neural mechanisms of the testosterone-aggression relation: The role of orbitofrontal cortex. *Journal of Cognitive Neuroscience*, *22*(10), 2357–2368. https://doi.org/10.1162/jocn.2009.21389

107. Mehta, P. H., & Josephs, R. A. (2010). Testosterone and cortisol jointly regulate dominance: Evidence for a dual-hormone hypothesis. *Hormones and Behavior*, *58*(5), 898–906. https://doi.org/10.1016/j.yhbeh.2010.08.020

108. Mehta, P. H., Welker, K. M., Zilioli, S., & Carré, J. M. (2015). Testosterone and cortisol jointly modulate risk-taking. *Psychoneuroendocrinology*, *56*, 88–99. https://doi.org/10.1016/j.psyneuen.2015.02.023

109. Mendelowitz, D. (1996). Firing properties of identified parasympathetic cardiac neurons in nucleus ambiguus. *American Journal of Physiology - Heart and Circulatory Physiology*, *271*(6), H2609-2614. https://doi.org/10.1152/ajpheart.1996.271.6.H2609

110. Natarajan, A., Pantelopoulos, A., Emir-Farinas, H., & Natarajan, P. (2020). Heart rate variability with photoplethysmography in 8 million individuals: a cross-sectional study. *The Lancet Digital Health*, *2*(12), e650–e657. https://doi.org/10.1016/S2589-7500(20)30246-6

111. Neave, N. (2008). *Hormones and Behaviour: A Psychological Approach*. Cambridge University Press. https://doi.org/10.1017/CBO9780511808203

112. Nelson, R. J. (2005). *An Introduction to Behavioral Endocrinology*. MA: Sinauer Associates.

113. Nicholson, N., Soane, E., Fenton-O'Creevy, M., & Willman, P. (2005). Personality and domain-specific risk taking. *Journal of Risk Research*, *8*(2), 157–176. https://doi.org/10.1080/1366987032000123856

114. Nofsinger, J. R., Patterson, F. M., & Shank, C. A. (2018). Decision-making, financial risk aversion, and behavioural biases: The role of testosterone and stress. *Economics and Human Biology*, *29*, 1–16. https://doi.org/10.1016/j.ehb.2018.01.003

115. Oxford Learner's Dictionary. (2024). *Definition of Risk*. https://www.oxfordlearnersdictionaries.com/definition/english/risk_1

116. Padoa-Schioppa, C., & Conen, K. E. (2017). Orbitofrontal Cortex: A Neural Circuit for Economic Decisions. *Neuron*, *96*(4), 736–754. https://doi.org/10.1016/j.neuron.2017.09.031

117. Peper, J. S., Braams, B. R., Blankenstein, N. E., Bos, M. G. N., & Crone, E. A. (2018). Development of Multifaceted Risk Taking and the Relations to Sex Steroid Hormones: A Longitudinal Study. *Child Development*, *89*(5), 1887–1907. https://doi.org/10.1111/cdev.13063

118. Peper, J. S., Koolschijn, P. C. M. P., & Crone, E. A. (2013). Development of Risk Taking: Contributions from Adolescent Testosterone and Orbito-frontal Cortex. *Journal of Cognitive Neuroscience*, *25*(12), 2141–2150. https://doi.org/10.1162/jocn_a_00445

119. Platt, M. L., & Huettel, S. A. (2008). Risky business: The neuroeconomics of decision making under uncertainty. *Nature Neuroscience*, *11*(4), 398–403. https://doi.org/10.1038/NN2062

120. Porges, S. W. (2007). A phylogenetic journey through the vague and ambiguous Xth cranial nerve: A commentary on contemporary heart rate variability research. *Biological Psychology*, *74*(2), 301–307. https://doi.org/10.1016/j.biopsycho.2006.08.007

121. Prell, R., Starcke, K., & Maggioni, M. A. (2024). Following your heart: Cardiac autonomic modulation as a feature of decision-making under ambiguity and risk. *Personality and Individual Differences*, *226*, 112686. https://doi.org/10.1016/j.paid.2024.112686

122. Purves-Tyson, T. D., Owens, S. J., Double, K. L., Desai, R., Handelsman, D. J., & Weickert, C. S. (2014). Testosterone induces molecular changes in dopamine signaling

pathway molecules in the adolescent male rat nigrostriatal pathway. *PLoS ONE*, *9*(3), 1–12. https://doi.org/10.1371/journal.pone.0091151

123. Ramírez, E., Ortega, A. R., & Reyes Del Paso, G. A. (2015). Anxiety, attention, and decision making: The moderating role of heart rate variability. *International Journal of Psychophysiology*, *98*(3), 490–496. https://doi.org/10.1016/j.ijpsycho.2015.10.007

124. Rangel, A., Camerer, C. F., & Montague, P. R. (2008). Neuroeconomics: The neurobiology of value-based decision-making. *Nature Reviews Neuroscience*, *9*(7), 545–556. https://doi.org/10.1038/nrn2357.Neuroeconomics

125. Rolison, J. J., Hanoch, Y., Wood, S., & Liu, P. J. (2014). Risk-Taking Differences Across the Adult Life Span: A Question of Age and Domain. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences*, *69*(6), 870–880. https://doi.org/10.1093/geronb/gbt081

126. Sapienza, P., Zingales, L., & Maestripieri, D. (2009). Gender differences in financial risk aversion and career choices are affected by testosterone. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(36), 15268–15273. https://doi.org/10.1073/pnas.0907352106

127. Sarin, R. K., & Weber, M. (1993). Risk-value models. *European Journal of Operational Research*, *70*(2), 135–149. https://doi.org/10.1016/0377-2217(93)90033-J

128. Sassi, R., Cerutti, S., Lombardi, F., Malik, M., Huikuri, H. V., Peng, C. K., Schmidt, G., & Yamamoto, Y. (2015). Advances in heart rate variability signal analysis: Joint position statement by the e-Cardiology ESC Working Group and the European Heart Rhythm Association co-endorsed by the Asia Pacific Heart Rhythm Society. *Europace*, *17*(9), 1341–1353. https://doi.org/10.1093/europace/euv015

129. Savage, L. J. (1954). *The Foundations of Statistics*. Wiley.

130. Schipper, B. C. (2023). Sex hormones and choice under risk. *Journal of Economic Psychology*, *96*, 1–24. https://doi.org/10.1016/j.joep.2023.102607

131. Schonberg, T., Fox, C. R., & Poldrack, R. A. (2011). Mind the gap: Bridging economic and naturalistic risk-taking with cognitive neuroscience. *Trends in Cognitive Sciences*, *15*(1), 11–19. https://doi.org/10.1016/j.tics.2010.10.002

132. Schultz, W., Preuschoff, K., Camerer, C. F., Hsu, M., Fiorillo, C. D., Tobler, P. N., & Bossaerts, P. (2008). Explicit neural signals reflecting reward uncertainty.

