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Decision making under stress:

Mild hypoxia leads to increased risk-taking

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Abstract

People tend to take more risks under stressful conditions. In the present study, we examined the effect of mild hypoxia, an unconscious and ongoing stressor, on decisions under uncertainty where probabilities are unknown. Participants completed the Balloon Analogue Risk Taking task (BART) in both a normoxic (20.9% oxygen concentration) and a mildly hypoxic (14.1% oxygen concentration) environment. The results indicate that people take more risks in a mildly hypoxic than in a normoxic environment. Despite inducing significant changes in physiological parameters, the oxygen manipulation remained undetected by participants allowing us to rule out a cognitive appraisal account for the effect. Moreover, the stressor was ongoing allowing us to discount possible post-stress reaction explanations. The current findings extend previous ones about the effect of stress on risk-taking and demonstrate that undetected stressors can increase risk-taking in decision making under ambiguity.

Keywords: hypoxia; stress; risk; uncertainty; decision-making; oxygen-depleted environment

Introduction

Decision-making is a fundamental cognitive function that involves a combination of cognitive and emotional processes that ultimately propels behavior. The majority of the decisions people make are made without definite knowledge of the consequences. Decisions accompanied by some degree of risk or ambiguity are so pervasive and inevitable in daily life that a greater understanding of human behavior cannot disregard the investigation of decisional processes under uncertainty. Indeed, such an investigation may allow us to predict and account for possible performance decrements, as well as identify potential strategies aimed at overcoming suboptimal decisions.

It is generally assumed that both situational factors (e.g., decision domain, environmental factors, and perceived threat) and individual characteristics (e.g., personality traits, age, gender, and expertise) impact these kinds of decisions. Among these factors, stress has received growing attention by raising both scientific and public interest. Overall, empirical findings suggest that stressful conditions lead to greater reward seeking and riskier behavior compared to non-stressful conditions (Nowacki et al., 2019; Starcke & Brand, 2016). This seems to be the case when stress is incidental, that is, when stress does not arise from the decisions or choices at issue but rather it is carried over from an unrelated situation. In contrast, when stress results from and/or is an integral part of the decisional process itself, then stress tends to decrease the willingness to engage in risky behavior (see Bonini, Gregucci, Nicolé, & Savadori, 2018; Traczyk, Sobkow, & Zaleskiewicz, 2015). Different mechanisms have been proposed to explain how stress affects risk taking, such as increased reliance on immediate rewards through an increased dopaminergic activity (Mather & Lighthall, 2012; Shohamy, Myers, Kalanithi, & Gluch, 2008; Kobayashi & Schultz, 2008), or an impairment of executive control functions via reductions of prefrontal functioning (see Hermans, Henckens, Joëls, & Fernández, 2014).

Most of the research has focused on stressors that require the interpretation of a situation to initiate a stress response. These stressors are known as *processive* stressors and include stressors such as time

pressure, giving a public speech, or the exposure to a novel environment. Research has focused less on the impact of another type of stressor, *systemic* stressors such as water deprivation, extreme temperature, pain reception, hypotension, and fatigue, which do not necessarily require processing by higher-order brain structures but initiate an immediate stress response by activating low-order processing stress neuronal circuits directly. Usually, systemic stressors challenge individual well-being by representing a concrete threat for the organism with an immediate survival value. Their relative neglect within psychological research is surprising because systemic stressors are strongly entrenched in everyday life: critical judgments in several occupations (e.g., health profession, safety service, financial managing) are very frequently made under either brief or prolonged physiologically stressful conditions. Since systemic and processive stressors engage different brain networks and require different functional neuroanatomical processing (e.g., Godoy et al., 2018), it cannot be assumed that they exert a similar impact on cognitive functions.

Mild hypoxia is a systemic stressor because the response triggered by the disruption of cardiovascular or respiratory homeostasis does not require the involvement of higher-order cognitive processes (Herman & Cullian, 1997). As most aircrew members, mountain climbers, and high-altitude skydivers know, mild oxygen deprivation is difficult to detect consciously since the physiological alterations driven by the sympathetic nervous system (e.g., increased heart rate and ventilation) reach awareness only if oxygen depletion is sufficiently high. Therefore, the possibility of activating and implementing protective coping strategies is mostly hampered.

