Resting Vagally Mediated Heart Rate Variability is Associated with Financial Risk Preferences under Stress

Mario García-Molina[1], *Juan Carlos Caicedo*[2], *Liliana Alejandra Chicaíza-Becerra*[3], *Christian Camilo Garcia-Lopez*[4], *Jorge Martínez-Cotrina*[5] & *Diego Mauricio Aponte-Canencio*[6]

KEYWORDS
Autonomous nervous system, risk aversion, decision making, heart rate variability, stress

JEL CODES
G11, G41, M29

RECEIVED
23/03/2024

APPROVED
20/08/2024

PUBLISHED
01/10/2024

SECTION
Finance

Abstract: Business financial risk-taking usually occurs under conditions of stress. Biologically, the stress response has two components: one linked to the hypothalamic-pituitary-adrenal (HPA) axis and the other to the autonomic nervous system (ANS). The existing literature on financial risk-taking has primarily focused on the effects of cortisol, related to the HPA axis. This article, however, examines the influence of the ANS, as measured by vagally mediated heart rate variability at rest (vmHRV). A total of 121 participants (60 female) were divided based on whether their vmHRV was below the median. Participants were then randomly assigned to either a stress test group (TSST) or a control group. Financial risk preferences were assessed using an incentive-compatible 50-50% Eckel and Grossman task. Participants in the TSST with high vmHRV had a higher probability of choosing riskier lotteries compared to the other participants (P = 0,0189). This finding suggests that greater parasympathetic modulation enables individuals to make riskier financial decisions when under stress. Thus, the article contributes to the literature by demonstrating that individuals with a higher physiological capacity to cope with external stressors are less risk-averse in financial decisions under social stress conditions.

Suggested citation: García-Molina, M., Caicedo, J.C., Chicaíza-Becerra, L.A., García-López, C.C., Martínez-Cotrina, J., & Aponte-Canencio, D.M. (2024). Resting Vagally Mediated Heart Rate Variability is Associated with Financial Risk Preferences under Stress. *Innovar*, *34*(94). e116813. https://doi.org/10.15446/innovar.v34n94.116813

[1] Ph. D. in Economics. Professor, Universidad Nacional de Colombia. Bogotá, Colombia. Research Group *Teoría e Investigación Aplicada en Ciencias Económicas* – GITIACE. Author's role: Intellectual. mgarciamo@unal.edu.co; https://orcid.org/0000-0003-2680-8326.
[2] Ph. D. in Medicine. Professor, Universidad Externado de Colombia. Bogotá, Colombia. Research Group *Centro de Investigaciones sobre Dinámica Social*. Author's role: Intellectual. juan.caicedo@uexternado.edu.co; https://orcid.org/0000-0002-6754-6142.
[3] Ph. D. in Economics and Health Management. Professor, Universidad Nacional de Colombia. Bogotá, Colombia. Research Group *Teoría e Investigación Aplicada en Ciencias Económicas* – GITIACE. Author's role: Intellectual. lachicaizab@unal.edu.co; https://orcid.org/0000-0003-0144-1900.
[4] M. Sc. in Psychobiology. Professor, Universidad Externado de Colombia. Bogotá, Colombia. Research Group *Centro de Investigaciones sobre Dinámica Social*. Author's role: Intellectual. garcialopez.christian.c@gmail.com; https://orcid.org/0000-0002-4484-8391.
[5] M. Sc. in Environmental Sciences. Professor and Researcher, Universidad Externado de Colombia. Bogotá, Colombia. Research Group *Salud, Conocimiento Médico y Sociedad del Centro de Investigaciones sobre Dinámica Social* (CIDS). Author's role: Intellectual. jorgea.martinez@uexternado.edu.co; https://orcid.org/0000-0003-0825-6679.
[6] M. Sc. in Political Studies. Full Professor, Universidad Externado de Colombia. Bogotá, Colombia. Research Group *Centro de Investigaciones sobre Dinámica Social*. Author's role: Intellectual. diego.aponte@uexternado.edu.co; https://orcid.org/0000-0002-4129-9980.

VARIABILIDAD DE LA FRECUENCIA CARDÍACA EN REPOSO MEDIADA POR EL NERVIO VAGO Y SU ASOCIACIÓN CON LAS PREFERENCIAS DE RIESGO FINANCIERO BAJO ESTRÉS

Resumen: la toma de riesgos financieros en el ámbito empresarial generalmente ocurre bajo condiciones de estrés. Biológicamente, la respuesta al estrés tiene dos componentes: uno vinculado al eje hipotálamo-hipófisis-adrenal (HHA) y el otro al sistema nervioso autónomo (SNA). La literatura sobre la toma de riesgos financieros se ha centrado principalmente en los efectos del cortisol, relacionado con el eje HHA. Sin embargo, este artículo examina la influencia del SNA, medida a través de la variabilidad de la frecuencia cardíaca en reposo mediada por el nervio vago (VMHRV). Un total de 121 participantes (60 mujeres) fueron divididos en función de si su VMHRV estaba por debajo de la mediana. Paso seguido, los participantes fueron asignados al azar a un grupo de prueba de estrés (TSST) o a un grupo de control. Las preferencias de riesgo financiero se evaluaron utilizando una tarea de Eckel y Grossman con una probabilidad del 50-50% compatible con incentivos. Los participantes en el TSST con alta VMHRV tenían una mayor probabilidad de elegir loterías con nivel de riesgo más alto, en comparación con los otros participantes (*P* = 0,0189). Este hallazgo sugiere que una mayor modulación parasimpática permite a los individuos tomar decisiones financieras más arriesgadas bajo condiciones de estrés. Por lo tanto, el presente artículo contribuye a la literatura al demostrar que las personas con una mayor capacidad fisiológica para afrontar estresores externos son menos renuentes al riesgo en decisiones financieras en condiciones de estrés social.

Palabras clave: sistema nervioso autónomo, aversión al riesgo, toma de decisiones, variabilidad de la frecuencia cardíaca, estrés.

