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Stressed individuals exhibit pessimistic bursting beliefs and a lower risk preference in the balloon analogue risk task

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ABSTRACT

Stress alters decision-making by usually promoting risk-taking and reward-seeking, which could be advantageous in a context where risk is rewarded, such as the Balloon Analogue Risk Task (BART). However, previous studies addressing this issue showed inconsistencies which could emerge from assessing decision-making as a single dimension. Our aim is to study through computational modelling how stress influences cognitive subprocesses of the decision-making during the BART. For this purpose, 94 healthy participants were submitted to BART, but only half were exposed to the virtual Trier Social Stress Test (TSST-VR). The Experimental-Weight Mean-Variance (EWMV) model was used to gain insight into the subprocesses involved in risk-taking during BART. Rather than reward-seeking, our results showed a pessimistic prior belief about the balloons bursting likelihood, and a lower risk preference in the stressed participants. This cautious attitude could be attributable to an alertness state promoted by stress. Yet, since risk is rewarded in BART, it could also evidence a maladaptive decision-making derived from learning difficulties and altered feedback-processing under stress.

1. Introduction

From the simplest decisions such as which movie to watch, to the more complex ones made by doctors regarding surgery, we make decisions under uncertainty every day. All of them exhibit interindividual variability, depending on basic aspects as gender, age or culture [4, 23, 52]; but there is also some intrapersonal variability. Thus, as the embodied brain approach explains [19], cognition and, in our case decision-making, cannot be dissociated from fundamental aspects such as the physiological state of the organism. Hunger, sexual arousal, or emotional state, among many other factors, can modulate decision-making [22, 43, 51]. One of these factors, widely addressed, is stress.

Acute stress, considered as a transitory psychophysiological response that prepares us to face stimuli that threaten the stability of the organism, can influence decision-making through its two main pathways. On the one hand, the fast activation of the sympathetic nervous system (SNS), which triggers catecholamines release [15], promotes the relocation of resources from the brain executive-network to the salience-network [13, 14, 25]. Thus, the activity of regions such as the amygdala are intensified, which lead to an alertness state that facilitates the detection of salient stimuli, especially negative or threatening ones [25]. Therefore, conservative, and risk-avoidance decisions can be found at this early stage [31, 34]. Nevertheless, catecholamines also enhance key regions of the reward-system such as the striatum [13], so a higher sensitivity for rewards may also be observed [29][30]. On the other hand, the slower hypothalamus-pituitary-adrenal axis (HPA-axis) activation, resulting in a secretion of cortisol [15], would expand the latter effect by promoting higher levels of striatal dopamine [40, 54]. The STARS model propose that "stress enhances reward salience via modulation of the dopamine system, resulting in reward-biased learning" ([27], p. 2); i.e., stress bias in weighing positive over negative aspects during decision-making, especially when cortisol rises. It is not surprising therefore that in their recent meta-analysis, Starcke et al. [48] mainly conclude that under stress people use to take more risks and seek immediate reinforcement when making decisions.

It should be noted that this is not good or bad *per se* but would depend on the context and type of decisions. Thus, decision-making can be classified according to the amount of information available when deciding, moving on a continuum from risky uncertainty (probabilities and prospects are well defined) to the complete ignorance (the possible outcomes are unknown); but also in terms of the consequences of risk-

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taking or reward-seeking [48]. Most prominent tasks, such as the Game of Dice Task (GDT; [3]) or the Iowa Gambling Task (IGT; [2]), have been developed to make reward-seeking disadvantageous, and it should be learned that although some options bring large immediate gains, they also bring large losses in the long term; therefore, choosing smaller gains is the best strategy. Nevertheless, there are other paradigms such as the Balloon Analogue Risk Task (BART; [21]) where reward-seeking and risk-taking, at least to some extent, are advantageous.

In BART, participants are required to pump up a balloon to gain money. Every pump is associated with a monetary reward, but if the balloon pops they lose the amount accumulated on that single balloon. Participants can stop pumping at any point, however, if they stop pumping at a very early stage this leads to a small monetary gain. Thus, a balance between a certain degree of risk-taking versus risk-avoidance leads to optimal results [48]. Under these settings, acute stress should favor decision-making by promoting risk-taking, yet studies addressing stress and BART yield mixed results. So, while some studies found the expected results only in men, but the contrary pattern (risk-avoidance) in women [5, 23], Reynolds et al. [38] observed increased risk-taking in both sexes as long as they suffered social anxiety, but not in healthy stressed individuals. In turn, Lighthall et al. [24] did not find any differences in risk-taking between stress and non-stress conditions, and Finy et al. [9] even found risk-avoidance under stress in both men and women.