Two laboratory studies have empirically demonstrated that undetected mild hypoxia can influence decision-making (Pighin et al., 2012; Pighin, Bonini, Savadori, Hadjichristidis, & Schena, 2014). Pighin et al. (2012) showed that mild oxygen deprivation exacerbates individuals' tendency towards risk-seeking in the loss domain (Kahneman & Tversky, 1979). Specifically, participants preferred a risky gamble (e.g., "lose €25 with a 20% probability") over a sure loss with the same expected value

(e.g., “lose €5 for sure”) more frequently in a mild hypoxic than in a normoxic environment. Mild hypoxia also decreases individuals’ tendency to weigh losses more than gains (known as *loss aversion*, Kahneman & Tversky, 1979): whereas in a normal oxygen condition participants accepted gambles if the gain was about 2.4 times larger than the loss (e.g., “win 24 € with 50% probability or lose 10 € with 50% probability”), in a mild hypoxic condition they accepted gambles even if the gain was just 1.7 times larger than the loss (e.g., “win 17 with 50% probability or € lose 10 € with 50% probability”) (Pighin et al., 2014). In sum, participants accepted less advantageous gambles in a mild hypoxic condition.

Whereas these findings indicate that undetected mild hypoxia can alter decision-making processes, both studies employed tasks entailing explicitly stated outcome probabilities (i.e., decision under *risk*). Does mild hypoxia alter decision-making processes even when outcome probabilities are unknown (i.e., decision under *ambiguity*)?

The dichotomy between decision under risk and under ambiguity has a long-standing tradition in the decision-making literature (see Camerer & Weber, 1992; Ellsberg, 1961), and it is not just a matter of terminology. Indeed, in the case of risk (i.e., when the probabilities of the outcomes are known) individuals can (theoretically) evaluate the outcomes by computing the expected utility of the different options and choose the option that is associated with the highest expected utility. In contrast, ambiguity renders calculating expected utility impossible since the probabilities are unknown. Hence, the individual cannot maximize expected utility, as prescribed by the normative economic model. Indeed, most decisions in real life are taken under ambiguity rather than under risk. This is because the probability of events is often unknown to the decision maker or it is controversial because multiple conflicting evidence exists. Frisch and Baron (1988) define ambiguity as the subjective perception of missing information. Should we eat cow meat during a mad cow epidemic? Should we believe in climate change? Should we insure our homes against floods? Should we take the prescribed medicines

against heart failure? In all these examples of decision making under ambiguity, the probabilities of possible negative consequences occurring are unknown to the decision-makers. But ambiguity also arises when experts disagree about the probability of an event. Examples include the recent debates on the effectiveness of environmental policies or whether guns should be banned in the United States. Research aiming to define whether people decide differently under risk than under ambiguity have often measured the correlation between risk aversion and ambiguity aversion as an instance of the presence of one or two distinct processes. Although the overall evidence suggests a positive correlation between risk and ambiguity aversion (Lauriola, Levin, & Hart, 2007), some findings suggest a small or insignificant correlation (Cohen, Tallon, & Vergnaud, 2011; Levy, Snell, Nelson, et al., 2010), or even a moderately negative correlation (e.g., Sutter et al., 2013).

The same pattern of findings has been observed when looking at neural activations. Whereas some findings support an overlap in the neural activation of participants choosing under risk and under ambiguity (e.g., Levy, et al., 2010) other findings have revealed distinct neural patterns between these decision contexts (e.g., Huettel, Stowe, Gordon, et al., 2006) showing that the posterior inferior frontal sulcus (pIFS) within lateral prefrontal cortex, the anterior insular cortex (aINS), and posterior parietal cortex (pPAR) have a significantly different activation between gambles involving ambiguity and those involving risk. It has been suggested that greater activation in pIFS plays a particularly important role in behavioral flexibility which is a requirement for successfully dealing with ambiguity (Huettel et al., 2006).