Philosophical Transactions of the Royal Society B: Biological Sciences, *363*(1511), 3801–3811. https://doi.org/10.1098/rstb.2008.0152

133. Šimić, G., Tkalčić, M., Vukić, V., Mulc, D., Španić, E., Šagud, M., Olucha-Bordonau, F. E., Vukšić, M., & Hof, P. R. (2021). Understanding emotions: Origins and roles of the amygdala. *Biomolecules*, *11*(6), 823. https://doi.org/10.3390/biom11060823

134. Smilie, L. D., Pickering, A. D., & Jackson, C. J. (2006). The New Reinforcement Sensitivity Theory: Implications for Personality Measurement. *Personality and Social Psychology Review*, *10*(4), 320–335. https://doi.org/10.1207/s15327957pspr1004_3

135. Stanton, S. J., Liening, S. H., & Schultheiss, O. C. (2011). Testosterone is positively associated with risk taking in the Iowa Gambling Task. *Hormones and Behavior*, *59*(2), 252–256. https://doi.org/10.1016/j.yhbeh.2010.12.003

136. Stanton, S. J., Mullete-Gillman, O. A., McLaurin, R. E., Kuhn, C. M., LaBar, K. S., Platt, M. L., & Huettel, S. A. (2011). Low- and High-Testosterone Individuals Exhibit Decreased Aversion to Economic Risk. *Psychological Science*, *22*(4), 447–453. https://doi.org/10.1177/0956797611401752

137. Stanton, S. J., Welker, K. M., Bonin, P. L., Goldfarb, B., & Carré, J. M. (2021). The effect of testosterone on economic risk-taking: A multi-study, multi-method investigation. *Hormones and Behavior*, *134*, 105014. https://doi.org/10.1016/j.yhbeh.2021.105014

138. Starcke, K., & Brand, M. (2012). Decision making under stress: A selective review. *Neuroscience and Biobehavioral Reviews*, *36*(4), 1228–1248. https://doi.org/10.1016/j.neubiorev.2012.02.003

139. Starmer, C. (2000). Developments in Non-expected Utility Theory: The Hunt for a Descriptive Theory of Choice under Risk. *Journal of Economic Literature*, *38*(2), 332–382. https://doi.org/10.1257/jel.38.2.332

140. Steingroever, H., Wetzels, R., Horstmann, A., Neumann, J., & Wagenmakers, E.-J. (2013). Performance of healthy participants on the Iowa Gambling Task. *Psychological Assessment*, *25*(1), 180–193. https://doi.org/10.1037/a0029929

141. Symmonds, M. (2011). *The Neurobiology of Decision Making under Risk* [Doctoral dissertation, UCL Discovery]. https://discovery.ucl.ac.uk/id/eprint/1336527/

142. Tecan. (2019). *Instructions for Use: Testosterone Saliva ELISA*.

143. Thayer, J. F. (2006). On the Importance of Inhibition: Central and Peripheral Manifestations of Nonlinear Inhibitory Processes in Neural Systems. *Dose-Response*, *4*(1), 2–21. https://doi.org/10.2203/dose-response.004.01.002.thayer

144. Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: The neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine*, *37*(2), 141–153. https://doi.org/10.1007/s12160-009-9101-z

145. Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders*, *61*(3), 201–216. https://doi.org/10.1016/S0165-0327(00)00338-4

146. Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart-brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience and Biobehavioral Reviews*, *33*(2), 81–88. https://doi.org/10.1016/j.neubiorev.2008.08.004

147. Thayer, J. F., & Sternberg, E. (2006). Beyond Heart Rate Variability. *Annals of the New York Academy of Sciences*, *1088*(1), 361–372. https://doi.org/10.1196/annals.1366.014

148. Tobler, P. N., & Weber, E. U. (2014). Valuation for Risky and Uncertain Choices. In P. W. Glimcher & E. Fehr (Eds.), *Neuroeconomics: Decision-Making and the Brain* (pp. 149–172). Elsevier Inc.

149. Tom, S. M., Fox, C. R., Trepel, C., & Poldrack, R. A. (2007). The Neural Basis of Loss Aversion in Decision-Making Under Risk. *Science*, *315*(5811), 515–518. https://doi.org/10.1126/science.1134239

150. Tung, Y. H., & Hsieh, J. C. (2019). The Impacts of Mindfulness on Heart Rate Variability: A Brief Review. *International Journal of Pharma Medicine and Biological Sciences*, *8*(4), 132–137. https://doi.org/10.18178/ijpmbs.8.4.132-137

151. Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty*, *5*(4), 297–323. https://doi.org/10.1007/BF00122574

152. Van Anders, S. M., Steiger, J., & Goldey, K. L. (2015). Effects of gendered behavior on testosterone in women and men. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(45), 13805–13810. https://doi.org/10.1073/pnas.1509591112

153. Van Honk, J., Schutter, D. J. L. G., Hermans, E. J., Putman, P., Tuiten, A., & Koppeschaar, H. (2004). Testosterone shifts the balance between sensitivity for punishment and reward in healthy young women. *Psychoneuroendocrinology*, *29*(7), 937–943. https://doi.org/10.1016/j.psyneuen.2003.08.007

154. Von Neumann, J., & Morgenstern, O. (1944). *Theory of games and economic behavior*. Princeton University Press.

155. Wakker, P. P. (2001). Testing and characterizing properties of nonadditive measures through violations of the sure-thing principle. *Econometrica*, *69*(4), 1039–1059.

156. Waxenbaum, J. A., Reddy, V., & Varacallo, M. (2021). *Anatomy, Autonomic Nervous System* (StatPearls). StatPearls Publishing.

157. Weber, E. U. (1997). The utility of measuring and modeling perceived risk. In A. A. J. Marley (Ed.), *Choice, Decision, and Measurement: Essays in Honour of R. Duncan Luce* (pp. 45–57). Lawrence Erlbaum Associates Publishers.

158. Weber, E. U., Blais, A.-R., & Betz, N. E. (2002). A domain-specific risk-attitude scale: Measuring risk perceptions and risk behaviors. *Journal of Behavioral Decision Making*, *15*, 263–290. https://doi.org/10.1017/S1930297500000334

159. Weber, E. U., & Hsee, C. (1998). Cross-Cultural Differences in Risk Perception, but Cross-Cultural Similarities in Attitudes Towards Perceived Risk. *Management Science*, *44*(9), 1167–1320. https://doi.org/10.1287/mnsc.44.9.1205

160. Weber, E. U., & Johnson, E. J. (2009). Decisions Under Uncertainty: Psychological, Economic, and Neuroeconomic Explanation of Risk Preferences. In P. W. Glimcher, C. F. Camerer, E. Fehr, & R. A. Poldrack (Eds.), *Neuroeconomics: Decision-Making and the Brain* (pp. 127–144). Elsevier Academic Press. https://doi.org/10.1016/B978-0-12-374176-9.00010-5

161. Welker, K. M., Gruber, J., & Mehta, P. H. (2015). A positive affective neuroendocrinology approach to reward and behavioural dysregulation. *Frontiers in Psychiatry*, *6*(93), 1–10. https://doi.org/10.3389/fpsyt.2015.00093

162. Welker, K. M., Roy, A. R. K., Geniole, S., Kitayama, S., & Carré, J. M. (2019). Taking risks for personal gain: An investigation of self-construal and testosterone responses to competition. *Social Neuroscience*, *14*(1), 99–113. https://doi.org/10.1080/17470919.2017.1407822

163. Westbrook, A., Yang, X., Bylsma, L. M., Daches, S., George, C. J., Seidman, A. J., Jennings, J. R., & Kovacs, M. (2023). Economic Choice and Heart Rate Fractal Scaling Indicate That Cognitive Effort Is Reduced by Depression and Boosted by Sad Mood. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *8*(7), 687–694. https://doi.org/10.1016/j.bpsc.2022.07.008

164. White, S. F., Lee, Y., Schlund, M. W., Shirtcliff, E. A., & Ladouceur, C. D. (2020). Response to Reward in Early Adolescence. *Behavioral Brain Research*, *387*, 112593. https://doi.org/10.1016/j.bbr.2020.112593.Testosterone

165. Williams, D. W. P., Cash, C., Rankin, C., Bernardi, A., Koenig, J., & Thayer, J. F. (2015). Resting heart rate variability predicts self-reported difficulties in emotion regulation: A focus on different facets of emotion regulation. *Frontiers in Psychology*, *6*. https://doi.org/10.3389/fpsyg.2015.00261

166. Wood, R. I., & Newman, S. W. (1999). Androgen receptor immunoreactivity in the male and female Syrian hamster brain. *Journal of Neurobiology*, *39*(3), 359–370. https://doi.org/https://doi.org/10.1002/(SICI)1097-4695(19990605)39:3<359::AID-NEU3>3.0.CO;2-W

167. Wulff, D. U., Mergenthaler-Cansexo, M., & Hertwig, R. (2018). A meta-analytic review of two models of learning and the description-experience gap. *Psychological Bulletin*, *144*(2), 140–176. https://doi.org/10.1037/bul0000115