These inconsistencies could be at least partially explained by the variability of the paradigms employed. Thus, different stressors were used (procedural vs. systemic) which may promote somewhat different psychophysiological responses [15]. Likewise, BART was assessed at different points from the stressor onset, so some studies may be dealing with the early effects of catecholamines (e.g., [38]), while others with the later effects of cortisol (e.g., [5]). In addition, some samples with particular characteristics were included, which may introduce some extra variability (e.g., adolescents; [9]). However, it is also worth noting that all studies analyzed BART with general or crude measures such as the total number of pumps or explosions, but decision-making is complex and is composed of multiple cognitive sub-processes [1]. In fact, several computational models have been developed to extract more accurate information from decision-making tasks, and specifically from BART (see [41] for a complete review). Here we focus on the novel Experimental-Weight Mean-Variance (EWMV; [35]) model because it outperformed other existing BART models (see [35] for a discussion). This model provides information on 5 specific parameters underlying risk-taking during BART: risk preference, sensitivity to losses (loss aversion), prior belief of bursting probability, updating rate of this belief as one learns from the outcomes, and consistency during the task. Using this model, we can gain further insight and analyze subtle differences that stress may cause in BART, and which could remain hidden if we only attend to more general measures. Nevertheless, to our knowledge, it has never been used any computational model when addressing stress effects on BART.

Thus, by exposing an experimental group to a prominent stressor such as the Trier Social Stress Test (TSST; [18]), we hypothesized that this group would display a higher risk-taking during the BART than a control group: that is, stressed participants would exhibit higher number of pumps, explosions, and risk preference. In line with previous studies on stress and loss aversion (e.g., [25, 29,[30] 31]), and since stress could prompt an alignment of reward- with loss-sensitivity [25], a diminished loss aversion would be also expected under stress. Additionally, this higher risk propensity and lower loss aversion may be accompanied by a more optimistic prior belief about the probability of bursting the balloon, in line with the lower perception of risk that stress could produce [7, 16]. Finally, stress can be detrimental to key structures of the executive-network, such as the prefrontal cortex [13]. These alterations can result into altered feedback-processing, altered reward and punishment sensitivity, and higher inconsistency in the preferences [8, 12, 34]. Complementarily, a lower loss aversion could difficult learning since the increased sensitivity to punishments (e.g., losses) plays a key role in the reinforcement-learning processes [31]. Therefore, it would have sense that stressed participants also show lower learning (updating rate) and consistency during BART. This work aimed to shed light on the question of whether acute stress would support the STARS model [27] and, therefore, whether it would lead to reward-seeking and riskier decisions in a context such as BART, where this would be adaptive.

2. Methods

2.1. Participants

Previous studies on stress and BART ranged from 48 to 132 participants. Additionally, based on the effect size reported in only one of them [5], an a priori power analysis using G*Power indicated a requisite of 90 participants ($\eta_p^2 = 0.08$, power = 80%, $\alpha = 0.05$) to perform an ANOVA and compare risk-taking between groups (stress vs. control group). We recruited 95 participants, but 1 had to be eliminated due to registration problems, so a total of 94 participants (age: $M = 19.13$, $SD = 1.88$; women: $N = 78$, 83%) were finally included. They met the following inclusion criteria: not having cardiovascular, endocrine, neurological, or psychiatric diseases; not consuming more than 5 cigarettes a day; not consuming drugs habitually; not doing more than 10 h of exercise per week and not having experienced a highly stressful event in the last month. In addition, participants were asked to not perform extenuating exercise or take drugs or alcohol in the last 24 h, and not smoke or take stimulant drinks in the 2 h before the experimental session. Participants were randomly distributed into two conditions, stress ($N = 46$) and control ($N = 48$).

2.2. Procedure

This study was approved by the Ethics Research Committee of the University of Valencia in accordance with the ethical standards of the 1969 Declaration of Helsinki. Experimental session was carried out between 15:00 pm and 20:00 pm and lasted approximately one and a half hours. Participants were connected to the electrocardiogram (ECG) and had 10 min of rest as habituation. The last 5 min were taken as baseline. Then, stress group was exposed to the virtual version of the Trier Social Stress Test (TSST-VR), while the control group was submitted to a distractor task (watch a length-matched documentary). Before and after the stressor/distractor, participants were evaluated for positive and negative mood with the Positive and Negative Affect registry (PANAS; [53]) and were asked about the subjective stress they felt. After that, both groups performed the Balloon Analogue Risk Task (BART).