VARIABILIDADE DA FREQUÊNCIA CARDÍACA MEDIADA POR VIA VAGAL EM REPOUSO ASSOCIADA A PREFERÊNCIAS DE RISCO FINANCEIRO SOB ESTRESSE

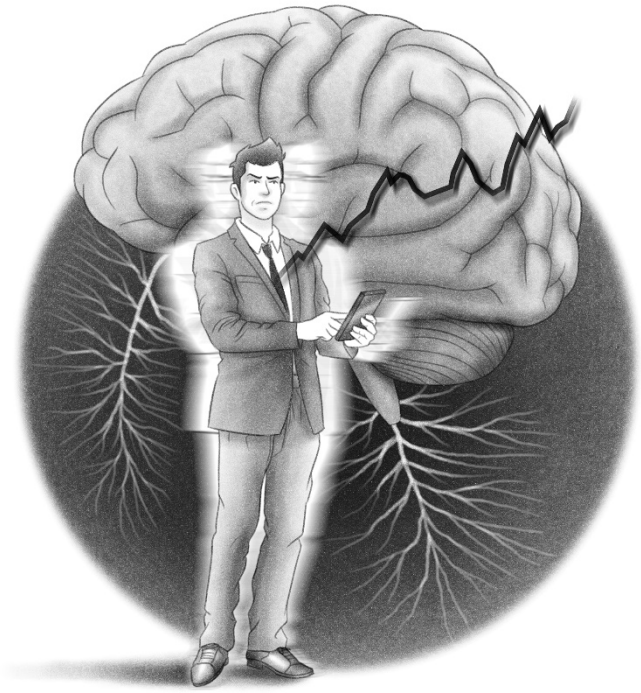
Resumo: Assumir riscos financeiros empresariais geralmente é algo que ocorre sob condições de estresse. Biologicamente, a resposta ao estresse tem dois componentes: um ligado ao eixo hipotálamo-pituitária-adrenal (HPA) e outro ao sistema nervoso autônomo (SNA). A literatura existente sobre a assunção de riscos financeiros tem se concentrado principalmente nos efeitos do cortisol relacionados ao eixo HPA. Este artigo, no entanto, examina a influência do SNA, medida pela variabilidade da frequência cardíaca mediada por via vagal em repouso (VMHRV). Um total de 121 participantes (60 mulheres) foram divididos com base no fato de sua VMHRV estar abaixo da mediana. Os participantes foram então designados aleatoriamente para um grupo de teste de estresse (TSST) ou um grupo de controle. As preferências de risco financeiro foram avaliadas usando uma tarefa de Eckel e Grossman compatível com incentivos de 50%-50%. Os participantes do TSST com alta VMHRV tiveram maior probabilidade de escolher loterias mais arriscadas em comparação com os demais participantes (P = 0,0189). Essa descoberta sugere que uma maior modulação parassimpática permite que os indivíduos tomem decisões financeiras mais arriscadas quando estão sob estresse. Assim, o artigo contribui para a literatura ao demonstrar que indivíduos com maior capacidade fisiológica para lidar com estressores externos são menos avessos ao risco em decisões financeiras sob condições de estresse social.

Palavras-chave: sistema nervoso autônomo, aversão ao risco, tomada de decisão, variabilidade da frequência cardíaca, estresse.

INTRODUCTION

Business financial decisions are influenced by the degree of risk aversion of decision-makers (Gong *et al.*, 2024; Honjo *et al.*, 2024; Liu *et al.*, 2024). These decisions are often made under conditions of stress, which is both a psychological and biological response to challenging or threatening situations. Biologically,

the stress response has two components: one linked to the hypothalamic-pituitary-adrenal (HPA) axis and the other to the autonomic nervous system (ANS). The HPA axis is associated with increased cortisol levels and their effects, while the ANS is related to the ability to manage stressors through changes in heart rate. The literature on financial risk-taking has predominantly focused on the effects of cortisol and the HPA axis. The ANS, however, has received less attention. Therefore, we focus on the impact of the ANS, measured by vagally mediated heart-rate variability at rest (vmHRV), a standard neurophysiological measure of the ANS. By incorporating biological insights on stress, our aim is to provide a more comprehensive understanding of financial decision-making.



In what follows, we aim to contribute by examining whether inter-individual differences in vagally mediated heart rate variability (vmHRV) at rest are associated with inter-individual differences in financial risk preferences under stress. Given that vmHRV is linked to physiological resilience against stress, we hypothesize that higher vmHRV at rest will be associated with riskier financial preferences under stress. The rationale is that individuals with better adaptability to cope with stressors are more inclined to take risks in the gains domain. Therefore, vmHRV at rest would be positively correlated with risky choices, suggesting that people with a higher physical capacity to manage external stressors are less financially risk-averse under conditions of social stress. This is the first research of its kind conducted in an emerging country.

To demonstrate the effect of the ANS, we measured vmHRV for 121 participants (60 female), who were categorized based on whether their vmHRV was below the median. Participants were then randomly assigned to either a trier social stress test (TSST) group or a control group. Financial risk preferences were assessed using an incentive-compatible 50-50% Eckel and Grossman task. Participants in the TSST with high vmHRV

had a higher probability of choosing riskier lotteries compared to the remaining participants ($P = 0.0189$). This result suggests that greater parasympathetic modulation enables individuals to make riskier financial choices under stress. The article contributes by showing that individuals with a higher physiological capacity to cope with external stressors are less financially risk-averse under social stress conditions. However, the approach has some limitations, including variations in the time of day the experiment was conducted, the use of cortisol levels to assess stress, the 3-minute duration of the vmHRV measurement, potential self-selection bias in the sampling method, and concerns regarding external validity.

The article is organized as follows. The first section is this introduction, followed by a review of the literature relevant to the issue being addressed. The subsequent section describes the materials and methods used in the research. This is followed by the results and discussion of the findings. The final section provides the conclusion and discusses potential limitations of the study.

LITERATURE REVIEW

An emerging interdisciplinary approach

In the contemporary realm of financial decision-making, neuroeconomics emerges as a key interdisciplinary field that goes beyond the neoclassical economic assumption of rational, profit-maximizing agents. Traditional theories often fail to account for the complexities and nuances of human behavior, such as emotions, cognitive limitations, and biological factors. Research in neuroeconomics and neurofinance integrates these complexities, offering a more comprehensive understanding of financial decision-making processes (Faris *et al.*, 2024; Yaghoubian *et al.*, 2024).

Central to this approach is the idea that the human brain evolved for survival in natural ecosystems rather than financial markets, often leading to cognitive biases that inhibit optimal financial decisions (Hammerstein & Stevens, 2012). Miendlarzewska *et al.* (2017) emphasize the role of acceptance and avoidance in human behavior, which are neurologically grounded and contribute to individual differences in risk-taking. Unlike traditional economics, which treats the human mind as a simplistic "black box" that transforms input into output, this new approach suggests a complex biological machinery driven by neural pathways, hormones, and individual predispositions.

Interestingly, research indicates that emotional and physiological states can impact even the most experienced traders. Lo and Rapin's (2002) study highlights the physiological variables correlated with financial market events. Additionally, Coates and Herbert's (2008) work on steroid secretion in traders demonstrated the effects of hormones like testosterone and cortisol on market activities. These findings show the need for a reevaluation of the role of emotions and stress, suggesting that human behavior in financial markets is far from purely rational.

Genetic influences add another layer of complexity. Cesarini *et al.* (2010) propose that financial decisions are not solely nurtured by our environment but are also shaped by our nature. In line with this, Nazaripour *et al.* (2016) reveal significant correlations between personality types and investment choices, introducing more variables into the equation. Such evidence challenges traditional economic models that often apply a one-size-fits-all approach to heterogeneous market actors.