In an attempt to extend previous findings on the effect of undetected mild hypoxia, here we present a laboratory experiment that examined its effect on risk-taking under ambiguity. To this end, we used the Balloon Analogue Risk Taking task (BART – Lejuez et al., 2002), a standard decision-making game in which participants have to inflate a series of virtual balloons on a computer screen, accumulating money each time they pump the balloon. The objective of the task is to accumulate the

largest amount of money possible while avoiding balloon explosions. Performance on the BART is said to represent a reliable indication of individuals' attitudes toward risk as it has been found to be correlated with several behavioral measures connected with addiction, safety and health (see Aklin, Lejuez, Zvolensky, Kahler, & Gwadz, 2005; Clay et al., 2018; Fernie, Cole, Goudie, & Field, 2010; Fernie et al., 2013; Lauriola, Panno, Levin, & Lejuez, 2014; Lejuez, Aklin, Daughters, Zvolensky, Kahler, et al., 2007; Lejuez, Simmons, Aklin, Daughters, & Dvir, 2004).

Previous studies have shown that under incidental stress individuals' choices on the BART become more risky. On average, participants decide to make more balloon pumps during the BART task following laboratory-based stress manipulations, such as submerging their non-dominant hand in a pitcher of ice water for three minutes (i.e., cold pressor task; Lighthall, Mather, & Gorlick, 2009, 2014), trying to free a screaming bird from its cage by finding the correct number combination (Daughters, Gorka, Matusiewicz, & Anderson, 2013), and performing a public speech (Reynolds et al. 2013). In all these instances, participants were aware that they were under stress. This awareness, in turn, might have activated coping strategies or caused behavioral changes through cognitive appraisal mechanisms. Interestingly, some of the studies that investigated the effect of (incidental and detectable) psychological and physiological stressors on BART performance revealed significant gender differences. Lighthall et al. (2009), for example, showed that after the cold pressor task, male participants increased their risk-taking behavior whereas females decreased it. Pighin et al. (2015) obtained a very similar finding by investigating the risk-taking behavior of amateur athletes during acute exercise or while at rest. The interaction between stress and gender was also supported by brain imaging evidence that showed gender differences in brain activation of the insula and the putamen, two areas related to decisional and reward processing under stress (see Mather & Lighthall, 2012). It must be noted that in the present study we did not aim to test for gender effects because this would

necessitate a much greater number of participants. However, we included both male and female participants to ensure that the results generalize to both genders.

In the present study, the use of mild hypoxia creates an ideal testing ground for examining the impact of physiological (not psychological) stress on risk-taking behavior. Unlike most previous studies, our stressor is not consciously known to participants since a slight decrease in oxygen concentration is likely to remain undetected by individuals. Furthermore, unlike previous experiments on stress and risk-taking, there is no time lag between stress onset and decision making. The delay between stress induction and measurement is indicated as an important factor in determining the effect of stress on behavior (Pabst, Brand, & Wolf, 2013; Starke & Brand, 2016). On average, previous studies employed a 18 to 40 minutes time interval between the stress manipulation and the beginning of the BART task. One exception is the anticipated speech task where the stress was ongoing (Reynolds et al. 2013). The time delay between the stress onset and the output measurements leaves open the possibility that the ultimate cause of the observed behavioral change is not stress itself, but a post-stress reaction. In our experiment, we used mild hypoxia as a stressor that activates a stress reaction that is ongoing throughout the task.

In summary, the use of mild hypoxia as stressor allow us to test the basic effect of physiological stress-induced alterations on risk-taking behavior. Based on the assumption that the effect of mild hypoxia on risk-taking is comparable to that of previously investigated stressors, we predicted increased risk-taking in the BART task under mild hypoxia than under normoxia.

Method

The minimum sample size needed to test our main hypothesis concerning the effect of mild hypoxia on participants' risk-taking in a within-participants design (with two measurements) was computed using G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009). The power analysis showed

that in order to detect a medium to large effect size of $f = .3$, assuming $\alpha = .05$ and $1 - \beta = .80$, the minimum sample required was 24. We planned to recruit 26 participants to cope with potential withdrawals from the study as it involved three research sessions spaced apart. Participants were undergraduate student volunteers ($M_{age} = 23.3 \pm 6.8$; 14 females), recruited through advertisements at the university.