2.3. Virtual reality version of the trier social stress test (TSST-VR)

Following Montero-López et al. [32], we utilized a software that enables the design of a 3D audience, which was projected onto a Screen of 27″ at a distance of 1 m from the participant. This is a virtual-reality adaptation of the traditional TSST [18] and consists of four phases. First, participants faced the screen showing a 3D image of a stage curtain and were told that they had to give a speech to convince an audience that they were suitable for a position in their dream job. To lend credibility, a microphone and a camera were added, telling them that both the content and formal aspects of their speech would be analyzed in real time and that the virtual audience would react accordingly. The second phase, the anticipatory stress period, lasted 5 min, during which participants had to prepare the speech. They were given a sheet of paper where they could write down notes, however, that sheet was taken away when the participants were required to give their speech. The third phase was the speech itself. During this period, the curtain came up, the virtual audience appeared, and participants had to deliver their speeches. They were instructed to speak for the entire 5 min without interruption. The virtual audience remained neutral for 2.5 min but was manipulated to show signs of boredom for the remaining time. Finally, the last phase of the stressful task was an arithmetic task. In it, participants had to repeatedly subtract a fixed amount from a given number (e.g., subtracting 7 from 123 as quickly as possible). If they completed a series, they were given a new number and started over. Similarly, if they made a mistake they also had to start over.

TSST-VR facilitated the execution of the study despite COVID-19, avoiding the overcrowding that would involve including real audience in the laboratory. Comparable to the original TSST, this protocol demonstrated good reliability in inducing stress responses, which are manifested by the increase in HR, blood pressure, adrenaline and cortisol levels, as well as the negative mood [32]. However, to ensure that our stress induction was also effective, we assessed HR, negative and positive mood, and subjective stress perception.

2.3.1. Heart rate (HR)

The ECG was recorded using the third Einthoven derivation with 3 re-usable electrodes, BIOPAC MP150, a transducer ECG-100C and the AcqKnowledge 4.2.0 software. The sampling frequency was 1000 Hz. The ECG was filtered by digital Band Pass FIR filter, with a low cut-off frequency of 1 Hz and a high cut-off frequency of 35 Hz [6]. 6 participants showed some ectopic beats which were corrected using the Heart Timing Signal method [26]. For each period (Baseline, Stress and BART), the mean HR (bpm) was extracted.

2.3.2. Positive and negative affect registry (PANAS)

PANAS [53] is a 20 Likert-type items scale (from 1, more than usual, to 4, much less than usual) that evaluates positive and negative mood. Each dimension contains 10 items that must be added. The higher the score, the more positive or negative the mood. PANAS was evaluated before and after the stressor/distractor.

2.3.3. Perceived stress

Before and after the stressor/distractor, participants were also asked about the subjective stress they felt. This question, designed *ad hoc* for the study, asked: "How much stress do you feel right now?". The answer was given on a Likert scale where 0 is "no stress", and 10 is "a lot of stress".

2.4. Balloon analogue risk task (BART)

The BART [21] was presented on a computer screen, which showed a simulated balloon accompanied by both the “Pump” and the “Collect €€€” buttons. Each click on the Pump button inflated the balloon in all directions (about 2–3 mm) and 5 € were added to a temporary reserve (this reserve was not indicated on the screen). At any point during each balloon, participants could stop pumping and click the Collect button, which would transfer all money from the temporary reserve to the permanent bank, always displayed on the screen and labeled as “Total earned”. Then, a new balloon appeared until a total of 30 balloons were completed. If a balloon was pumped past its individual explosion point, a “pop” effect sounded, all money in the temporary reserve was lost, and the next uninflated balloon appeared on the screen. Participants were given no detailed information about the probability of an explosion, but they were told that each balloon could explode as early as the first pump. As in the original BART [21], the probability that a balloon explodes was arranged by constructing an array of 128 numbers. The number 1 was matched with the pop. On each pump, a number was selected without replacement from the array. The balloon exploded if the number 1 was selected. Thus, the explosion probability on the first pump was 1/128. If the balloon did not explode after the first pump, the explosion probability was 1/127 on the second pump, and so on up until the 128th pump, at which the probability of an explosion was 1/1. According to this algorithm, the average break point would be 64 pumps.