The interaction with neuroscience is not limited to the role of the brain. Recent research has shown the complex effects of hormones. For instance, different levels of testosterone before birth have long-term effects that manifest in risk aversion, as measured by incentive-compatible lotteries (Brañas-Garza *et al.*, 2018; Chicaiza-Becerra & Garcia-Molina, 2017). Meanwhile, circulating levels of testosterone in the blood have a short-term effect on individuals' risk aversion (Apicella *et al.*, 2008).

The new view on risk aversion and stress

Risk aversion is a critical factor in financial decision-making. Traditionally considered a given, there is now a growing body of literature aiming to elucidate its determinants. As financial decisions in business are often made under stress, recent attention has shifted to examining stress as a determinant of risk attitudes. Given that stress can be analyzed as a biological phenomenon, research from this perspective has focused on biological mechanisms, particularly the role of hormones such as cortisol.

The seminal study by Coates and Herbert (2008) highlighted the significance of cortisol in financial decision-making on trading floors in the city of London. They demonstrated that cortisol levels were elevated among brokers dealing with markets exhibiting higher volatility. Subsequent studies have continued to explore this relationship under more controlled conditions in laboratory settings. For example, Kandasamy *et al.* (2014) administered hydrocortisone to increase participants' cortisol levels and investigated whether there was a causal relationship between cortisol and risk aversion. Their findings indicated that an acute increase in cortisol, such as that induced by short-term stress, did not affect risk preferences. However, a sustained increase in cortisol over a week, akin to chronic stress, significantly heightened risk aversion among participants.

Studies on this topic have focused on the role of sex hormones, particularly cortisol (Coates *et al.*, 2010; Cueva *et al.*, 2015; Nofsinger *et al.*, 2018). Given cortisol's association with stress, these responses have been attributed to the inherently stressful nature of the trading floor (Coates & Gurnell, 2017; Herbert, 2018). The emphasis on cortisol has also been predominant in research directly addressing stress (Buckert *et al.*, 2014; Cahlikova & Cingl, 2017). For instance, Buckert *et al.* (2014) conducted experiments where participants had their cortisol levels elevated beyond a threshold after exposure to the trier social stress test and observed an increased rate of risk-taking. This effect was noted only when lotteries were in the gain domain, contrasting with findings from other studies, such as Pabst *et al.* (2013). It is important to consider that including negative outcomes in the lotteries (i.e., making decisions in the loss or mixed domains) necessitates measuring not only risk aversion but also loss aversion. Given that loss aversion involves different neurological systems, such as the amygdala (De Martino *et al.*, 2010), this may introduce a confounding factor.

A different but related area of research examines the effect of emotions, particularly fear. Marini (2023) conducted a meta-analysis of this literature and identified a small effect of fear on risk-taking. However, since the methodologies for inducing fear and stress differ, the precise relationship between these types of studies remains unclear.

Stress and biology

Stress is a complex phenomenon involving two complementary systems: the hypothalamic-pituitary-adrenal (HPA) axis and the autonomic nervous system (ANS). The HPA axis response is typically measured by cortisol secretion. This hormonal system is associated with emotional activation, excitability, suppression, information encoding, and experience consolidation, which facilitates future adaptive behavior and is linked to experiential learning (Oitzl *et al*., 2010). While studies on financial risk-taking have predominantly focused on cortisol and the HPA axis, this system represents only one aspect of the stress response.

The ANS is associated with primary and automatic fight-or-flight reactions that activate during acute stress (Taylor *et al*., 2000). It operates through synaptic transmission in two branches that affect heart rate: the sympathetic and parasympathetic nervous systems. The sympathetic system increases heart rate, whereas the parasympathetic system decreases it (Rotenberg & McGrath, 2016).

A common measure in ANS research is heart rate variability (HRV), defined as the variation in the intervals between heartbeats (Malik & Camm, 1995). HRV indicates how responsive the heart is to various stimuli. Low HRV suggests a reduced ability to cope with stressors, reflecting lower adaptability to stress. The typical methods for measuring HRV are based on frequency domain analysis. vmHRV is assessed through the high-frequency (0.15-0.4 Hz) component of HRV at rest and is associated with parasympathetic modulation (Rotenberg & McGrath, 2016).

Resting vmHRV is lower in subjects with post-traumatic stress disorder (Cohen *et al*., 1998). It has also been suggested as a biomarker for social behavior (Porges, 2007; Smith *et al*., 2020; Thayer *et al*., 2012). Inter-individual differences in this index have been associated with inter-individual differences in social cognition and behavior. For instance, individuals with high resting vmHRV have been found to have more empathy and less alexithymia (i.e., the difficulty to identify one's own emotions) (Lischke *et al*., 2018), as well as more cooperative behavior (Beffara *et al*., 2016; Lischke *et al*., 2018).

Neuroimaging studies generally support the notion that higher vmHRV at rest is linked to a greater capacity to assess the appropriateness of threat appraisals depending on the context. Specifically, resting vmHRV has been found to be associated with the inhibition of the amygdala in relation to threat representations in safe contexts (Thayer *et al*., 2012).

The research gap

In a financial context, these findings suggest that vmHRV at rest may be associated with riskier preferences for lotteries involving zero or positive gains (i.e., in safe contexts). However, this association has not been extensively studied in the literature. The few studies that have investigated this area are dated and limited in scope. For example, Kandasamy *et al*. (2014) conducted research with a small sample (N = 36, 20 male) and found no significant association between cortisol exposure and HRV, measured as the square root of the mean of the sum of the squares of differences between adjacent normal-to-normal intervals. To our knowledge, this is the only study to date that has employed an HRV measure in the context of financial risk, though it did not specifically address vmHRV.

Other research has identified a negative correlation between vmHRV at rest and scores on the South Oaks Gambling Screen Revised (a tool used to screen for pathological gambling) (Brunborg *et al*., 2010) or

with trading experience among traders (Fenton-O'Creevy *et al.*, 2012). Some studies, such as those by Buckert *et al.* (2014), have included heart rate in their analyses but not HRV or vmHRV. Conversely, articles examining the relationship between stress and heart rate variability have predominantly focused on non-financial aspects, such as affect, empathy, and craving for sustances (Moon *et al.*, 2023; Sassenrath *et al.*, 2020).

MATERIALS AND METHODS

Sample

This study was approved by the Ethics Committee of the Faculty of Medicine at the National University of Colombia. We performed a controlled experiment with 121 participants (60 female), all of them university students (age between 18 and 25) studying economics or engineering related programs (26%), psychology (36%), and other social sciences and humanities (38%) degrees, during the second semester of 2018. Participants were randomly assigned to two groups. The randomization procedure was as follows: random numbers were generated in a worksheet for each sex, corresponding to the two groups. Consequently, the experimenters were aware in advance of the group assignment for each subsequent participant. Two subjects were excluded from the analysis due to incomplete heart rate recordings. Therefore, the final sample size was 119 (59 female), with 61 participants in the control group (30 female) and 58 participants in the treatment group (29 female).