Each participant was tested individually and took part in three research sessions which were separated by a 7-day interval: a familiarization session, a control session in normoxic environment (oxygen concentration of 20.9%, simulating an altitude of 0 meters above sea level), and an experimental session in mild hypoxic environment (oxygen concentration of 14.1%, simulating an altitude of 3,000 meters above sea level[1]). The mild hypoxic environment was created through the manipulation of the fraction of inspired oxygen (FiO2) by means of an oxygen dilution system based on the vacuum–pressure swing absorption principle (B-Cat, Tiel, The Netherlands). Each participant completed the familiarization session first. In the familiarization session the participant was acquainted with the experimenters, the room, the instruments, the procedure of the experiment, and the experimental task. Completing a familiarization session before the real experiment is an important step in studies manipulating stress in within-subjects designs because the novelty of the test situation can itself create a stressful reaction (see Beery & Kaufer, 2015), potentially overlapping with the intended stress manipulation. Each participant was then randomly assigned to one of two order conditions: control session first or experimental session first. The participants assigned to the control session first, completed the control session followed by the experimental one, while those assigned to the experimental session first, completed the tasks in the reverse order.

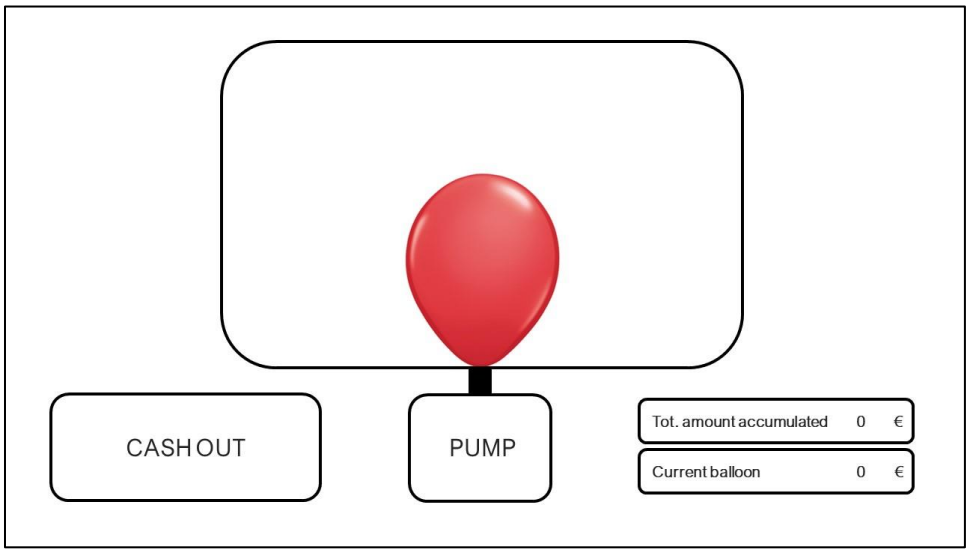
[1] There is no clear empirical data concerning the precise point in which normobaric hypoxia is detectable. The magnitude of the oxygen depletion was decided in accordance with previous studies (Pighin et al., 2012; Pighin et al., 2014), which were based on a pilot experiment (N=7) that identified the 14.1% of oxygen concentration as the one producing the best tradeoff between significant physiological alterations and lack of awareness of the oxygen manipulation itself (see also Heath & Williams, 1995).

Potential demand characteristics were eliminated by keeping the order and type of session blind to both participants and the experimenter. Participants were informed that the aim of the study was to investigate the effect of mild hypoxia on decision making. They were told that they would have to participate in three sessions and that each session would be held either in a mild hypoxic or normoxic environment. Participants were instructed that they would not be informed in which environment each session was held, and that all three sessions could also be in the same environment. All three sessions were conducted in the same normobaric chamber, with constant temperature (21° C) and air dampness (32%). The data collected during the familiarization session were not included in the analysis.

When participants entered the room, they were presented with a 20 min nature documentary video clip, which is the time required for the physiological alterations induced by mild hypoxia to take place (see Heath & Williams, 1995). After that, participants had to perform the risk-taking task described below. At the end of the task, participants were asked to indicate which session they believed they were in (i.e., “normoxic” or “mildly hypoxic”). In all sessions, two physiological parameters were measured: heart rate and oxygen arterial saturation (SaO2). The former was recorded in 5 sec intervals (Polar Electro Oy, Kempele, Finland) throughout the whole session, while the latter was measured by a portable pulsoximeter (Intermed SAT-500) placed on the index finger of the right hand and was recorded at three points during the session (i.e., at the end of the 20 min. nature documentary video clip, before the beginning of the task but after instructions, and at the end of the task).