168. Yaroslavsky, I., Rottenberg, J., & Kovacs, M. (2013). The utility of combining RSA indices in depression prediction. *Journal of Abnormal Psychology*, *122*(2), 314–321. https://doi.org/10.1037/a0032385

169. Yellon, S. M., Hutchison, J. S., & Goldman, B. D. (1989). Sexual differentiation of the steroid feedback mechanism regulating follicle-stimulating hormone secretion in the Syrian hamster. *Biology of Reproduction*, *41*(1), 7–14. https://doi.org/10.1095/biolreprod41.1.7

170. Zethraeus, N., Kocoska-Maras, L., Ellingsen, T., Von Schoultz, B., Lindé N Hirschberg, A., & Johannesson, M. (2009). A randomized trial of the effect of estrogen and testosterone on economic behavior. *Economic Sciences*, *106*(16), 6535–6538. https://doi.org/10.1073/pnas.0812757106

171. Zilioli, S., & Watson, N. V. (2014). Testosterone across successive competitions: Evidence for a "winner effect" in humans? *Psychoneuroendocrinology*, *47*, 1–9. https://doi.org/10.1016/j.psyneuen.2014.05.001

172. Zuckerman, M. (2002). Zuckerman-Kuhlman personality questionnaire (ZKPQ): An alternative five-factorial model. In B. de Raad & M. Perugini (Eds.), *Big Five Assessment* (pp. 376–392). Hogrefe & Huber Publishers.

173. Zuckerman, M., & Kuhlman, D. M. (2000). Personality and risk-taking: Common biosocial factors. *Journal of Personality*, *68*(6), 999–1029. https://doi.org/10.1111/1467-6494.00124

174. Žunkovič, B., Kejžar, N., & Bajrović, F. F. (2023). Standard Heart Rate Variability Parameters—Their Within-Session Stability, Reliability, and Sample Size Required to Detect the Minimal Clinically Important Effect. *Journal of Clinical Medicine*, *12*(9), 3118. https://doi.org/10.3390/jcm12093118

APPENDICES

Appendix 1: Daljši povzetek (Extended summary in Slovene language)

Naslov v slovenskem jeziku: Povezava psiholoških in fizioloških značilnosti z nagnjenostjo k tveganju pri finančnih odločitvah

1. Uvod

Odločanje je večfazni proces, ki ga običajno sestavljata dve glavni fazi: vrednotenje in izbira (Rangel et al., 2008). Na vrednotenje vplivajo številne spremenljivke, med katerimi je tveganost možnih izidov ključna za razumevanje finančnih odločitev posameznika (Tobler & Weber, 2014). V ekonomiji sta odločanje v razmerah tveganja in odločanje v razmerah negotovosti povezana pojma, vendar predstavljata različna koncepta (De Groot & Thurik, 2018). Pri odločanju v razmerah tveganja je izid neznan, vendar je porazdelitev verjetnosti tega izida znana, nasprotno pa sta pri odločanju v razmerah negotovosti tako izid kot porazdelitev verjetnosti neznana (Platt & Huettel, 2008). Psihologija in nevrobiologija empirično podpirata razlikovanje med tveganjem in negotovostjo, saj kažeta, da sta ta dva koncepta v možganih različno kodirana (Blankenstein et al., 2017; Huettel et al., 2006; Schultz et al., 2008). Kljub temu številne obstoječe študije pogosto ne razlikujejo ustrezno med obema, tako na konceptualni kot metodološki ravni (De Groot & Thurik, 2018).

Tradicionalne ekonomske teorije nagnjenost k tveganju pri odločanju v razmerah tveganja in negotovosti opredeljujejo z vidika funkcije koristnosti in racionalne izbire v okviru modelov pričakovane koristnosti (modeli EU – angl. expected utility models) (Bernoulli, 1954). Čeprav je ta normativni in matematični pristop teoretično privlačen, v praksi pogosto sistematično krši svoja temeljna načela (Starmer, 2000). Področje vedenjske ekonomije se je razvilo, da bi lahko z vključevanjem psiholoških spoznanj obravnavali izzive klasičnih modelov odločanja (Glimcher & Fehr, 2014). Eden izmed vplivnejših teoretičnih okvirov, ki uspešno pojasnjuje številne paradokse in navidezno neracionalno vedenje, je teorija obetov, ki sta jo razvila Kahneman in Tversky (1979). Kljub temu pa tudi ta teorija ostaja nezadostna pri nekaterih vidikih deskriptivnega pristopa k odločanju v razmerah tveganja in negotovosti (Camerer, 1998; Kahneman et al., 1991). Alternativni pristop izhaja iz finančnih teorij in je znan kot model tveganja in donosa (angl. risk-return model) (Markowitz, 1952). V tem modelu odločevalci ocenjujejo tvegane možnosti tako, da tehtajo pričakovane donose v primerjavi s povezanimi tveganji, pri čemer poskušajo zmanjšati tveganje za dani pričakovani donos (Tobler & Weber, 2014). Čeprav model tveganja in donosa ponuja prednosti pred EU modeli, se pod določenimi pogoji ujema z njimi in si tudi deli nekatere omejitve (Fox et al., 2015).

Kot odgovor na omejitve klasične in vedenjske ekonomije pri pojasnjevanju odločanja v razmerah tveganja in negotovosti, se je razvilo novo, interdisciplinarno raziskovalno področje – nevroekonomija. Znana tudi kot nevroznanost odločanja, je eno od področij kognitivne in vedenjske nevroznanosti, katere glavni cilj je razumevanje procesa

človekovega odločanja prek bioloških temeljev ekonomske kognicije in vedenja (Bashir et al., 2023; Camerer et al., 2015).

Vpliv kognicije in čustev na telesna stanja in posledično na naše vedenje je vzajemen in moduliran s povratnimi mehanizmi, pri čemer imata avtonomno živčevje (angl. autonomic nervous system – ANS) in endokrini sistem ključno vlogo pri tej integraciji (Thayer & Lane, 2000; Welker et al., 2015). Osrednji del ANS, ki je imenovan osrednje avtonomno omrežje (angl. central autonomic network – CAN), vključuje več možganskih struktur, ki uravnavajo pretok informacij med nižjimi in višjimi ravnmi osrednjega živčnega sistema in integrirajo visceromotorične, nevroendokrine, bolečinske in vedenjske odzive, ki so bistveni za preživetje, prilagodljivost spremembam v okolju in ciljno usmerjeno vedenje (Benarroch, 1993; Laborde et al., 2018). Prefrontalni korteks pri tem izvaja inhibicijski nadzor nad subkortikalnimi strukturami, kar omogoča zatiranje impulznih in refleksnih odzivov ter spodbuja bolj premišljeno odločanje. CAN sprejema in pošilja informacije v telesne organe in tkiva preko simpatičnega (angl. sympathetic nervous system – SNS) in parasimpatičnega živčnega sistema (angl. parasympathetic nervous system – PNS), ki imata običajno nasprotujoče si učinke na določeno tkivo. SNS prevladuje med nujnimi odzivi v fazi "boj ali beg" in med vadbo, PNS pa prevladuje med mirnimi pogoji počitka, ki spodbujajo obnovitvene procese (Waxenbaum et al., 2021). Čeprav srce inervirata obe vrsti živčnih vlaken, ima zaradi razlike v hitrosti sprememb odzivov glavni vpliv na srce parasimpatični zaviralni vpliv (Laborde et al., 2018). Tako večja modulatorna parasimpatična aktivnost povečuje sposobnost ustreznega odzivanja na hitre spremembe v okolju (Thayer & Lane, 2009). Modulatorno aktivnost simpatičnega in parasimpatičnega živčnega sistema lahko ocenjujemo z variabilnostjo srčne frekvence (angl. heart rate variability – HRV), ki odraža časovno variabilnost med dvema zaporednima srčnima utripoma (Malik, 1996). Višja modulatorna parasimpatična aktivnost kaže na boljšo samoregulacijo in prilgodljivost, saj odraža močnejši inhibicijski nadzor prefrontalnega korteksa nad subkortikalnimi strukturami, kar posamezniku omogoča boljše obvladovanje impulznih odzivov. Posamezniki z višjo bazalno vrednostjo modulatorne parasimpatične aktivnosti so pri sprejemanju odločitev v razmerah tveganja in negotovosti bolje opremljeni za zaviranje začetnih odzivov na nagrade, kar vodi do sprejemanja manj tveganih odločitev.