General procedure

Participants first signed an informed consent form, which outlined the experiment's procedures and emphasized their right to withdraw at any time. They then spent five minutes in a neutral state to stabilize any prior emotional states. Following this, a first sample of salivary cortisol was collected. Electrodes were then applied according to the Einthoven derivation, with placement on the participant's chest with the heart as the reference point (Cacioppo *et al.*, 2007). The electrocardiogram (ECG) was initiated, with the first five minutes serving as the baseline period.

After the baseline ECG, individuals in the treatment group underwent stress induction using the TSST for 20 minutes. In contrast, the control group was instructed to relax and let thoughts emerge spontaneously for 20 minutes, with no external stimuli to promote stimulus-independent thought (Mason *et al.*, 2007).

Immediately following this, participants provided a second cortisol sample and then engaged in financial lotteries. Subsequently, they completed an unrelated task and filled out a sociodemographic questionnaire. Finally, the lottery results were executed, and payment was processed. Participants received COP 20,000 for their participation, plus any earnings from the lottery, resulting in total compensation ranging from COP 20,000 to 44,000 (approximately USD 6.62 to 14.56). At the time, the daily minimum wage in Colombia was COP 26,041 (USD 8.62). The experiment was conducted using Superlab® 4.5, and physiological data were collected with LabChart.

Stress induction

We adapted a version of the TSST (Birkett, 2011; Kirschbaum *et al.*, 1993) for this study, applying this tool individually to participants. Each participant first prepared a five-minute speech for ten minutes in front of a non-recording video camera. Following this preparation, two examiners entered the room, and the participant delivered the speech to them. The examiners maintained a neutral and inexpressive demeanor throughout the presentation.

After the speech, participants completed an arithmetic task, starting from 1,022 and subtracting 13 sequentially for five minutes. If a participant made a mistake, they were instructed to restart the task from 1,022.

Financial risk task

All participants chose a 50-50% lottery task (Binswanger, 1980; Eckel & Grossman, 2002) as adapted for the Colombian population by Attanasio *et al.* (2012). Payments appear in table 1. Participants had 6 lotteries to choose from with different levels of risk aversion. They were asked to pick one to play. At the end of the session a coin would be tossed, and they would be paid accordingly in cash.

Table 1.

Lottery payoffs.

Lottery	Low payoff COP	High payoff COP	Expected value COP	Standard deviation	Risk aversion	Constant Relative Risk Aversion (CRRA)
1	6,000	6,000	6,000	0	Extreme	Infinity to 7.49
2	5,400	11,400	8,400	4,242	High	7.49 to 1.73
3	4,800	14,400	9,600	6,788	Medium	1.73 to 0.81
4	3,600	18,000	10,800	10,182	Moderate	0.81 to 0.46
5	2,000	22,000	12,000	14,142	Somewhat neutral	0.46 to 0.00
6	0	24,000	12,000	16,970	Neutral/negative	0 to negative infinity

Source: adapted from Attanasio *et al.* (2012).

Heart rate variability

ECG was recorded using a Dual Bio Amp Power Lab 16/32 and ADInstruments cardiac monitoring electrodes. After connecting and preparing the recording devices, the accuracy of cardiac information recording was verified. A baseline ECG recording was taken while subjects were in a resting state for five minutes. Following this, the ECG continued to be recorded throughout the TSST, cortisol sampling, and financial task.

Cortisol

Two saliva samples were collected via passive drooling into assay tubes, one before and one after the TSST. The second sample was collected 30 minutes after the first. The samples were stored at subzero temperatures and transported in dry ice to the Hormonal Lab, where they were analyzed using electroluminescence with a Roche Cobas-6000 device. The cortisol response was assessed by calculating the rate of change between the first and second salivary cortisol measurements.

Statistical analysis

The first step was to verify that stress was effectively induced in the TSST group but not in the control group. To do this, we assessed whether cortisol levels and heart rate increased in the TSST group compared to the control group using Mann-Whitney U tests (Mann & Whitney, 1947). We compared these variables before and after the intervention within each group. Vagally mediated heart rate variability (vmHRV) was measured using the high-frequency (0.15-0.4 Hz) component of HRV.

To test the main hypothesis, we categorized participants based on whether their resting vmHRV was above or below the median and whether they were in the TSST or control group. We conducted Mann-Whitney U tests to compare the lotteries chosen by participants with resting vmHRV above the median to those chosen by the rest of the population, as well as to compare them with participants in the TSST group who had resting vmHRV below the median. All analyses were performed using STATA®.

RESULTS AND DISCUSSION

Results

Data—including those for figures 1 and 2, table 2, and hypothesis tests—are available at Mendeley Data[7]. Descriptive statistics are shown in table 2.

Table 2.

Descriptive statistics.

	No.	Mean	Standard deviation	Min	Max
Age	119	20,08403	1,658083	18	25
Lottery	119	3,201681	1,678234	1	6
HFPower	119	2272,672	3353,481	112,4182	23101,34
Cort 1	119	7,347311	4,874383	1,5	33,77
Cort 2	119	7,717059	5,441194	1,98	33,18
HR1	119	79,19012	10,17997	51,8494	103,2171
HR2	119	80,19635	10,87107	51,4431	115,8122

Source: authors' calculations.

Stress induction

In the TSST group, the mean heart rate increased from 80.14 beats per minute before treatment to 83.09 after treatment ($P = 0.0004$, $N = 58$, two-tailed t-test). In contrast, the mean heart rate for the control group decreased from 78.28 to 77.45 beats per minute, with the change not being statistically significant ($P = 0.0658$, $N = 61$, two-tailed t-test).

Similar results were observed for salivary cortisol levels. In the TSST group, cortisol levels increased from 7.14 to 8.55 nmol/l ($P = 0.0445$, $N = 58$, two-tailed t-test). Conversely, in the control group, cortisol levels

[7] https://data.mendeley.com/datasets/wpcw6zcxrf/draft?a=51585728-a4e2-4271-a824-285b73fbf919

decreased from 7.54 to 6.93 nmol/l, and this change was not statistically significant ($P = 0.2448$, $N = 61$, two-tailed t-test).

According to the literature, a reliable indicator of stress induction is an increase in cortisol levels exceeding 2.5 nmol/l (e.g., Buckert *et al.*, 2014). In this study, 17 out of 58 participants in the TSST group surpassed this threshold, while only 10 out of 61 participants in the control group did.

Figure 1 shows stress induction. Figure 1A shows the cumulative distribution function of the heart rate and cortisol before and after for the control and TSST groups. Stochastic dominance (a curve being on the right/below of the other one) means a higher probability of higher values of the variable. Figure 1A also shows that participants in the TSST group (except for one observation) were more likely to have higher cortisol increases than the control group. Figure 1B shows that the participants in the TSST group (except for one observation) were more likely to have increases in the heart rate than the control group.