Decision making under ambiguity was assessed through the Balloon Analogue Risk Taking task (BART), a computer-based task created by Lejuez et al. (2002) that measures the extent to which an individual is willing to risk in order to win more money (Figure 1).

Figure 1. The Balloon Analogue Risk Taking task.



The task comprised 30 trials. In each trial participants had the opportunity to pump a virtual balloon. For each pump they earned €0.01. The total amount accumulated with the pumps in each trial was visible at the bottom left of the screen, along with the amount accumulated until that trial. Participants were informed that the probability of a balloon exploding increased with the number of pumps, but the exact probability (i.e., "1 in 128" at the first pump) was not explicitly provided. At any point during the task, the participant could stop inflating the balloon and receive the money gained until that pump. If the balloon exploded, the participant lost the money earned in that trial and proceeded to the next trial. At the end of the study, participants received a financial reward contingent on their performance in the task. However, to avoid portfolio effects, they were instructed that only one of the three sessions would be randomly selected and actually paid.

The study and the informed consent procedure were approved by the Research Ethics Committee of the University of Verona (Verona, Italy, Prot. N. 58 Tit. II/9) and the experiment was embedded in a larger research project exploring the effect of mild hypoxia on decision making (Pighin et al., 2014).

Statistical analysis

To test if the oxygen manipulation significantly altered participants' physiological responses, we performed two paired sample *t*-tests comparing heart rate and SaO2 in the control and the experimental sessions, respectively. A McNemar's test was used to compare the paired nominal data concerning participants' awareness of the oxygen manipulation in each session.

Due to a software error, the data concerning the adjusted number of pumps in trials from 1 to 10 for one participant was not reported and, consequently, the participant was excluded from all analyses. An examination of the data from the remaining participants did not reveal outliers or violations of the assumption of normality. In line with previous studies, BART performance was measured by analyzing the average number of adjusted (unexploded balloons) pumps. To test the main hypothesis regarding a difference between sessions in the number of adjusted pumps we ran an ANOVA with session (control vs. experimental) and time (time periods: trials from 1 to 10 vs. trials from 11 to 20 vs. trials from 21 to 30) as within-participants factors, and order and gender as between-participants factors. Time was introduced in the analysis in an effort to outline the temporal dynamic of decisions by separating the time period into initial trials (trials 1 to 10), interim trials (trials 11 to 20), and final trials (trials 21 to 30); order was introduced to control for session order effects, and gender was introduced because previous studies using BART have shown gender differences under stress conditions (Lighthall et al.,2009; Pighin et al., 2015). We then ran the same ANOVA on the total amount of money earned by participants in the BART task. Significant main effects were followed up with pairwise comparisons using Bonferroni correction, and significant interactions were analyzed by performing separate pairwise tests adjusted for multiple comparisons. We also compared the time required to complete the task in the mild hypoxic and in the normoxic session by a paired-samples *t*-test. Significance level was considered as $p < .05$.

Finally, in order to investigate a possible relationship between participants' physiological measures and performance in the BART task, for each participant, we computed the difference in heart rate, SaO2, and adjusted number of pumps between the two sessions (normoxic and mild hypoxic), and then computed the Spearman correlation coefficient between these new variables.

All analyses were conducted with IBM SPSS statistics version 22 (IBM Corp., Armonk, NY).

Results

Table 1 reports the descriptive statistics (mean and standard deviation) for both physiological parameters and behavioral measures by gender (male or female) and type of session (normoxic or mild hypoxic).

Table 1. Mean (and *SD*) of participants' physiological parameters and adjusted number of pumps by type of session and gender.

	Physiological parameters				Risk taking (adjusted n° of pumps)	
	Heart rate		SaO2			
	Normoxic Session	Mild hypoxic session	Normoxic session	Mild hypoxic session	Normoxic session	Mild hypoxic session
Male	76.1 (*10.7*)	85.7 (*13.3*)	97.8 (*0.9*)	90.5 (*2.4*)	44.4 (*9.7*)	47.6 (*10.9*)
Female	81.9 (*10.5*)	89.6 (*7.4*)	98.1 (*0.5*)	90.4 (*1.6*)	42.6 (*10.1*)	46.1 (*8.1*)
All sample	79.0 (*10.8*)	87.9 (*10.4*)	97.9 (*0.7*)	90.5 (*1.9*)	43.4 (*9.8*)	46.8 (*9.2*)