Standard BART measures, i.e., adjusted pumps (average pumps on unpopped balloons) and the total pops, were computed for each participant. In addition, the EWMV model was used to study the underlying cognitive processes that guide risk-taking in the BART.

2.4.1. Experimental-weight mean-variance (EWMV) model

First, although the literature indicates that the EWMV model outperformed other existing BART models [35], we wanted to verify whether it was also the best fit for our sample. We used as a baseline a model preceding the EWMV: the reparametrized version of the four-parameters (Par4) model, which also has a good predictive accuracy and its parameters are close to those of the EWMV [35]. We compared the goodness-of-fit of both models based on the Leave-One-Out Information Criterion (LOOIC; [50]). Note that the lower LOOIC is, the better its model-fit is. As expected, the EWMV model (LOOIC = 15,083.94) outperformed the Par4 model (LOOIC = 15, 210.04), so the parameters analyzed in our sample were those of the EWMV.

The EWMV model [35] assumes that decision-makers have a prior belief about the probability of bursting the current balloon when they pump it (prior belief of burst, ψ), and that this belief is updated as they obtain experience throughout the BART trials (updating exponent, ξ). This framework also assumes that the probability of pumping on a pump opportunity depends on the mentioned prior belief of burst, but also on the subjective utility that pumping the balloon has for the decision-maker (that is, how beneficial it is perceived to keep pumping the balloon). The subjective utility borrows from the principles of Prospect Theory [17] and is influenced by the decision-maker’s risk-taking preferences (risk preference, ρ), and their loss aversion (λ). For a detailed math description of the model see Park et al. [35].

Higher values for the prior belief (ψ) indicate more pessimistic beliefs (i.e., participants think that the balloon is more likely to burst). Higher values for the updating rate (ξ) indicate that participants are readily incorporating new evidence into their prior beliefs (i.e., they exhibit higher learning during BART). Higher values for the risk preference (ρ) indicate higher risk propensities, and higher loss aversion (λ) indicates greater sensitivity to losses than to proportional gains. Finally, the model also extracts a fifth parameter: the inverse temperature or consistency (τ). A lower τ indicate that decisions change more erratically throughout the trials.

Each parameter of the EWMV model was estimated for each participant through Hierarchical Bayesian Analyses (HBA; see Anh, 2008 for more details), performed with the hBayesDM package (Ahn et al., 2017) for the R software. The hBayesDM uses Stan 2.1.1 [45] with the Hamiltonian Monte Carlo (HMC) algorithm as MCMC for sampling the posterior distributions. Following Alacreu-Crespo et al. [1], we drawn 40.000 samples, after burn-in of 23.333 samples, in three different chains (in sum, a total of 120.000 samples and 70.000 burn-in). The Gelman-Rubin test [11] was used to study if the chains converged ($\hat{R}$) to the target distribution. $\hat{R}$ values of all parameters were 1, which means that convergence was achieved. In addition, to confirm this convergence, the MCMC chains were visually inspected.

2.5. Statistical analyses

Outliers were analyzed with the 2.5 standard deviations method and Mahalanobis distance for repeatedly measured variables (e.g., HR). Kolmogorov-Smirnoff with Lilliefors correction was used to check normality. Analyses included repeated-measures ANOVAs, with the group (stress vs control) as a between-participants factor, to test the stress induction effectiveness, both at the physiological (HR) and at the subjective level (perceived stress, positive affect, and negative affect). In addition, adjusted pumps, total pops, and parameters of the EWMV model were compared between groups through one-way ANOVA. The α significance level was set at 0.05 and partial eta square (η_p^2) symbolizes the effect size. All analyses were performed with IBM SPSS Statistics 25.

3. Results

3.1. Preliminary analyses

Stress and control groups were homogeneously distributed with no significant differences in age (stress: $M = 22.27$, $SD = 2.21$; control: $M = 22.41$, $SD = 2.42$), $p = 0.32$; in BMI (stress: $M = 22.06$, $SD = 3.03$; control: $M = 21.69$, $SD = 3.46$), $p = 0.58$; nor in socioeconomic status (stress: $M = 6.42$, $SD = 0.89$; control: $M = 6.43$, $SD = 1.16$), $p = 0.93$. Moreover, there were more women than men, but the chi-square test revealed that both women (stress: 83.3%; control: 82.6%) and men (stress: 17.4%; control: 16.7%), $p = 0.92$, maintained similar percentages in both groups.