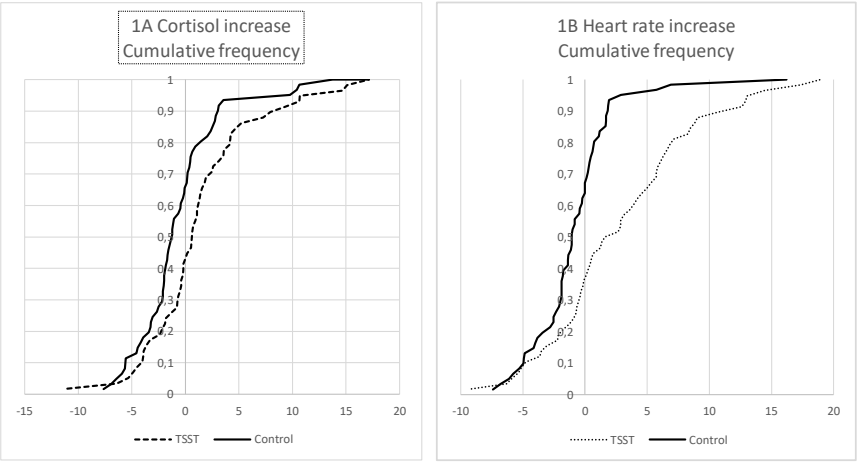


Figure 1. *Stress induction.* **Source:** authors' calculations.

vmHRV at rest

There was noise in the five-minutes measurement in the resting vmHRV. This was due to the movements of several participants at the beginning of the five-minute rest period. In order to avoid this problem, we used only the last three minutes of the measurement for all participants.

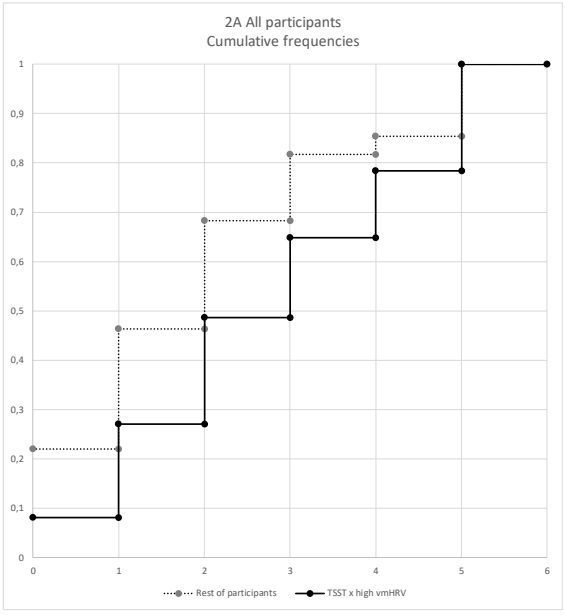
Risk differences

Risk preferences were measured based on the chosen lottery. The expected outcome was that the interaction between stress and high vmHRV at rest would increase the willingness to take more risks (i.e., choosing higher lotteries). We first compared this interaction between two groups: those in the TSST group with high resting vmHRV and the combined group of the control group plus those in the TSST group with low resting vmHRV. As anticipated, the Mann-Whitney U test rejected the null hypothesis of equal medians ($P = 0.0189$, $N = 119$). The probability that participants with high resting vmHRV in the TSST group chose less risky lotteries compared to the rest of the sample was 0.368.

This indicates an interaction effect. Within the TSST group, the medians of high versus low resting vmHRV differed significantly ($P = 0.0411$, N = 58, Mann-Whitney U test), with the probability of selecting less risky lotteries being 0.340 for the low resting vmHRV subgroup. In contrast, no significant difference in medians was found within the control group ($P = 0.9939$, N = 61, Mann-Whitney U test).

Figure 2 illustrates these results through the lens of stochastic dominance. Stochastic dominance analysis reveals that the interaction between the TSST and high vmHRV is associated with a higher probability of choosing riskier lotteries. The X-axis represents the level of risk of the lottery (with higher values indicating riskier options), and the Y-axis shows the cumulative frequency as a percentage. For clarity, the graph can be interpreted as depicting the probability of choosing a lottery with a risk level less than or equal to lottery X. Stochastic dominance, indicated by a curve that lies to the right of and below another curve, signifies a higher probability of selecting higher-risk options.

Figure 2A compares participants in the TSST group with high resting vmHRV to the rest of the participants. The curve for the TSST group with high resting vmHRV demonstrates stochastic dominance, indicating that these participants are more likely to choose riskier lotteries. Figure 2B compares participants with high versus low resting vmHRV within the TSST group. The curve for high resting vmHRV participants exhibits stochastic dominance, meaning that within the TSST group, individuals with high resting vmHRV are more likely to select riskier lotteries compared to those with low resting vmHRV. Figure 2C compares participants with high versus low vmHRV within the control group. No stochastic dominance is observed within the control group, indicating that, in the absence of stress, resting vmHRV does not influence the probability of choosing riskier lotteries.



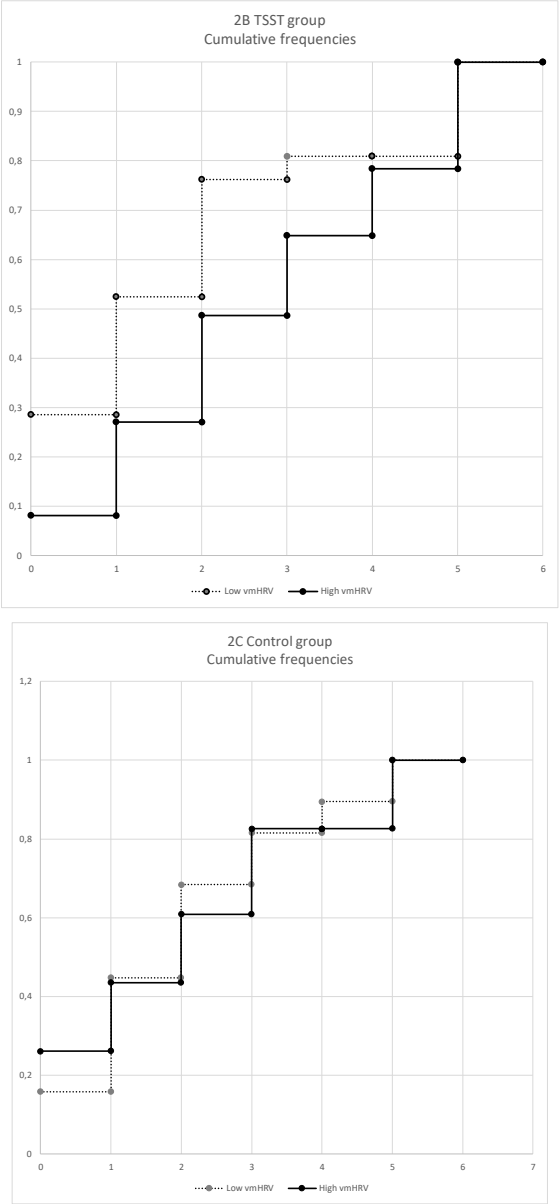


Figure 2. *Stochastic dominance.* **Source:** authors' calculations.