The results showed that oxygen manipulation significantly altered participants' physiological responses: compared to the control session, in the experimental session heart rate increased [M_{exp} = 87.9 ± 10.4 vs. M_{con} = 79.3 ± 10.8; $t(24) = 5.32$; $p < .001$; $d = 1.06$; 95% CI, 5.2-11.9], and SaO2 levels decreased [M_{exp} = 90.5± 1.9 vs. M_{con} = 97.9 ± 0.7; $t(24) = -17.84$; $p < .001$; $d = 3.57$, 95% CI,

8.33-6.61]. Nonetheless, participants failed to detect in which session they were in: 10 out of 25 participants correctly guessed that they were in the control session when they actually were in the control session, while 7 out of 25 correctly guessed that they were in the experimental session when they actually were in the experimental session. Overall, only 4 out of 25 participants correctly guessed both the control and experimental sessions (McNemar test, $p = .508$).

Figure 2 displays the average number of adjusted pumps across the 30 trials of the BART task in the normoxic and mild hypoxic sessions. The results of the ANOVA on the adjusted number of pumps showed a significant main effect of session [$F(1,21) = 16.00$; $p = .001$, $\eta^2 = .432$], no effect of time [$F(2,42) = 0.22$; $p = .800$], no effect of order [$F(1,21) = 3.37$, $p = .081$] and no effect of gender [$F(1,21) = 0.33$; $p = .571$]. The main effect of session was explained by the fact that the average number of pumps before deciding to stop and collect the money was significantly greater in the experimental session ($M_{exp} = 46.8 \pm 9.2$) than in the control session ($M_{con} = 43.4 \pm 9.8$). The ANOVA also revealed a significant three-way interaction between session, order and gender [$F(1,21) = 13.86$; $p = .001$, $\eta^2 = .398$], and between session, order and time [$F(1,42) = 5.69$; $p = .007$, $\eta^2 = .213$]. These three-way interactions are difficult to interpret in light of the fact that the present study is underpowered to compare sub-groups specific performances. Inspection of the means, however, suggests that the first interaction effect may be due to the fact that males pumped on average more in the hypoxic session than in the normoxic session when they encountered the normoxic session first ($M_{exp} = 54.65 \pm 6.6$ vs. $M_{con} = 48.31 \pm 4.9$), but not when they encountered the hypoxic session first ($M_{exp} = 41.67 \pm 10.5$ vs. $M_{con} = 41.16 \pm 11.9$). Females, on the contrary, pumped on average more times in the mild hypoxic session than in the normoxic session when they encountered the mild hypoxic session first ($M_{exp} = 46.34 \pm 8.7$ vs. $M_{con} = 39.21 \pm 11.5$), but not when they encountered the normoxic session first ($M_{exp} = 45.95 \pm 8.1$ vs. $M_{con} = 45.98 \pm 8.0$). Thus, the session order might have a different influence on the effect of hypoxia, depending on gender. The second interaction suggests that participants pumped on

average a greater number of times under mild hypoxia than under normoxia in the earlier trials (trials from 1 to 10), when they participated first in the normoxic session (M_{exp} = 51.33 ± 10.3 vs. M_{con} = 45.17 ± 9.9); on the contrary, they pumped on average a greater number of times under hypoxia than normoxia in the subsequent trials (trials from 11 to 30) when they participated first in the mild hypoxic session (M_{exp} = 44.93 ± 8.3 vs. M_{con} = 38.62 ± 11.3). Thus the session order might affect participants' performances differently at different stages of the game.

The same analysis was performed on the total amount of money earned by participants (i.e., €0.01 per pump). The results revealed a significant main effect of time [$F(2,42) = 4.30$; $p = .020$, $\eta^2 = .170$], and a significant interaction between session and order [$F(1,21) = 6.41$; $p = .019$, $\eta^2 = .234$]. Overall, the amount of money accumulated in the final trials (i.e., trials 21 to 30) was significantly greater than that accumulated in the initial trials (i.e., trials 1 to 10), [$M_{21\text{-}30}$ = 304.8 ± 6.6 vs. $M_{1\text{-}10}$ = 274.4 ± 8.4, $p = .028$]. To analyze the significant interaction between session and order, we performed separate pairwise tests (adjusted for multiple comparisons) on the effect of session within the two order conditions. These tests revealed that participants earned more money in the mild hypoxic than in the normoxic session when they encountered the mild hypoxic session first [M_{exp} = 293.5 ± 31.3 vs. M_{con} = 262.1 ± 28.38; $F(1,12) = 8.23$, $p = .014$, $\eta^2 = .407$], but not when they encountered the normoxic session first [M_{exp} = 293.6 ± 34.9 vs. M_{con} = 300.4 ± 28.31; $F(1,11) = .42$, $p = .530$, $\eta^2 = .037$].