3.2. Stress induction

3.2.1. Physiological stress

A repeated-measures ANOVA including group (stress vs. control) as a between-factor was performed to test whether the stress induction was effective at the physiological level. Analyses revealed a significant group × moment interaction, $F(2, 184) = 80.04$, $p < 0.001$, $\eta_p^2 = 0.47$, which indicates that HR evolution was different for both groups (see Fig. 1). This effect was then further explored.

When contrasting by groups, the stress group's HR was significantly higher during the TSST-VR compared to the baseline, $F(1, 45) = 88.872$, $p < 0.001$, $\eta_p^2 = 0.66$. This level was reduced again during BART, showing no significant differences with regard to the baseline, $F(1, 45) = 0.067$, $p = 0.79$, $\eta_p^2 = 0.001$. Furthermore, the control group did not show differences between any of the HR measurement levels (p's > 0.05). All means can be seen in the Table 1. Lastly, the intergroup analysis controlling for basal levels (see Table 1) revealed that, although both groups did not differ in their HR at the baseline nor during the BART, the stress group showed significantly higher HR than the control group during the TSST-VR/distractor.

3.2.2. Psychological stress

Regarding the psychological impact of the stress, repeated measures ANOVAs (including group as between-factor) were carried out to study differences pre- and post-TSST-VR/distractor in the subjective-perceived stress and both the positive and the negative affect measured with PANAS. Focusing on the perceived stress, it was found a significant group × moment interaction, $F(1, 92) = 52.21$, $p < 0.001$, $\eta_p^2 = 0.36$. So, while the control group did not show differences between pre- ($M = 4.00$, $SD = 1.97$) and post-distractor ($M = 3.85$, $SD = 1.87$) levels, $F(1, 47) = 0.44$, $p = 0.50$, $\eta_p^2 = 0.01$; the stress group experienced an increase in perceived stress after being submitted to the TSST-VR ($M = 6.50$, $SD = 2.18$), compared to their pre-stressor level ($M = 3.78$, $SD = 1.90$), $F(1, 45) = 66.07$, $p < 0.001$, $\eta_p^2 = 0.59$. Complementarily, both groups did not differ at their basal level, $F(1, 92) = 0.29$, $p = 0.58$, $\eta_p^2 = 0.003$; but the perceived stress of the stress group was significantly higher than the level reported by the control group after the stressor/distractor, $F(1, 92) = 39.65$, $p < 0.001$, $\eta_p^2 = 0.30$.

By the other side, regarding positive affect assessed with PANAS, no pre-post changes or differences between groups were found (p's > 0.05). However, regarding negative affect, analyses also revealed a significant group × moment interaction, $F(1, 92) = 80.42$, $p < 0.001$, $\eta_p^2 = 0.46$. Stress ($M = 20.78$, $SD = 4.89$) and control ($M = 21.00$, $SD = 4.19$) groups did not present differences pre-stressor/distractor, $F(1, 92) = 0.054$, $p = 0.81$, $\eta_p^2 = 0.001$. Yet, the stress group suffered a significant increase in negative affect after TSST-VR ($M = 25.96$, $SD = 5.80$), $F(1, 45) = 53.97$, $p < 0.001$, $\eta_p^2 = 0.54$; while the control group kept a similar level ($M = 19.94$, $SD = 4.12$), $F(1, 47) = 0.22$, $p = 0.56$, $\eta_p^2 = 0.006$. So, levels post TSST-VR/distractor significantly differed between groups, $F(1, 92) = 52.68$, $p < .001$, $\eta_p^2 = 0.36$.

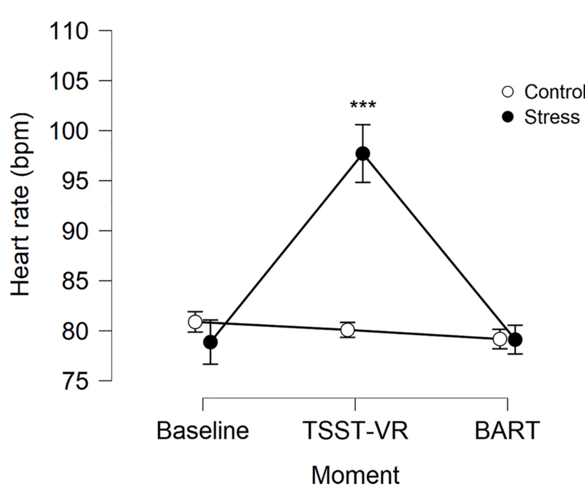

Fig. 1. Heart rate during baseline, TSST-VR/distractor, and BART by group. Stress and control groups significantly differed in their HR level during the TSST-VR/distractor. *** Significant contrast at the 0.001 level; $M \pm 95\%$ confidence interval.