Discussion of results

The literature review encompasses two primary branches: the first focuses on financial risk as related to the HPA axis and cortisol (e.g., Buckert *et al.*, 2014; Kandasamy *et al.*, 2014), while the second examines vmHRV and the ANS in non-financial stress situations (e.g., Lischke *et al.*, 2018; da Estrela *et al.*, 2021). Our findings suggest a role for the ANS that aligns more closely with the second branch of literature. Specifically, these results indicate that individuals with higher physiological resilience to stress, as evidenced by higher resting vmHRV, are more likely to take financial risks when faced with stressful conditions.

This is consistent with a two-regime model of risk behavior. In the absence of stress, individuals typically exhibit risk aversion. Under stress, however, two outcomes are possible: individuals with lower resting vmHRV (indicating greater HPA axis dominance) may struggle to accurately assess the situation and

therefore adopt a more cautious approach. In contrast, those with higher resting vmHRV (indicating greater ANS dominance) may have a clearer perspective on potential opportunities—represented here by riskier lotteries in the gains domain—and may be more inclined to take risks.

It is important to note that the lotteries in this study were within the gains domain, meaning there were no potential losses involved. Therefore, the results cannot be attributed to loss aversion. In scenarios involving potential losses, loss aversion would also need to be measured, as apparent risk aversion might actually be a result of an attempt to avoid losses rather than a preference for lower variance in outcomes. De Martino *et al*. (2010) found that the cerebral amygdala plays a key role in loss aversion. Given that the amygdala is involved in processing emotions, particularly fear, its potential response to stress could have been a confounding factor if the lotteries had included losses or were in the mixed domain.

It is also crucial to emphasize that vmHRV at rest is a basal measure. This measurement was taken prior to the induction of stress and reflects a trait-like, stable characteristic.

The HPA axis and the ANS function differently, with the HPA axis being associated with learning. A hypothesis for financial decision-making could be that the HPA axis maintains its regulatory role in the absence of stress, operating with minimal input from the ANS and showing sensitivity to learned experiences. Conversely, under stress, the HPA axis appears to defer to the ANS to facilitate a quicker response in extreme decision-making scenarios (either taking or avoiding risks), thus mimicking primary fight-or-flight responses. A resilient ANS may enable risk-taking in a safe context, suggesting that financial risk behavior could be influenced by this more fundamental biological decision-making system.

CONCLUSIONS

Financial decisions are frequently made under conditions of stress, and these decisions are influenced by the decision maker's attitude towards risk. Existing research has primarily examined the effects of one component of the stress response, namely the HPA axis. Our findings highlight the significance of the other component, the autonomic nervous system (ANS). The ANS can be measured by vagally mediated heart rate variability (vmHRV), an indicator of the body's ability to cope with external stressors, and which has been associated with parasympathetic modulation mediated by the ventromedial prefrontal cortex.

Our results indicate that, under stress and when faced with lotteries in the gains domain (i.e., without actual risk of loss), a higher ability to cope with external stressors—reflected by higher vmHRV—predicts a greater propensity to make risky financial decisions. In other words, individuals with a higher capacity to manage stress are more likely to engage in risk-taking behavior in the presence of social stressors.

This result is relevant for studies on financial risk behavior in real-world settings, such as trading floors or business environments, where decisions are made under stress. In such studies, vmHRV at rest should be included as a control variable. While this finding does not have immediate practical applications, it is noteworthy that vmHRV is not a static measure; it can be influenced by individual actions, such as engaging in physical activities like sports. Future research could explore whether improving vmHRV through physical activity can alter financial risk preferences. If such a relationship is established, it could imply that businesses might influence their employees' financial risk-taking behavior by encouraging physical exercise.

This study is the first to examine the role of vmHRV in financial risk-taking and to analyze this issue from a biological perspective in an emerging economy. It is also the first to utilize an incentive-compatible experiment, meaning participants were paid real money for their lottery choices. This standard protocol in neuroeconomics ensures that the decisions made during the experiment were not hypothetical but had real-world relevance. Although the monetary rewards might seem modest, they were significant relative to the minimum wage.

One limitation of the study is that it was conducted at various times throughout the day (between 9:00 am and 5:00 pm), which could introduce variability due to circadian or environmental factors affecting basal cortisol levels. However, this effect is expected to be minimal (Starcke *et al*., 2011; van den Bos *et al*., 2009). To address this concern, we did not use cortisol levels as an independent variable; instead, we focused on the change in cortisol levels before and after the stress induction to verify stress response.

Another potential limitation relates to the threshold used to determine stress induction. Previous studies have often defined stress as an increase in cortisol levels of 2.5 nmol/L. In this study, 17 out of 58 participants in the TSST group and 10 out of 61 participants in the control group met this criterion, but this was not the case for the majority of the TSST group. Nevertheless, cortisol and heart rate increased more in the TSST group compared to the control group. Employing both cortisol and heart rate to establish stress induction is sensible because relying solely on cortisol would account only for the HPA axis response, neglecting the ANS component. The fact that behavioral changes were observed in participants with high vmHRV in the TSST group, but not in the control group, indicates that something did indeed change in the TSST group.

The vmHRV measure was taken over a period of 3 minutes rather than the usual 5 minutes due to movement by some participants at the beginning of the 5-minute period. However, vmHRV measurements over 3 minutes have been reported to be highly consistent with those over 5 minutes and 60 seconds (Lischke *et al*., 2019).

There is a possibility that the sampling method (open announcements in classes and social networks) could have introduced a self-selection bias, potentially attracting more risk-prone individuals. However, this bias should affect both the control and stress groups similarly, and the study primarily aimed to assess the impact of stress on risk preferences, focusing on differences between the two groups.

A question might arise regarding the use of only one measure of risk behavior. The methodology used by Eckel and Grossman (2002) was designed to elicit risk aversion with a single choice. Research has shown that this method is significantly correlated with more complex elicitation methods while providing less noisy estimates and being easier for participants with lower mathematical abilities to understand (Charness *et al*., 2013; Dave *et al*., 2010; Reynaud & Couture, 2012).

Finally, the external validity of the study may be questioned as the experiments were conducted with university students. However, biological differences between university students and other populations are likely to be minimal.

DISCLOSURES

Authors declare no institutional or personal conflicts of interest.