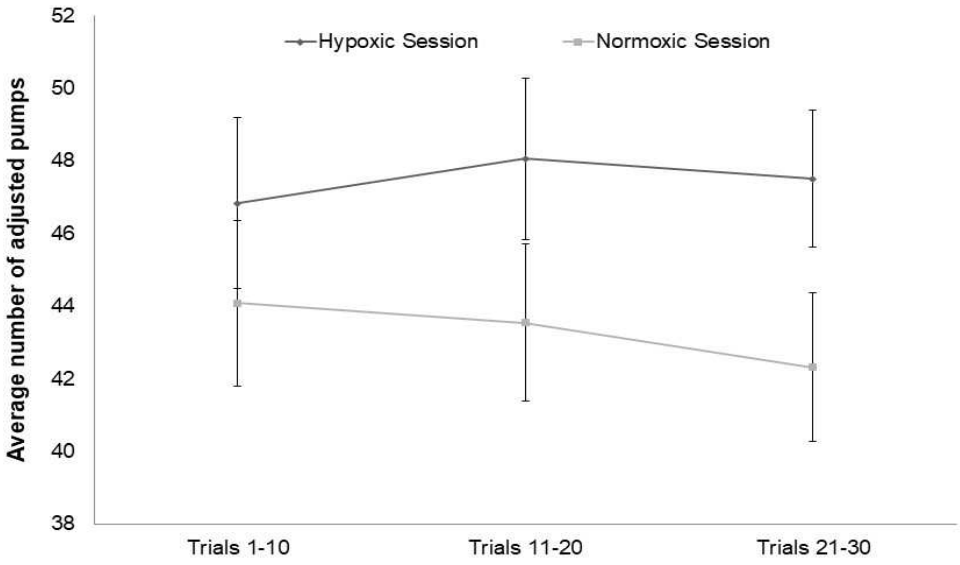
A paired sample *t*-test on the time spent on completing the BART indicated that participants' took (on average) more time to complete the BART in the mild hypoxic than in the normoxic session [M_{exp} = 517.84 ± 45.8 vs. M_{con}= 427.52 ± 21.1, $t(24) = 2.09$, $p = .047$; $d = .39$, 95% CI, 4.98-180.15]. A longer duration of the task under mild hypoxia is compatible with a higher number of pumps registered in that session.

Finally, we tested the relationships between heart rate and SaO2 levels and performance in BART. The individual variation in the adjusted number of pumps between the hypoxic and normoxic session

did not correlate significantly with the individual variation in heart rate (r = .166; p >.05) and SaO2 (r = -.047, p > .05). As in previous studies (Pighin et al., 2012; Pighin et al., 2014), the two physiological parameters (i.e., heart rate and arterial saturation) have to be considered simple manipulation checks aimed at determining whether or not the manipulation of the independent variable (i.e., oxygen depletion) has had the predicted biological effects on the participants, and not mediation (explicative) factors.

In sum, the results indicated that, although it remained undetected by participants, the mild oxygen manipulation significantly affected physiological measures and increased risk-taking behavior. Indeed, in the mild hypoxic environment, participants exhibited an increase in heart rate, a decrease in SaO2 levels, and an increase in the average number of pumps in the BART task. Such behavioral modification was observed throughout the whole task (initial, interim, and final trials), and was not qualified by gender.

Figure 2. Average number of adjusted pumps across the 30 trials of the BART task in the normoxic and hypoxic sessions (bars represent standard errors of the mean).



Discussion

The present study extends previous findings and provides further empirical support that mild oxygen depletion affects decision-making processes. The results showed that participants were more willing to risk in exchange for greater rewards under mild hypoxia than under normoxia.