V zadnjem desetletju je bilo opravljenih nekaj raziskav, ki so preučevale povezavo med HRV in nagnjenostjo k tveganju pri sprejemanju odločitev v razmerah tveganja in negotovosti, vendar rezultati niso enotni (Forte et al., 2022). Pri odločanju v razmerah negotovosti so v nekaj študijah ugotovili negativno povezavo med nagnjenostjo k tveganju in parametri HRV v mirovanju, ki odražajo parasimpatično modulacijo srčne frekvence (Bhatt et al., 2015; Forte et al., 2021). V eni od raziskav so ugotovili pozitivno povezavo med izogibanjem negotovosti in parametri HRV v mirovanju, kar odraža ravnovesje simpatično-parasimpatične modulacije (Jiryis et al., 2022). Nasprotno pa je druga študija pokazala negativno povezavo med parametri HRV v mirovanju, ki prav tako odražajo simpatično-parasimpatično modulacijo, in nagnjenostjo k tveganju (Drucaroff et al., 2011).

Medtem ko je povezava med HRV in nagnjenostjo k tveganju v razmerah negotovosti bolje raziskana, ostaja povezava med HRV in nagnjenostjo k tveganju pri odločitvah v razmerah tveganja manj raziskana. V treh študijah niso ugotovili pomembne povezave med različnimi parametri HRV, ki odražajo bodisi parasimpatično modulacijo bodisi simpatično-parasimpatično ravnovesje, in nagnjenostjo k tveganju (Drucaroff et al., 2011; Jiryis et al., 2022; Prell et al., 2024). Poleg tega je le ena študija doslej ločeno obravnavala odločanje v razmerah tveganja in negotovosti ter preučila povezavo s HRV (Prell et al., 2024). V tej raziskavi niso ugotovili pomembne povezave med HRV v mirovanju in nagnjenostjo k tveganju pri odločanju v razmerah tveganja in negotovosti, zato je potrebnih več podatkov za boljše razumevanje povezave med parametri HRV v mirovanju in nagnjenostjo k tveganju v različnih kontekstih.

Prilagoditveni odzivi na spremembe v okolju vključujejo živčni sistem ter interakcijo slednjega z drugimi telesnimi sistemi, kot je endokrini sistem, ki komunicira s telesom preko hormonov (Breedlove & Watson, 2020). Nekateri hormoni lahko prehajajo krvno-možgansko pregrado, se vežejo na možganske receptorje in lahko tako neposredno vplivajo na vedenje (Breedlove & Watson, 2020). Med temi hormoni je tudi testosteron, steroidni hormon, ki je zaradi svoje vloge v reproduktivni fiziologiji in vedenju, še posebej pri moških, pritegnil veliko pozornosti tudi v kontekstu finančnega odločanja (Apicella et al., 2008, 2015; Herbert, 2018). Testosteron predstavlja hormonski mehanizem vedenjske disregulacije[10], saj povečuje nevronsko aktivnost v možganskih regijah, povezanih z nagrajevanjem, kar spodbuja vedenje, usmerjeno k iskanju nagrad, hkrati pa lahko zmanjša zaznavanje tveganja, kar lahko vodi do povečanega tveganega vedenja (Hermans et al., 2010; Van Honk et al., 2004; Welker et al., 2015).

Na podlagi nevroendokrinološkega teoretičnega okvirja PANE bi lahko na povezavo med hormonskim mehanizmom vedenjske disregulacije in nagnjenostjo k tveganju vplivale tudi individualne razlike v procesiranju nagrad, ki so povezane z vedenjskimi sistemi približevanja in umika in se odražajo v osebnostnih lastnostih družabnosti in nevroticizma-anksioznosti (Corr, 2004; DeYoung & Blain, 2020; Welker et al., 2015). Posamezniki z visoko aktivnim vedenjskim sistemom približevanja so bolj občutljivi na nagradne dražljaje, kar bi moralo okrepiti učinek testosterona na nagnjenost k tveganju preko funkcije procesiranja nagrad, medtem ko so posamezniki z visoko aktivnim vedenjskim sistemom umika bolj občutljivi na potencialne nevarnosti, kar bi moralo zavirati učinek testosterona na nagnjenost k tveganju preko funkcije procesiranja nagrad. Študije o možnih moderacijskih učinkih individualnih razlik na povezavo med ravnmi testosterona in nagnjenostjo k tveganju so preliminarne in bi jih bilo treba sistematično podrobneje preučiti.

[10] Hormoni imajo ključno vlogo pri uravnavanju vedenja in lahko vplivajo na tveganje, ki je v določenih kontekstih lahko prilagodljivo. Obenem pa lahko določene ravni hormonov prispevajo tudi k vedenjski disregulaciji, kar vodi do neprilagodljivih vedenj, kot je pretirano tveganje. Glede na to, da namen te disertacije ni razlikovati med prilagodljivimi in neprilagodljivimi oblikami tveganja, se izraz 'vedenjska disregulacija' uporablja v širšem kontekstu za opis tveganega vedenja na splošno.

2. Namen in hipoteze

Namen te disertacije je preučiti, kako so različni fiziološki (sistem samoregulacije in prilagodljivosti merjen s HRV ter hormonski mehanizem vedenjske disregulacije merjen s testosteronom) in psihološki mehanizmi (osebnostne značilnosti nevroticizem-anskioznost in družabnost, ki so povezani z vedenjskim sistemom umika in približevanja) povezani z nagnjenostjo k tveganju pri odločanju v razmerah tveganja in v razmerah negotovosti.

Da bi preučili učinke bazalne sposobnosti samoregulacije in prilagodljivosti na nagnjenost k tveganju pri odločanju v razmerah tveganja in negotovosti postavljamo naslednjo hipotezo:

1. Višja modulatorna parasimpatična aktivnost v mirovanju je povezana z manjšo nagnjenostjo k tveganju pri odločanju v razmerah tveganja in negotovosti.

Da bi preučili medsebojne učinke bazalne ravni testosterona in osebnostnih lastnosti, povezanih z individualnimi razlikami v vedenjskem sistemu umika in približevanja, na nagnjenost k tveganju pri odločanju v razmerah tveganja in negotovosti postavljamo naslednji hipotezi:

2. Bazalna raven testosterona je pozitivno povezana z nagnjenostjo k tveganju pri odločanju v razmerah tveganja in negotovosti le pri posameznikih z nizko oceno osebnostne lastnosti nevrotičnost-anksioznost.
3. Bazalna raven testosterona je pozitivno povezana z nagnjenostjo k tveganju pri odločanju v razmerah tveganja in negotovosti le pri posameznikih z visoko oceno osebnostne lastnosti družabnosti.

3. Metode

V naši študiji so sodelovali diplomanti Univerze v Ljubljani in njeni alumni, ki so imeli vsaj nekaj let delovnih izkušenj. Pred sodelovanjem v raziskavi so morali predložiti podpisan obrazec o informiranem soglasju. Zasnovo raziskave in vse s tem povezane postopke sta odobrili Komisija za etiko in raziskovanje Ekonomske fakultete Univerze v Ljubljani in Nacionalna komisija za medicinsko etiko Republike Slovenije.

Udeleženci so bili pred eksperimentom naprošeni, da vsaj dve uri prej ne kadijo, ne jedo, ne pijejo kave, ne žvečijo, ne uporabljajo zobne nitke, ne jemljejo zdravil in se ne ukvarjajo s telesno dejavnostjo. Poleg tega so morali 24 ur pred eksperimentom izključiti uživanje alkohola in se izogniti ekstremni telesni dejavnosti.