REFERENCES

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

Arakaki, X., Arechavala, R. J., Choy, E. H., Bautista, J., Bliss, B., Molloy, C., Wu, D. A., Shimojo, S., Jian, Y., Kleinman, M. T., Kloner, R. A. (2023). The connection between heart rate variability (HRV), neurological health, and cognition: A literature review. *Frontiers in Neuroscience*, *17*, 1-10. https://doi.org/10.3389/fnins.2023.1055445

Attanasio, O., Barr, A., Cardenas, J. C., Genicot, G., & Meghir, C. (2012). Risk pooling, risk preferences, and social networks. *American Economic Journal: Applied Economics*, *4*(2), 134-167. https://doi.org/10.1257/app.4.2.134

Beffara, B., Bret, A. G., Vermeulen, N., & Mermilod, M. (2016). Resting high frequency heart rate variability selectively predicts cooperative behavior. *Physiology & Behavior*, *164*(Part A), 417-428. https://doi.org/10.1016/j.physbeh.2016.06.011

Binswanger, H. P. (1980). Attitudes toward risk: Experimental measurement in rural India. *American Journal of Agricultural Economics*, *62*(3), 395-407. https://doi.org/10.2307/1240194

Birkett, M. A. (2011). The Trier Social Stress Test Protocol for Inducing Psychological Stress. *Journal of Visualized Experiments*, *56*(3238). https://doi.org/10.3791/3238

Brañas-Garza, P., Galizzi, M. M., & Nieboer, J. (2018). Experimental and self-reported Measures of risk Taking and Digit Ratio (2D:4D): Evidence from a large systematic study. *International Economic Review*, *59*(3), 1121-1157. https://doi.org/10.1111/iere.12299

Brunborg, G. S., Johnsen, B. H., Pallesen, S., Molde, H., Mentzoni, R. A., & Myrseth, H. (2010). The relationship between aversive conditioning and risk-avoidance in gambling. *Journal of Gambling Studies*, *26*(4), 545-559. https://doi.org/10.1007/s10899-010-9178-0

Buckert, M., Schwieren, C., Kudielka, B. M., & Fiebach, C. J. (2014). Acute stress affects risk taking but not ambiguity aversion. *Frontiers in Neuroscience*, *8*, 82. https://doi.org/10.3389/fnins.2014.00082

Cacioppo, J. T., Tassinary, L. G., & Berntson, G. (2007). *Handbook of psychophysiology*. Cambridge University Press.

Cahlikova, J., & Cingl, L. (2017). Risk preferences under acute stress. *Experimental Economics*, *20*(1), 209-236. https://doi.org/10.1007/s10683-016-9482-3

Cesarini, D., Johannesson, M., Lichtenstein, P., Sandewall, O., & Wallace, B. (2010). Genetic variation in financial decision-making. *The Journal of Finance*, *65*(5), 1725-1754. http://doi.org/10.1111/j.1540-6261.2010.01592.x

Charness, G., Gneezy U., & Imas, A. (2013). Experimental methods: eliciting risk preferences. *Journal of Economic Behavior & Organization*, *87*, 43-51. http://dx.doi.org/10.1016/j.jebo.2012.12.023

Chicaiza-Becerra, L., & Garcia-Molina, M. (2017). Prenatal testosterone predicts financial risk taking: Evidence from Latin America. *Personality and Individual Differences*, *116*(1), 32-37.

http://doi.org/10.1016/j.paid.2017.04.021

Coates, J., & Gurnell, J. (2017). Combining field work and laboratory work in the study of financial risk-taking. *Hormones and* Behavior, 92, 13-19. https://doi.org/10.1016/j.yhbeh.2017.01.008

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

Coates, J. M., Gurnell, M., & Sarnyai, Z. (2010). From molecule to market: Steroid hormones and financial risk-taking. *Philosophical Transactions of the Royal Society of London. Series B Biological Sciences*, *365*(1538), 331-343. https://doi.org/10.1098/rstb.2009.0193

Cohen, H., Kotler, M., Matar, M. A., Kaplan, Z., Loewenthal, U., Miodownik, H., & Cassuto, Y. (1998). Analysis of heart rate variability in posttraumatic stress disorder patients in response to a trauma-related reminder. *Biological Psychiatry*, *44*(10), 1054-1059. https://doi.org/10.1016/S0006-3223(97)00475-7

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

da Estrela, C., MacNeil, S., & Gouin, J. P. (2021). Heart rate variability moderates the between- and within-person associations between daily stress and negative affect. *International Journal of Psychophysiology*, *162*, 79-85. https://doi.org/10.1016/j.ijpsycho.2021.02.001

Dave, C., Eckel, C. C., Johnson, C. A., & Rojas C. (2010). Eliciting risk preferences: when is simple better? *Journal of Risk and Uncertainty*, *41*(3), 219-243. https://doi.org/10.1007/s11166-010-9103-z

De Martino, B., Camerer, C. F., & Adolphs, R. (2010). Amygdala damage eliminates monetary loss aversion. *Proceedings of the National Academy of Science of the United States of America*, *107*(8), 3788-3792. https://doi.org/10.1073/pnas.0910230107

Eckel, C. C., & Grossman, P. J. (2002). Sex differences and statistical stereotyping in attitudes toward financial risk. *Evolution and Human Behavior*, *23*(4), 281-295. https://doi.org/10.1016/S1090-5138(02)00097-1

Faris, A. A., Jwan, H. K., & Al-Bidari, K. H. A. (2024). From traditional finance to neurofinance: Literature review. *Periodicals of Engineering and Natural Sciences*, *12*(1), 191-204. http://dx.doi.org/10.21533/pen.v12i1.4006

Fenton-O'Creevy, M., Lins, J. T., Vohra, S., Richards, D. W., Davies, G., & Schaaff, K. (2012). Emotion regulation and trader expertise: Heart rate variability on the trading floor. *Journal of Neuroscience, Psychology, and Economics*, *5*(4), 227-237. https://doi.org/10.1037/a0030364

Gong, J., Wang, G. J., Xie, C., & Uddin, G. S. (2024). How do market volatility and risk aversion sentiment inter-influence over time? Evidence from Chinese SSE 50 ETF options. *International Review of Financial Analysis*, *95*(B), 103440. https://doi.org/10.1016/j.irfa.2024.103440

Hammerstein, P., & Stevens, J. R. (2012). Evolution and the mechanisms of decision making. MIT Press.