Unlike previous experiments that examined the effect of mild hypoxia on risky decision-making where the probabilities of the outcomes were explicitly stated (Pighin et al., 2012; Pighin et al. 2014), the present study is the first to demonstrate its impact under conditions of ambiguity where the outcome probabilities are unknown. This aspect increases the ecological validity of the results by generalizing them to everyday situations where individuals trade greater risks in exchange for greater (but unpredictable) rewards. The lack of precise probability information about the outcomes makes these decisions more realistic than the decisions required in other tasks. The behavioral modification observed in the mild hypoxic environment of the present study can be read as a decrease in the

individual's capacity to abstain from taking a riskier action (i.e., pumping) that is associated with a larger potential reward, to the disadvantage of a safer, more conservative action (i.e., stop pumping and collect the money). Translating this into real-life behaviors, an undetected physiological stressor might reduce people's capacity to avoid the temptation of satisfying immediate and impelling needs. For example, under mild hypoxia people may be more likely to use short-cuts, eat junk food, buy lottery tickets, shop impulsively, or continue on with a mountain expedition even in prohibitive weather conditions.

What makes this study particularly compelling is that, in contrast to previous studies, the stressor remained undetected despite a significant alteration of participants' heart rate and SaO2 in the mild hypoxic condition, and was ongoing throughout the task. These characteristics avoid two caveats inherent in previous studies: that participants are aware of the stressor and that the stress onset precedes the outcome variable. Our results indicate that cognitive appraisal of a stressor is not necessary to induce behavioral modifications: changes appear regardless of participants' awareness of being under stress. Such lack of awareness creates a perfect experimental environment to examine behavioral cause-effect relationships but it also highlights that mild hypoxia represents a serious threat for individuals (e.g., soldiers, emergency rescue teams, professional sport athletes) who are used to adopting coping strategies to counteract stressful situations since they might fail to realize that a stressful condition is ongoing.

The gender differences observed in previous studies have been explained in evolutionary terms (see Lightall et al., 2009; Taylor et al., 2000). According to some authors, even if "fight-or-flight" is the primarily response to stress for both males and females, the pressure imposed by natural selection may have develop a different stress response pattern in females (termed "tend-to-befriend"), which focuses on maximizing the survival of self and off-spring. In the present study (as well as in Pighin et al., 2012, and Pighin et al., 2014) no main gender effect was observed, which suggests that the

cognitive appraisal of the stressor may play a role in determining which response pattern is activated. When a stress response is triggered by an unconscious systemic stressor (such as mild hypoxia), both females and males activate the primary "fight-or-flight" stress response. In contrast, when a stress response is triggered by a conscious stressor (such as a cognitive or physical demand) with the unavoidable involvement of higher-order cognitive processes, females may preferably activate a "tend-to-befriend" response aimed at maximizing safety and self-protection, while males the "fight-or-flight" response. Future studies could test this hypothesis and elucidate the role of cognitive appraisal in determining possible gender differences in risk taking behavior under stress.

Finally, it is noteworthy to mention that, due to its intrinsic characteristics, an increase in risk taking behavior in the BART task can have beneficial consequences. Indeed, on average, the participants earned slightly more money in the experimental than in the control session (but note this effect was not statistically significant, $F < 1$). However, there are other situations in which risk-taking can be dysfunctional, such as when a low probability, high rewards alternate with very high probability severe punishments. This is the case, for example, in the Iowa Gambling Task (Bechara, Damasio, Damasio, & Anderson, 1994), which simulates decision-making under ambiguity where risky behavior (driven by a focus on potential high rewards) generally leads to poor outcomes. Of course, the processing of the trade-off between potential rewards and potential punishments assumes an even greater relevance outside the laboratory, where punishments can represent concrete threats for health and well-being. Although future studies are needed to support the validity and generalizability of the present result, the current effect of mild hypoxia on risk-taking highlights the permeability of our decisional processes and represents a warning against the effect of hidden environmental stressors.

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Author contributions

All authors devised the paper's central idea as part of a larger study. S.P., F.S., and L.S. designed the study. S.P. collected data and performed the analyses. N.B. and L.S. supervised the statistical analyses. S.P., L.S., and K.H. wrote the original manuscript and all authors contributed to the final manuscript.

Competing interests

The authors declare no competing interests.

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