Zbiranje podatkov je potekalo v več terminih, od aprila 2022 do septembra 2022, v istih časovnih intervalih, od približno 7:30 do 9:30 zjutraj. Ko so preiskovanci vstopili v laboratorij, smo jim namestili trak s senzorjem Polar H10 okoli prsnega koša in jim dodelili uro Polar V800 za beleženje srčnega utripa. Zbiranje podatkov smo izvedli v dveh delih, z vmesnim 20-minutnim odmorom. Vsak del je bil sestavljen iz faze počitka, faze reaktivnosti

in faze okrevanja, pri čemer je vsaka trajala deset minut. Srčna frekvenca je bila beležena skladno s smernicami za merjenje variabilnosti srčne frekvence (Malik, 1996). Takoj po prvi desetminutni fazi počitka so bili odvzeti vzorci sline za testiranje hormonov, kar je trajalo povprečno štiri minute.

Po začetni fazi počitka so udeleženci opravili vedenjski test za oceno nagnjenosti k tveganju pri odločanju v razmerah negotovosti, in sicer nalogo tveganja z baloni (angl. Balloon Analogue Risk Task – BART) (Lejuez et al., 2002), za oceno nagnjenosti k tveganju pri odločanju v razmerah tveganja pa nalogo igre s kockami (Game of Dice Task – GDT) (Brand et al., 2004). Vrstni red vedenjskih testov je bil za vsako testno skupino naključno določen. Po prvem delu eksperimenta so imeli udeleženci 20-minutni odmor, zatem pa je sledil drugi del eksperimenta, kjer so opravili drugi vedenjski test. Ob koncu eksperimenta so udeleženci izpolnili splošni vprašalnik o svoji starosti, izobrazbi, telesni dejavnosti in zdravstveni anamnezi. Izpolnili so tudi Zuckerman-Kuhlmanov osebnostni vprašalnik (angl. Zuckerman-Kuhlman Personality Questionnaire – ZKPQ) (Zuckerman & Kuhlman, 2000) za oceno osebnostnih lastnosti nevroticizem-anksioznost in družabnost. Da bi spodbudili čim bolj realno vedenje pri obeh vedenjskih testih smo iz vsake testne skupine naključno izbrali enega udeleženca, ki je prejel darilni bon za nakup v športni trgovini v višini skupnega zaslužka pri vedenjskem testu BART. Udeleženci so bili vnaprej obveščeni o možnosti prejema finančne nagrade v višini njihovega skupnega zaslužka pri vedenjskem testu BART.

Za analizo prve hipoteze smo izvedli multiplo linearno regresijo. V dodatnih analizah, kjer smo preverjali morebitne učinke interakcije med HRV v mirovanju in HRV reaktivnosti, smo v multipli linearni regresiji upoštevali tudi interakcijske učinke. Za razlago statistično značilnih interakcij smo uporabili t. i. angl. simple slope analysis (Hayes, 2022).

Za preverjanje druge in tretje hipoteze smo prav tako izvedli multiplo linearno regresijo z vključenimi interakcijskimi učinki. Za razlago statistično značilnih interakcij smo uporabili t. i. angl. simple slope analysis (Hayes, 2022).

4. Rezultati

Za preverjanje **prve hipoteze** smo na vzorcu 82 udeležencev preučevali povezavo med HRV v mirovanju in nagnjenostjo k tveganju pri odločanju v razmerah tveganja in v razmerah negotovosti. Pri nobenem od preučevanih parametrov HRV v mirovanju ali reaktivnosti (standardni odklon NN intervalov, angl. standard deviation of NN intervals – SDNN; kvadratni koren povprečne kvadrirane razlike med sosednjima intervaloma NN, angl. root mean square of successive differences – RMSSD; nizkofrekvenčna komponenta HRV, angl. low frequency component of HRV – LF; visokofrekvenčna komponenta HRV, angl. high frequency component of HRV – HF; visokofrekvenčna komponenta HRV v normaliziranih enotah, angl. high frequency component of HRV in normalized units – HFnu; razmerje med nizkofrekvenčno in visokofrekvenčno komponento HRV, angl. ratio between low frequency and high frequency component of HRV – LF/HF) nismo zaznali pomembne povezave z

nagnjenostjo k tveganju v nobenem od pogojev, zato prve hipoteze ne moremo potrditi. Naše ugotovitve se ujemajo z nedavno študijo, ki prav tako ni zaznala pomembne povezave med HRV v mirovanju in nagnjenostjo k tveganju pri odločanju v razmerah tveganja in v razmerah negotovosti (Prell et al., 2024), vendar je v nasprotju s predhodnimi študijami, ki so zaznale značilno povezavo med HRV in nagnjenostjo k tveganju pri odločanju v razmerah negotovosti (Bhatt et al., 2015; Forte et al., 2019; Ramírez et al., 2015). Naše ugotovitve bi lahko razložili s pomočjo teorije angl. vagal tank theory (Laborde et al., 2018), katere osrednja ideja je preučevanje HRV parametrov v vseh fazah preizkusa, vključno z mirovanjem in reaktivnostjo. Rezultati analize interakcije med dvema fazama lahko razkrijejo mehanizme samoregulacije in prilagodljivosti, ki sicer niso vidni, npr. v primerih, ko analiziramo samo HRV v mirovanju, kar pa nakazuje na pomembnost upoštevanja dinamike parasimpatične modulacije pri procesu odločanja v razmerah tveganja in negotovosti.

V naši raziskavi smo tako dodatno preučili potencialne interakcijske učinke med HRV v mirovanju in med odločanjem (faza reaktivnosti), kar odraža sposobnosti prilagajanja na spreminjajoče se okoljske zahteve ter na nagnjenost k tveganju pri odločanju v razmerah negotovosti in tveganja. Ugotovili smo, da posamezniki z visoko modulatorno parasimpatično aktivnostjo v mirovanju, pri katerih se ta med odločanjem ne zmanjša ali se še celo poveča, izkazujejo večjo nagnjenost k tveganju pri odločanju v razmerah negotovosti. V razmerah tveganja tovrstnih učinkov nismo zaznali.

Čeprav ta opažanja niso popolnoma primerljiva z drugimi študijami zaradi uporabe različnih parametrov HRV, podpirajo hipotezo, da je prilagodljivost, vključno z reaktivnostjo HRV med odločanjem, ključna za učinkovito sprejemanje odločitev (Laborde et al., 2018; Porges, 2007). Visoka modulatorna parasimpatična aktivnost v mirovanju je povezana z boljšo čustveno regulacijo, kognitivno prožnostjo in odpornostjo na stres, kar omogoča mirno in učinkovito vedenje v negotovem okolju (Forte et al., 2021). Med procesom odločanja se lahko za prilagodljiv odziv šteje tako povečanje kot zmanjšanje modulatorne parasimpatične aktivnosti. Povečanje nakazuje, da so viri usmerjeni v miselni napor, kar spodbuja umirjeno razmišljanje in zmanjšuje nagnjenost k tveganju (Porges, 2007), medtem ko se zmanjšanje parasimpatične modulacije lahko pojavi kot stresni odziv, kar poveča nagnjenost k tveganju (Laborde et al., 2018). Naše opažanje, da je bila visoka modulatorna parasimpatična aktivnost v mirovanju povezana z večjo nagnjenostjo k tveganju pri posameznikih, ki so imeli visoko modulatorno parasimpatično aktivnost tudi med odločanjem, je mogoče pojasniti z vplivom motivacijskih dejavnikov. Pomanjkanje dejanskih denarnih posledic v laboratorijskem okolju lahko zmanjša motivacijo, kar lahko vodi k bolj tveganemu vedenju kot sicer (Steingroever et al., 2013). Zmanjšana motivacija lahko tudi oslabi fiziološke odzive na kognitivne zahteve in tako zmanjša modulatorno parasimpatično aktivnost (Laborde et al., 2018; Westbrook et al., 2023). Odsotnost znatnih denarnih nagrad v naši študiji je morda znižala motivacijo za vedenjske teste, kar bi lahko vplivalo na modulatorno

parasimpatično aktivnost in s tem na vedenje, ki ne nujno odraža spontane in vsakodnevne odzive.