3.3. Risk-taking during the BART

First, we compared whether there were differences between groups in the standard BART measures, but neither adjusted pumps nor total pops yielded significant results (p's > 0.05).

However, as for the parameters of the EWMV model (see Fig. 2 for the distribution of the values), significant differences were found for the risk preference (ρ), $F(1, 92) = 4.25$, $p = 0.042$, $\eta_p^2 = 0.061$, where the stress group ($M = 0.0017$, $SD = 0.001$) showed a lower risk propensity than the control group ($M = 0.0022$, $SD = 0.001$). Furthermore, the stress group ($M = 0.0155$, $SD = 0.007$) showed a pessimistic prior belief of bursting (ψ) than the control group ($M = 0.0123$, $SD = 0.004$), $F(1, 92) = 7.98$, $p = 0.006$, $\eta_p^2 = 0.072$. That is, the experimental group displayed a higher belief of the balloon exploding when they pump it. Finally, differences were also found in the updating exponent (ξ), $F(1, 92) = 12.87$, $p = 0.001$, $\eta_p^2 = 0.123$, where the stress group ($M = 0.010$, $SD = 0.006$) exhibited a higher incorporation of new evidence into their prior beliefs (i.e., a higher learning), than the control group ($M = 0.006$, $SD = 0.002$). No differences were observed for the loss aversion (λ) nor the consistency (τ) parameters.

4. Discussion

This study aimed to shed light on how acute stress influences our decision-making and, more specifically, whether it would be beneficial in a context such as BART where, to some extent, increased reward-seeking and risk-taking would be advantageous. Both physiological and psychological measures suggest that our stress manipulation worked: compared to controls, participants exposed to TSST-VR exhibited significant increases in HR, as well as in their perceived stress and negative affect. However, our results would challenge the hypotheses of the STARS model [27] according to which, under stress, people would take more risks. Thus, our stressed participants showed more pessimistic beliefs about the probability of balloons bursting and a lower risk propensity. The reason for these discrepancies, as well as whether this conservative attitude reflects a beneficial or detrimental effect of stress on decision-making will be discussed in depth below.

First, it should be noted that the standard measures of BART (i.e., adjusted pumps and total pops) did not reveal significant differences between groups. Since our sample was composed of young, healthy adults, stress may have a lower influence on them than in other sensitive populations (e.g., gambling disorder patients), failing to be captured by such general measures. This was also the case for other tasks such as the Iowa Gambling Task where the stress effects remained hidden until more

Table 1
Intergroup differences in heart rate (HR) during baseline, TSST-VR/distractor, and BART.

		Stress ($N = 46$)	Control ($N = 48$)	F	df between	Df intra	p-value	η_p^2
HR	Baseline	$M = 78.86 \pm 11.91$	$M = 81.09 \pm 12.47$	0.78	1	92	0.37	0.01
	TSST-VR / distractor	$M = 97.71 \pm 16.07$	$M = 80.08 \pm 12.86$	86.6	1	92	<0.001***	0.49
	BART	$M = 79.11 \pm 9.84$	$M = 79.17 \pm 12.19$	0.01	1	92	0.98	0.001

M, mean; ± *SD*; df, degrees of freedom
***significant contrast at the 0.001 level.