Herbert, J. (2018). Testosterone, cortisol and financial risk-taking. *Frontiers in Behavioral Neuroscience*, *12*,101. https://doi.org/10.3389/fnbeh.2018.00101

Honjo, Y., Ikeuchi, K., & Nakamura, H. (2024). Does risk aversion affect individuals´ interests and actions in angel investing? Empirical evidence from Japan. *Japan and the Word Economy*, *70*, 101253. https://doi.org/10.1016/j.japwor.2024.101253

Kandasamy, N., Hardy, B., Page, L., Schaffner, M., Graggaber, J., Powlson, A. S., Fletcher, P. C., Gurnell, M., & Coates, J. (2014). Cortisol shifts financial risk preferences. *Proceedings of the National Academy of Sciences*, 111, 3608-3613. https://doi.org/10.1073/pnas.1317908111

Kirschbaum, C., Pirke, K. M., & Hellhammer, D. H. (1993). The 'Trier Social Stress Test' – A tool for investigating psychobiological stress responses in a laboratory setting. *Neuropsychobiology*, *28*(1-2), 76-81. https://doi.org/10.1159/000119004

Kvadsheim, E., Sorensen, L., Fasmer, O. B., Osnes, B., Haavik, J., Williams, D. P., Thayer, J. F., & Koenig, J. (2022). Vagally mediated heart rate variability, stress, and perceived social support: A focus on sex differences. *Stress*, 25(1), 113-121. https://doi.org/10.1080/10253890.2022.2043271

Lischke, A., Pahnke, R., Mau-Moeller, A., Behrens, M., Grabe, H. J., Freyberger, H. J., Hamm, A. O., & Weippert, M. (2018). Inter-individual differences in heart rate variability are associated with inter-individual differences in empathy and alesithymia. *Frontiers in Psychology*, 9. https://doi.org/10.3389/fpsyg.2018.00229

Lischke, A., Mau-Moeller, A., Jacksteit, R., Pahnke, R., Hamm, A., & Weippert, M. (2018). Heart rate variability is associated with social value orientation in males but not females. *Scientific Reports*, *8*, 7336. https://doi.org/10.1038/s41598-018-25739-4

Lischke, A., Weippert, M., Mau-Moellller, A., Päschke, S., Jacksteit, R., Hamm, A. O., & Pahnke, R. (2019). Sex-specific associations between inter-individual differences in heart rate variability and inter-individual differences in emotion regulation. *Frontiers in Neuroscience*, 12, 1040. https://doi.org/10.3389/fnins.2018.01040

Liu, P., Chen, Y., & Mu, Y. (2024). The impact of climate risk aversion on agribusiness share price volatility. *Finance Research Letters*, 61, 104797. https://doi.org/10.1016/j.frl.2023.104797

Lo, A. W., & Rapin, D. W. (2002). The psychobiology of real-time risk processing. *Journal of Cognitive Neuroscience*, 14(3), 323-339. https://doi.org/10.1162/089892902317361877

Malik, M., & Camm, A. J. (1995). *Heart rate variability*. Future House Publishing.

Mann, H., & Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *Annals of Mathematical Statistics*, 18(1), 50-60. https://doi.org/10.1214/aoms/1177730491

Marini, M. M. (2023). Emotions and financial risk-taking in the lab: A meta-analysis. *Journal of Behavioral Decision Making*, 36(4), e2342. https://doi.org/10.1002/bdm.2342

Mason, M. F., Norton, M. I., Van Horn, J. D., Wegner, D. M., Grafton, S. T., & Macrae, C. N. (2007). Wandering minds: The default network and stimulus-independent thought. *Science*, 315(5810), 393-395. https://doi.org/10.1126/science.1131295

Miendlarzewska, E. A., Kometer, M., & Preuschoff, K. (2017). Neurofinance. *Organizational Research Methods*, 22(1), 196-222. https://doi.org/10.1177/1094428117730891

Moon, S. J. E., Schlenk, E. A., & Lee, H. (2023). Heart rate variability in adults with substance use disorder: A comprehensive narrative review, 30(2). 240-251. https://doi.org/10.1177/10783903221145142

Nazaripour, M., Zakizadeh, B., Afshar, A., & Mohammadi, A. (2020). Investigating the behavior of investors in the Tehran Stoch Exchange based on the model of the five personality types. *Quarterly Journal of New Psychological Ideas*, 6(10), 1-14. https://jnip.ir/article-1-354-en.html

Nofsinger, J. R., Patterson, F. M., & Shank, C. A. (2018). Decision-making, financial risk aversion, and behavioral biases: The role of testosterone and stress. *Economics & Human* Biology, 29, 1-16.

https://doi.org/10.1016/j.ehb.2018.01.003

Oitzl, M. S., Champagne, D. L., van der Veen, R., & de Kloet, E. R. (2010). Brain development under stress: Hypotheses of glucocorticoid actions revisited. *Neuroscience & Biobehavioral Review*, *34*, 853-866. https://doi.org/10.1016/j.neubiorev.2009.07.006

Pabst, S., Brand, M., & Wolf, O. T. (2013). Stress effects on framed decisions: There are differences for gains and losses. *Frontiers in Behavioral Neuroscience*, 7, 142. https://doi.org/10.3389/fnbeh.2013.00142

Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology*, 74, 116-143. DOI: 10.1016/j.biopsycho.2006.06.009

Reynaud, A., & Couture, S. (2012). Stability of risk preference measures: results from a field experiment on French farmers. *Theory and Decision*, 73(2), 203-221. https://doi.org/10.1007/s11238-012-9296-5

Rotenberg, S., & McGrath, J. J. (2016). Inter-relation between autonomic and HPA axis activity in children and adolescents. *Biological Psychology*, *117*, 16-25. https://doi.org/10.1016/j.biopsycho.2016.01.015

Sassenrath, C., Barthelmas, M., Saur, J., & Keller, J. (2020). Inducing empathy affects cardiovascular reactivity reflected in changes in high frequency heart rate variability. *Cognition and Emotion*, *35*(2), 393-399. https://doi.org/10.1080/02699931.2020.1826910

Smith, T. W., Deits-Lebehn, C., Williams, P. G; Baucom, B., & Uchino, B. (2020). Toward a social psychophysiology of vagally mediated heart rate variability: Concepts and methods in self-regulation, emotional, and interpersonal processes. *Social and Personality Psychology Compass*, *14*(3), e12516. https://doi.org/10.1111/spc3.12516

Starcke, K., Polzer, C., Wolf, O. T., & Brand, M. (2011). Does stress alter everyday moral decision-making? *Psychoneuroendocrinology*, *36*(2), 210-219. https://doi.org/10.1016/j.psyneuen.2010.07.010

Taylor, S. E., Klein, L. C., Lewis, B .P., Gruenewald, T. L., Gurung, R. A., & Updegraff, J. A. (2000). Biobehavioral responses to stress in females: tend-and-befriend, not fight-or-flight. *Psychological Review*, 107(3), 411-429. https://doi.org/10.1037/0033-295x.107.3.411

Thayer, J. F., Ahs, F., Fredrikson, M., Sollers III, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health. *Neuroscience and Biobehavioral Reviews*. *36*(2), 747-756. https://doi.org/10.1016/j.neubiorev.2011.11.009

van den Bos, R., Harteveld, M., & Stoop, H. (2009). Stress and decision-making in humans: Performance is related to cortisol reactivity, albeit differently in men and women. *Psychoneuroendocrinology*, *34*(10), 1449-1458. https://doi.org/10.1016/j.psyneuen.2009.04.016

Yaghoubian, M. M., Moghaddam, A. N., Kashani, F. H., & Nasrolahi, B. (2024). Modeling the behavior of individual investors in the stock market based on the neuro-finance approach. *International Journal of Finance and Managerial Accounting*, *9*(32), 101-112.