Za preverjanje **druge in tretje hipoteze** smo ocenili morebitne učinke določenih osebnostnih lastnosti, kot sta nevroticizem-anksioznost in družabnost, na povezavo med bazalno ravnijo testosterona in nagnjenostjo k tveganju v dveh pogojih, pri odločanju v razmerah tveganja in pri odločanju v razmerah negotovosti. Ugotovili smo, da je bila bazalna raven testosterona pozitivno povezana z nagnjenostjo k tveganju pri odločanju v razmerah tveganja pri moških z nizko oceno nevroticizma-anksioznosti, medtem ko je bila pri moških z visoko oceno nevroticizma-anksioznosti negativno povezana z nagnjenostjo k tveganju pri odločitvah v razmerah tveganja. Ti rezultati delno podpirajo drugo hipotezo. Glede na teoretični pristop PANE, testosteron povečuje nevronsko aktivnost v možganskih območjih, povezanih z nagrajevanjem, kot sta ventralno tegmentalno območje in nukleus akumbens, kar poveča občutljivost na nagrade in potencialno vodi do sprejemanja bolj tveganih odločitev (Welker et al., 2015). Poleg tega lahko učinki testosterona delujejo tudi preko modulacije dopaminskih projekcij v amigdalo, ki skupaj s septo-hipokampalnim sistemom predstavljata osnovo za vedenjski sistem umika (Gray & McNaughton, 2000; Šimić et al., 2021; Welker et al., 2015). Pri zelo nevrotičnih in anksioznih posameznikih lahko povečana aktivnost amigdale poveča občutljivost na grožnje, kar vodi do bolj previdnega vedenja, medtem ko lahko tisti z nizkim nevroticizmom in anksioznostjo zaradi zmanjšane občutljivosti na grožnje izkazujejo večjo nagnjenost k tveganju (Everaerd et al., 2015). Naši rezultati delno podpirajo drugo hipotezo, ki predpostavlja, da na razmerje med testosteronom in nagnjenostjo k tveganju pri odločitvah v razmerah tveganja vplivajo osebnostne lastnosti povezane z vedenjskim sistemom umika, kot je nevroticizem-anksioznost.

V naši študiji pa nismo ugotovili pomembnih učinkov vedenjskega sistema približevanja in tako ne moremo potrditi tretje hipoteze. Ti rezultati kažejo, da je povezava med testosteronom in tveganjem bolj vezana na mehanizme, povezane z vedenjskim sistemom umika, in ne toliko z mehanizmi nagrajevanja, ki so vezani na vedenjski sistem približevanja. Skupaj rezultati podpirajo kompleksno vlogo testosterona pri odločanju v razmerah tveganja pri moških, ki je odvisna od osebnostnih lastnosti povezanih z vedenjskim sistemom umika, kot je nevroticizem-anksioznost.

Pri odločitvah v razmerah negotovosti nismo ugotovili vpliva nevroticizma-anksioznosti na povezanost med testosteronom in nagnjenostjo k tveganju pri moških. Razlike v vplivu nevroticizma-anksioznosti na morebitno povezavo med bazalno ravnjo testosterona in nagnjenostjo k tveganju pri odločanju v razmerah tveganja in negotovosti bi lahko razložili z nevrobiološkimi razlikami med tema dvema vrstama odločanja (De Groot & Thurik, 2018). Ena od hipotez predvideva, da razmere negotovosti aktivirajo drugačne možganske sisteme kot razmere tveganja. Druga hipoteza pa predvideva, da oboji pogoji aktivirajo skupne možganske mehanizme, čeprav v različni meri, pri čemer so odzivi na odločitve v enem ali drugem kontekstu lahko močnejši (Bach et al., 2009; Huettel et al., 2006; Krain et al., 2006; Platt & Huettel, 2008; Schultz et al., 2008).

Pri ženskah nismo ugotovili pomembnih učinkov v nobenem od pogojev (odločanje v razmerah tveganja in v razmerah negotovosti), ne glede na upoštevano osebnostno lastnost nevroticizem-anksioznost ali družabnost. Rezultati nekaj študij, ki so preučevale povezavo med bazalno ravnjo testosterona in nagnjenostjo k tveganju pri odločitvah v razmerah tveganja pri obeh spolih, niso enotni (Sapienza et al., 2009; Schipper, 2023; Stanton, Mullete-Gillman, et al., 2011). Razlike v rezultatih teh študij bi lahko pojasnili z ugotovitvami raziskav na živalih, ki so pokazale, da so samice manj odzivne na androgene (npr. testosteron) kot samci, tako glede nevroendokrinega delovanja kot spolnega vedenja (Yellon et al., 1989). Poleg tega ženske v primerjavi z moškimi proizvajajo bistveno manj testosterona in kažejo manjšo variabilnost v ravni testosterona, kar opažamo tudi v našem vzorcu. Manjša variabilnost ravni testosterona pri ženskah lahko zmanjša statistično moč za zaznavanje psiholoških in vedenjskih učinkov testosterona pri ženskah (Wood & Newman, 1999). Glede na to, da testosteron velja za pretežno moški spolni hormon, bi lahko imela ženska spolna hormona, estrogen in progesteron, pomembnejši vpliv na nagnjenost k tveganju pri odločanju v razmerah tveganja in negotovosti pri ženskah kot testosteron. Podobno kot testosteron tudi estrogen in progesteron vplivata na procesiranje nagrad v možganih, kar bi lahko vplivalo na tvegano vedenje (Dreher et al., 2007). Čeprav so nekatere študije preučevale te povezave, so bile ugotovitve mešane (Derntl et al., 2014; Diekhof, 2018; Zethraeus et al., 2009).

5. Omejitve raziskave

Tako kot večina študij, je imela tudi naša določene omejitve. Prvič, zaradi finančnih omejitev vsem udeležencem nismo mogli ponuditi resničnih denarnih nagrad, ki bi bile primerljive z zneski, simuliranimi pri vedenjskih testih BART in GDT. Ta omejitev vpliva na veljavnost naših ugotovitev, saj simulirane denarne nagrade morda ne odražajo resničnega procesa odločanja udeležencev v razmerah tveganja in negotovosti v finančnem kontekstu. Posledično je posplošljivost naših rezultatov omejena na laboratorijsko okolje, zato morda ne bodo neposredno aplikativni v vsakodnevnih finančnih situacijah. Za odpravo teh omejitev bi bilo v prihodnjih raziskavah potrebno potrditi vedenjske teste za merjenje nagnjenosti k tveganju v razmerah tveganja in negotovosti, kot sta GDT in BART v bolj vsakodnevnih življenjskih okoliščinah, z uporabo resničnih denarnih spodbud, ki odražajo dejanske finančne vložke. Ta pristop bi izboljšal uporabnost ukrepov pri sprejemanju finančnih odločitev v resničnem življenju in zagotovil boljše razumevanje tega, kako posamezniki ocenjujejo tveganje in negotovost ter se nanju odzivajo v finančnih okoliščinah.

Drugič, k neznačilnim rezultatom je morda prispevala relativno majhna velikost vzorca. Parametri HRV so zelo spremenljivi, zato je za odkrivanje pomembnih korelacij in razlik med skupinami potrebna zadostna velikost vzorca (Žunkovič et al., 2023). Glede na nedavno metodološko študijo, je v raziskavah HRV v mirovanju najmanjša potrebna velikost vzorca za zaznavanje pomembnih sprememb, kot denimo v logaritmiranih vrednostih RMSSD, HF in HFnu ob uporabi korekcije po Bonferroniju 54, 62 oziroma 171. Tako lahko sklepamo, da je bil naš vzorec 82 udeležencev zadosten za ugotavljanje razlik v parametru RMSSD

mejno zadosten za ugotavljanje razlik v parametru HF ter nezadosten za ugotavljanje razlik v parametru HFnu. To pomeni, da bi morale biti prihodnje študije o HRV opravljene na večjih vzorcih. Podobno velja za študijo o testosteronu. Kljub temu nam je uspelo delno potrditi drugo hipotezo in pokazati, da osebnostna lastnost nevroticizem-anksioznost vpliva na razmerje med bazalno ravnjo testosterona in nagnjenostjo k tveganju pri odločanju v razmerah tveganja pri moških. To podpira tezo, da je odločanje v razmerah tveganja kompleksen proces, ki je odvisen od nevrobioloških in psiholoških sistemov.