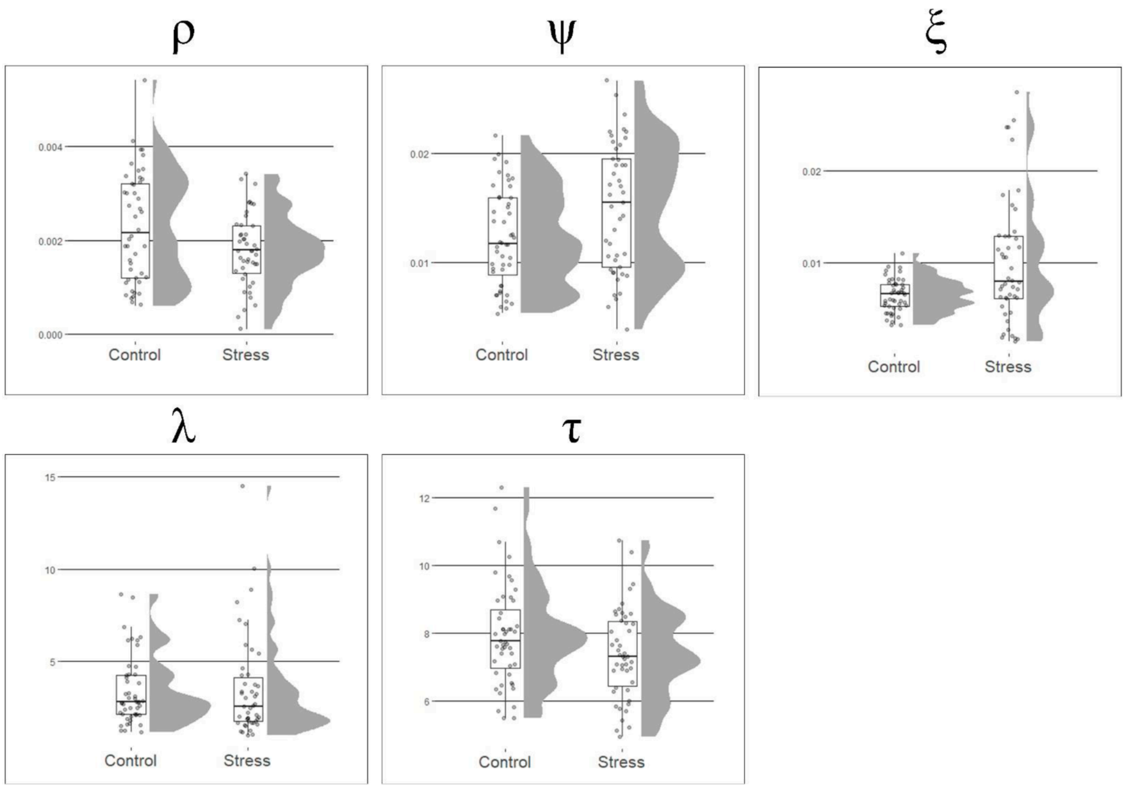

Fig. 2. Raincloud plots. Jittered individual points, box plot and halved violin plot for each parameter from the EWMV model; risk preference (ρ), prior belief of bursting (ψ), updating exponent (ξ), loss aversion (λ) and consistency (τ) parameters.

accurate measures were addressed [31]. Thus, our results constitute further evidence of the need to rely on new advances in computational modeling to explore specific cognitive processes underlying decision-making [41].

In fact, relevant information was found when the parameters from the EWMV model were analyzed. Contrary to our hypotheses, stress group exhibited more pessimistic beliefs about the probability of balloon bursting (ψ); in other words, they felt that balloons would be more likely to burst early if they inflated them. Moreover, this belief was accompanied by a lower risk propensity (ρ) during subsequent BART trials. These results seem to contradict the assumptions of the STARS model [27], according to which stress would increase the rewards attraction and, with it, risk-taking [25]. However, this effect would be especially evident when cortisol reaches its peak [25, 34], which is estimated between 20 and 40 min after stressor onset [13, 48], but our participants performed BART only 15 min after the TSST-VR onset. Additionally, although TSST-VR produces significant cortisol increases, these use to be smaller than those obtained when the speech is given in front of a real audience [32]. Thus, our results may reflect a lesser influence of this hormone and rather capture the catecholamines impact.

In this sense, the catecholaminergic stress response, especially in stressors that promote a negative mood [14, 34], would enhance the salience-network in detriment of the executive-network in our brain [13–15]. This translates into increased activity of regions such as the insula or the amygdala, which are key nodes in the detection and response to negative or threatening stimuli [13, 25, 44]. Thus, the other prominent hypothesis on how stress could influence our decisions is the salience-of-losses hypothesis [25, 28], according to which the psychological impact of negative stimuli would be amplified and, in line with our results, more conservative behaviors would be promoted. This was also observed by Pabst et al. [34], where 5 and 18 min after the original TSST onset, participants took fewer risks in the GDT; in contrast, when the cortisol peak was reached at 28 min, risk propensity was reversed and riskier decisions were found. Complementarily, greater attention to negative stimuli can facilitate reinforcement-learning processes by increasing sensitivity to punishments [31, 36, 47]. This could explain why the stress group also presented a higher updating exponent, which according to the EWMV model assumptions [35], would indicate that participants were readily incorporating new evidence into their prior beliefs of bursting. In other words, stressed participants learned better from the outcomes they obtained and adapted their prior beliefs based on them. This also fits with recent findings indicating that under threat perception (such as that induced by stress), it would be easier to update our beliefs with negative information [10]. Yet, the loss aversion parameter may contradict this explanation since it showed no differences between groups in terms of sensitivity to negative stimuli. In the absence of complementary measures to shed light on these questions (e.g., neural activity of the salience-network), caution is advisable when interpreting results.

In fact, alternative explanations are possible. Rather than learning, an elevated updating exponent could also indicate greater uncertainty and volatility in the prior belief [12, 20]. That is, the stress group could be showing difficulties in establishing a consistent belief about bursting probability and modifying it erratically, without really learning from the environment. This would fit with the impairment that stress produces on the executive-network and, therefore, on the prefrontal cortex activity (PFC; [13, 15, 34]), which plays a key role in valuation and learning processes [12, 39]. These changes in the PFC can result into insufficient adjustment from automatic response, altered feedback-processing, altered reward and punishment sensitivity, and higher inconsistency in the preferences [8, 12, 34]. Moreover, with a parameter similar to the updating exponent, Gu et al. [12] found that deficits in this region also led to volatility in the prior belief about inequity in a social decision-making task. Therefore, our results could suggest that stress is impairing learning capacity, in line with extensive previous evidence (e.g., [33, 34, 37, 42, 46, 47]). In fact, we must remember that, to some extent, a greater risk propensity would be advantageous in BART. If the higher updating exponent of the stress group involved learning, this group should have developed this propensity. Instead, they showed a lower preference for risk than controls. Nevertheless, despite this reduced risk preference, overall behavior in BART (adjusted pumps) did not differ between groups. Thus, more research is needed to conclude whether stress is hindering learning and promoting inappropriate strategies for the task or, on the contrary, only implies a more cautious attitude during the decisional process, but not altering the final reward-seeking and risk-taking. Additionally, it has been seen that the extent of learning deficits on decision-making under stress depends on the working memory capacity [33]; it is, a good working memory prevents from the deficits in reinforcement-learning processes due to stress. So, it is a key factor to consider in future studies if we want to enrich our understanding of the relationship between stress and decision-making.

It should be noted that our study is not exempt from limitations. As mentioned, the main one is the absence of complementary measures that would allow to investigate the neurobiological substrates of stress and its relationship to decision-making. In this sense, it is not possible to determine whether the stressor used influences decision-making through the role of catecholamines or, in line with a more delayed response, through cortisol; nor can we explore the neural activity that these substrates promote. New studies are needed including the measurement of catecholamines, cortisol or neuroimaging techniques to shed light on the effects that stress is exerting on the organism and then, on cognition. Similarly, it will be necessary to consider other factors that can modulate the relationship between stress and decision-making, such as the mentioned working memory [33]. On the other hand, all analyses were replicated controlling for sex and did not yield significant results. However, our sample was disproportionate and included significantly more women than men. Therefore, these analyses could be underpowered, and caution is advisable. In fact, previous studies showed sex differences in the psychophysiological response to stress, as well as in the effects of stress on decision making [15, 49]. For example, Daughters et al. [5] found that, while men took more risks in BART under stress, women showed the opposite response. As our sample is predominantly feminine, this explanation could fit with our results. Therefore, future studies should also address these issues and confirm whether our results are generalizable to both sexes. Finally, the control task during TSST usually involves some similar, but non-stressful, activity (e.g., talking in a room without anyone judging). Our study proposed the viewing of a documentary to reduce any source of stress in the control group, but the mere fact of having a different physical activity (one group talked and the other did not) may promote different physiological levels without implying that participants are becoming stressed. Although we also measured subjective stress, which may still indicate the effectiveness of our stressor, future studies should use more stressor-like control tasks to minimize potential confounding factors and assure the stressor effectivity.

Despite these limitations, this is the first study that analyzes through computational modeling how acute stress influences cognitive processes underlying risk-taking during BART. Thus, acute stress would promote pessimistic beliefs, thinking that the balloons will be more likely to pop and, with this, the adoption of a lower risk preference. Now we need to decipher whether this cautious attitude is attributable to an alertness state promoted by the stress or whether, rather, it is a consequence of the greater uncertainty derived from learning difficulties and altered feedback-processing. Finally, our work highlights the importance of studying the components that underlie decision-making, rather than addressing it as a single dimension

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Data availability

Data will be made available on request.

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