Pomembno omejitev študije o povezavi HRV z nagnjenostjo k tveganju vidimo tudi v možnem t. i. učinku prenosa (angl. carry-over effect) (Geng et al., 2022). Vedenjski testi v naši študiji so bili izvedeni v naključnem vrstnem redu z 20-minutnim odmorom med posameznimi deli poskusa. Kljub temu obstaja možnost, da so se učinki prvega vedenjskega testa prenesli v drugo fazo mirovanja, kar bi lahko vplivalo na HRV v mirovanju, vrednosti le-tega pa smo merili pred drugim vedenjskim testom. Za trdnejše zaključke v tem oziru bi bilo potrebno v prihodnosti opraviti raziskavo z ločenima protokoloma študije za vsak test posebej.

Pomembna omejitev naše študije o povezavi testosterona z nagnjenost k tveganju je, da smo preučevali zgolj povezave med endogenimi ravnmi testosterona, določenimi osebnostnimi lastnostmi in nagnjenostjo k tveganju pri odločanju v razmerah tveganja in negotovosti. Zaradi take narave raziskave ne moremo sklepati o vzročnih povezavah med testosteronom in vedenjem. V prihodnjih študijah bi bilo zato smiselno preučiti učinke eksogeno dodanega testosterona, da bi ugotovili vzročne povezave. Poleg tega je bila študija omejena na preučevanje učinkov zgolj enega hormona, testosterona. Mogoče pa je, da bi estradiol, tj. oblika estrogena in pomemben ženski spolni hormon, lahko imel vlogo pri tveganem vedenju pri ženskah (Bröder & Hohmann, 2003; Peper et al., 2018).

6. Prispevek k teoriji in praksi

Odločanje je kompleksen proces, ki vključuje številne psihološke in nevrobiološke mehanizme. Naše ugotovitve podpirajo pomembno vlogo teh dejavnikov pri sprejemanju odločitev v razmerah tveganja in negotovosti.

Na podlagi modela nevrovisceralne integracije bi pričakovali, da bosta samoregulacija in prilagodljivost, ki ju merimo s HRV parametri in odražajo modulatorno parasimpatično aktivnost, negativno povezani z nagnjenostjo k tveganju pri odločanju v razmerah tveganja in negotovosti (Thayer & Lane, 2000). Z drugimi besedami, pričakovali bi, da bodo posamezniki z boljšo sposobnost zaviranja refleksnih odzivov manj tvegali pri teh odločitvah. To hipotezo podpirajo rezultati nekaterih empiričnih raziskav, vendar pa rezultati nekaterih raziskav kažejo nasprotno – na pozitivno povezavo ali pa sploh ne ugotavljajo take povezave. Rezulati naše raziskave razširjajo obstoječe znanje, saj kažejo, da je povezava med samoregulacijo in prilagodljivostjo v mirovanju in nagnjenostjo k tveganju v razmerah negotovosti odvisna od samoregulacije in prilagodljivosti med samim procesom odločanja.

Natančneje, rezultati naše raziskave kažejo, da posamezniki z boljšo bazalno sposobnostjo samoregulacije, ki ostane visoka tudi med odločanjem, sprejemajo bolj tvegane odločitve v kontekstu negotovosti. To je v nasprotju z našimi pričakovanji, saj kaže, da obstaja segment posameznikov, ki so sicer sposobni zavirati impulzivne odzive, vendar kljub temu sprejemajo bolj tvegane odločitve v situacijah negotovosti. Te rezultate bi lahko pojasnili z modulacijsko vlogo motivacijskih procesov. Poleg tega naše ugotovitve nakazujejo, da je povezava med samoregulacijo in prilagodljivostjo ter nagnjenostjo k tveganju odvisna od konteksta, saj smo zaznali pomembno povezavo le pri odločanju v razmerah negotovosti, ne pa tudi v razmerah tveganja. Naš prispevek k praksi je torej razširjanje znanja o povezavi med samoregulacijo in prilagodljivostjo, ki je izmerjena s HRV parametri. To novo znanje lahko apliciramo v kontekstih sprejemanja finančnih odločitev v razmerah tveganja in negotovosti.

Na podlagi teoretičnega okvira PANE bi lahko na povezavo med hormonskim mehanizmom vedenjske disregulacije in nagnjenostjo k tveganju vplivale individualne razlike v procesiranju nagrad, ki so povezane z vedenjskim sistemom približevanja in umika in se odražajo v osebnostnih lastnostih, kot sta družabnost in nevroticizem-anksioznost (Welker et al., 2015). Rezultati naše raziskave kažejo, da na povezanost med bazalnimi vrednostmi testosterona in nagnjenostjo k tveganju pri odločanju v razmerah tveganja vpliva osebnostna značilnost nevroticizem-anksioznost, ne pa tudi družabnost, vendar zgolj pri moških. Naša študija je namreč pokazala, da je pri moških, ki niso pretirano nevrotični in anksiozni, višja bazalna vrednost testosterona povezana z višjo nagnjenostjo k tveganju pri odločanju v razmerah tveganja. Pri bolj nevrotičnih in anksioznih moških je ta povezava obratna, torej so višje vrednosti testosterona povezane z nižjo nagnjenostjo k tveganju pri odločanju v razmerah tveganja. Naši rezultati kažejo tudi na pomembnost konteksta, saj je vpliv osebnostne značilnosti nevroticizem-anksioznost pri moških na povezavo med bazalnimi vrednostmi testosterona in nagnjenostjo k tveganju značilen le pri odločanju v razmerah tveganja, ne pa tudi v razmerah negotovosti.

Naši rezultati prispevajo tudi k praksi, saj kažejo na to, da so nevrotični in anksiozni moški z visokimi bazalnimi vrednostmi testosterona bolj nagnjeni k tveganju pri odločanju v razmerah tveganja. To lahko apliciramo na finančne kontekste v tem smislu, da v razmerah tveganja za odločevalce ne postavimo nevrotičnih in anksioznih moških z višjimi bazalnimi vrednostmi testosterona, če ne želimo, da sprejemajo tvegane odločitve. Kljub vsemu se moramo zavedati omejitev raziskave in posledično ustrezne aplikativnosti raziskave v praksi.

Ob tem moramo poudariti, da smo raziskavo tako v prvem kot v drugem delu omejili na preučevanje fizioloških in psiholoških dejavnikov ter vpliva le-teh na nagnjenost k tveganju pri odločanju v razmerah tveganja in negotovosti v laboratorijskem okolju in z uporabo vedenjskih merskih instrumentov za oceno nagnjenosti k tveganju. Za pridobitev bolj trdnih zaključkov, ki jih lahko neposredno apliciramo na vsakodnevno sprejemanje finančnih odločitev v razmerah tveganja in negotovosti, bi bilo v prihodnje potrebno opraviti

raziskave, ki ocenijo razmerje med nagnjenostjo k tveganju in uspešnostjo izven laboratorija in z uporabo merskih instrumentov, ki bolje ponazarjajo odločanje v vsakodnevnih življenjskih okoliščinah.

Kljub omejitvam lahko zaključimo, da naša raziskava prispeva k obstoječi literaturi o sprejemanju odločitev v razmerah tveganja in negotovosti, saj pojasnjuje medsebojno delovanje psiholoških in nevrobioloških mehanizmov v različnih kontekstih odločanja.

Appendix 2: Zuckerman-Kuhlman Personality Questionnaire

On this page, you will find a series of statements that people might use to describe themselves. Read each statement and decide whether or not it describes you. If you agree with a statement or decide that it describes you, answer TRUE. If you disagree with a statement or feel that it is not descriptive of you, answer FALSE.[11]

Act	1	T F	I do not like to waste time just sitting around and relaxing.
Agg-Host	2	T F	When I get mad, I say ugly things.
Agg-Host	3	T F	It's natural for me to curse when I am mad.
Sy	4	T F	I do not mind going out alone and usually prefer it to being out in a large group.
Act	5	T F	I lead a busier life than most people.
ImpSS	6	T F	I often do things on impulse.
Agg-Host	7	T F	I almost never feel like I would like to hit someone.
Sy	8	T F	I spend as much time with my friends as I can.
N-Anx	9	T F	My body often feels all tightened up for no apparent reason.
N-Anx	10	T F	I frequently get emotionally upset.
Agg-Host	11	T F	If someone offends me, I just try not to think about it.
Act	12	T F	I like to be doing things all of the time.
ImpSS	13	T F	I would like to take off on a trip with no preplanned or definite routes or timetables.
N-Anx	14	T F	I tend to be oversensitive and easily hurt by thoughtless remarks and actions of others.
Sy	15	T F	I do not need a large number of casual friends.
Act	16	T F	I can enjoy myself just lying around and not doing anything active.
ImpSS	17	T F	I enjoy getting into new situations where you can't predict how things will turn out.
N-Anx	18	T F	I am easily frightened.
Agg-Host	19	T F	If people annoy me, I do not hesitate to tell them so.
Sy	20	T F	I tend to be uncomfortable at big parties.
Act	21	T F	I do not feel the need to be doing things all of the time.
N-Anx	22	T F	I sometimes feel panicky.

[11] The participants' copy of the questionnaire did not include the information on which statement belongs to which factor (Act, Agg-Host, Sy, N-Anx, ImpSS).

Sy	23	T F	At parties, I enjoy mingling with many people whether I already know them or not.
ImpSS	24	T F	I sometimes like to do things that are a little frightening.
Act	25	T F	When on vacation I like to engage in active sports rather than just lie around.
ImpSS	26	T F	I'll try anything once.
N-Anx	27	T F	I often feel unsure of myself.
Sy	28	T F	I would not mind being socially isolated in some place for some period of time.
Act	29	T F	I like to wear myself out with hard work or exercise.
ImpSS	30	T F	I would like the kind of life where one is on the move and travelling a lot, with lots of change and excitement.
N-Anx	31	T F	I often worry about things that other people think are unimportant.
Agg-Host	32	T F	When people disagree with me, I cannot help getting into an argument with them.
Sy	33	T F	Generally, I like to be alone so I can do things I want to do without social distractions.
ImpSS	34	T F	I sometimes do "crazy" things just for fun.
Agg-Host	35	T F	I have a very strong temper.
Act	36	T F	I like to be active as soon as I wake up in the morning.
Agg-Host	37	T F	I can't help being a little rude to people I do not like.
Sy	38	T F	I am a very sociable person.
ImpSS	39	T F	I prefer friends who are excitingly unpredictable.
N-Anx	40	T F	I often feel like crying sometimes without a reason.
Act	41	T F	I like to keep busy all the time.
ImpSS	42	T F	I often get so carried away by new and exciting things and ideas that I never think of possible complications.
N-Anx	43	T F	I don't let a lot of trivial things irritate me.
Agg-Host	44	T F	I am always patient with others even when they are irritating.
Sy	45	T F	I usually prefer to do things alone.
N-Anx	46	T F	I often feel uncomfortable and ill at ease for no real reason.
Sy	47	T F	I probably spend more time than I should socializing with friends.
Act	48	T F	When I do things, I do them with lots of energy.
ImpSS	49	T F	I like "wild" uninhibited parties.
Agg-Host	50	T F	When people shout at me, I shout back.

Appendix 3: Socio-demographic questionnaire

Please take a few moments and complete this survey by clicking on "Next page".

1. Write the ID code you received at the beginning of the experiment. _____

2. Choose your gender:
   a) Male
   b) Female

3. How old are you? _____

4. What is your educational background? Please state your highest completed degree thus far. _____

5. What is your job or are you still a student? _____

6. If you work part- or full-time, please provide a short description of your work or name your position. _____

7. Write your height (in cm). _____

8. Write your weight (in kg). _____

9. Are you a professional athlete?
   a) Yes
   b) No

10. How many cigarettes do you smoke per day? _____

11. How many times per week/month do you do aerobic activity (for example, running, hiking, swimming, cycling, etc.)?
    a) Never
    b) Less than 4 times a month
    c) Once a week
    d) A few times a week
    e) Everyday

12. How many times per week/month do you do anaerobic activities (for example, weight trainig, etc.)?
    a) Never
    b) Less than 4 times a month

c) Once a week
d) A few times a week
e) Everyday

13. What sports did you do in your childhood, puberty, in the last three years, and in the last year?

Sports in childhood	
Sports in puberty	
Sports in the last 3 years	
Sports in the last year	

14. Do you usually have lower blood pressure (around 100/60 mmHg or less)?
    a) Yes
    b) No

15. Did you ever experience a sudden loss of consciousness?
    a) Yes
    b) No

16. Are you diagnosed with:

High blood pressure	Yes	No
Chronic heart disease or respiratory disease	Yes	No
Allergies	Yes	No
Mental (for example, major depression) or neurological disorder disease (for example, epilepsy)	Yes	No

17. How many units of alcohol do you drink in a typical week? (1 beer = 2 units, 1 shot of vodka or other spirit = 1 unit, 1 glass of wine – small glass, not fully filled 125ml = 1 unit)? _____

18. How do you currently feel? (e.g., 1 means 'uncomfortable' and 'pleasant' means 7)

Uncomfortable – pleasant	1	2	3	4	5	6	7
Stressed – stress-free	1	2	3	4	5	6	7
Tired – rested	1	2	3	4	5	6	7
Tense – relaxed	1	2	3	4	5	6	7
Restless – calm	1	2	3	4	5	6	7
Slowed down/indifferent – excited	1	2	3	4	5	6	7

19. Were you in a hurry to come here?
    a) Yes
    b) No

20. Did you go to sleep last night as usual?
    a) Yes
    b) No

21. Did you get up this morning as usual?
    a) Yes
    b) No

22. When did you get up this morning? _____

23. When did you go to sleep last night? _____

24. How many hours did you sleep last night (insomnia)? _____

25. Did you have a strong breakfast in the morning (around 7:00)?
    a) Yes
    b) No

26. Did you drink caffeinated drinks in the morning (around 7:00)?
    a) Yes
    b) No

27. Did you smoke after 7:00 in the morning?
    a) Yes
    b) No

28. When was the last time you were physically active? _____

29. If you exercised in the last 24h, describe the type and length of the activity.

    _____

Appendix 4: Pearson correlations between variables in the second study: Effects of neuroticism-anxiety/sociability on the association between testosterone and risk propensity

Variable	N	M	SD	1	2	3	4	5	6	7	8	9
1. Sex	100	0.58	0.50	--								
2. Age	100	28.91	7.75	-.09	--							
3. Decision-making experience	100	0.40	0.49	-.17	**.83****	--						
4. T (pmol/L)	100	0.00	0.10	**-.74****	-.05	.01	--					
5. T (z-score)	100	168.22	124.57	.00	-.07	-.07	**.64****	--				
6. ln(Sy score)	100	1.47	0.66	-.04	-.06	-.07	.16	.16	--			
7. ln(N-Anx score)	100	1.28	0.76	**.21***	**-.36****	**-.36****	**-.22***	-.07	**-.22***	--		
8. ln(BART score)	100	3.53	0.49	.14	-.17	-.06	.06	-.04	-.06	.05	--	
9. ln(GDT score)	100	2.96	0.98	-.13	-.00	-.03	.05	-.05	.07	.03	.02	--

Notes. T = testosterone, Sy = sociability, N-Anx = neuroticism-anxiety, BART = Balloon Analogue Risk Task, GDT = Game of Dice Task. Sex is coded such that 0 represents males and 1 represents females. Decision-making experience is coded such that 0 represents students and 1 represents decision-makers. Significance is displayed at p < .05 (*) and p < .01 (**).

Source: own work.