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Sweating it out: The influence of sex and emotions on human sweat production

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A B S T R A C T

Human sweat conveys a wealth of information about its donors, including their emotional state at the time of release. While extensive research has examined the communicative potential of human sweat, the mechanisms underlying emotional sweat production remain underexplored. This study employed a data-driven approach with a large sample of sweat donors (N = 334; most participants were university students) to investigate the relation between sweat production and the emotional state of males and females across three conditions – fear, happiness, and rest. Four key questions were addressed: (i) Do males produce more sweat than females across emotional conditions? (ii) Does sweat production vary as a function of emotional experience? (iii) Is sweat production associated with self-ratings of emotional experience? and (iv) Are there sex differences in these associations? Results revealed that males produced significantly more sweat than females in fear-inducing conditions, which also showed the highest overall sweat production. Contrary to prior findings, happiness-related sweat production did not exceed that of rest in either sex, a discrepancy potentially due to contextual factors. Moreover, sweat production was positively associated with reported negative emotional experience during the fear-inducing sessions, but only for males. This suggests that male, but not female, donors may have the capacity to encode emotional intensity in sweat production. These findings provide new insights into the physiological and contextual factors that shape emotional communication through sweat, with potentially important implications for future research. Additionally, the observed sex asymmetries are discussed in light of a possible evolutionary explanation.

1. Introduction

The communicative potential of human sweat has become a growing area of research in recent decades (e.g. Pause, 2017). While sweating primarily serves the regulation of body temperature and maintaining homeostasis in warm conditions (thermoregulation; see Baker, 2019 for a discussion on other potential functions), sweat has also been shown to convey a wide range of information about its donor (see, for instance, Semin & de Groot, 2013). This information includes stable characteristics, such as biological sex (Penn et al., 2006), age (Mitro et al., 2012), genetic relatedness (Porter, 1998), and familiarity (Lundström et al., 2009), as well as more transient factors, including health status (Olsson et al., 2014), reproductive state (Lübke & Pause, 2015), and even the emotional state of the donor during sweat release (Chen et al., 2000; de Groot et al., 2012; de Groot, Smeets, Rowson, et al., 2015; Gomes et al., 2023). Nevertheless, to fully understand this information transfer phenomenon, it is critical to uncover the parameters of sweat production. Arguably, the amount of sweat produced may play an important role in conveying information, especially in more natural settings: the greater the amount of sweat released, the greater the number of volatile molecules available to transmit information, potentially increasing the likelihood of successful communication and the number of people reached – a neglected aspect of communication via chemosignals.

So far, in exploring emotional communication through sweat, existing studies have mainly focused on how receivers respond to sweat from others released under different emotion-inducing conditions (e.g., fear, anxiety, stress, disgust, happiness), with the donor's emotional experience and the amount of sweat produced being assessed primarily as a manipulation check (for exceptions see de Groot et al., 2014a, 2020). Although most research has gathered quantitative data regarding

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the donors' self-reported emotional experience and the amount of sweat produced, the relation between these two factors remains largely unexplored. Understanding such an association is relevant for uncovering the physiological mechanisms behind this information transfer phenomenon. It highlights how emotional intensity can affect sweat production, altering the quantity of volatiles released and potentially influencing communication efficacy. Clarifying such a relation is precisely the main objective of the research we report here. Below, we begin by briefly reviewing the existing research on emotional communication through sweat. Next, we outline the hypothetical mechanisms involved in releasing emotional sweat, followed by what is known regarding emotional sweat production. Finally, we present our primary objective of the current study: to investigate the association between the amount of sweat produced and self-reported emotional state across three distinct emotion-inducing conditions – fear, happiness, and rest. Furthermore, given that the literature indicates that men generally produce more emotion-related sweat than women (e.g., de Groot et al., 2014a) and are often recruited as sweat donors in this research field (e.g., fear: de Groot et al., 2012, 2014a; Gomes et al., 2020, 2023; happiness: de Groot et al., 2018; de Groot, Smeets, Rowson, et al., 2015), we examine the association between emotional experience and sweat production as a function of donors' sex to explore potential asymmetries.

Human sweat is a complex molecular mixture (e.g., Wyatt, 2015) that, as already mentioned, can convey a wide range of information about its donor (see Semin & de Groot, 2013). Sweat from the armpit region (axillary sweat) has been studied as a means to transfer emotion-related information, not only among humans (see de Groot & Smeets, 2017) but also from humans to other species (e.g., dogs: D'Aniello et al., 2018; horses: Jardat et al., 2023). In humans, whenever receivers are exposed to axillar sweat sampled from donors under different emotional conditions (e.g., fear: de Groot et al., 2012, 2014b; Gomes et al., 2023; Silva et al., 2020; happiness: de Groot et al., 2018; de Groot, Smeets, Rowson, et al., 2015; Richard Ortegón et al., 2022), they exhibit behavioral and physiological responses aligned with the emotion-related information in the sweat. For instance, receivers exposed to fear-related (vs. rest) sweat show patterns indicating increased sensory acquisition, such as higher activation of facial muscles associated with fear expression (responsible for widening eye aperture; e.g., de Groot et al., 2012; Gomes et al., 2020, 2023), increased sniffing volume, faster visual exploration strategies (de Groot et al., 2012), a more "local" cognitive processing style (de Groot et al., 2015) and increased attentiveness (Gomes & Semin, 2021; Semin et al., 2024). By contrast, whenever exposed to happiness-related sweat, receivers exhibited greater activation of facial muscles typically involved in the expression of happiness states (e.g., smiling), a more "global" cognitive processing style (de Groot et al., 2015), and increased creativity (Richard Ortegón et al., 2022).

Despite the large volume of research regarding this information transfer phenomenon, limited efforts have been made to understand the production of emotional sweat (see Smeets et al., 2020 as an exception), potentially relevant for this communication efficacy. Axillary sweat results from the activity of distinct glands (eccrine, apocrine, and apoeccrine; e.g., Noël et al., 2012), and its production depends on gland density, size, and their individual output (e.g., Randall, 1946). Some of these factors not only vary widely between individuals (e.g., Sato & Dobson, 1970) but are also strongly influenced by their physiological state (e.g., Harker, 2013). For instance, most of the emotional information transfer described in the literature is thought to be carried by sweat released by apocrine glands, which are most prolific in the axillae (see Parma et al., 2017; Pause, 2012; Pause et al., 2004). These glands seem to be activated by adrenergic stimulation and respond strongly to emotional arousal (Lindsay et al., 2008; Nakazato et al., 2004), releasing sweat in response to sympathetic activity (Shelley & Hurley, 1953; Wilke et al., 2007). Thus, it is reasonable to hypothesize that sweat production during emotion-inducing conditions should be directly related to the donor's emotional experience.

Although not routinely performed and often examined using relatively small samples ($N \leq 36$), some studies have cost-effectively assessed emotional sweat production by weighing pre- and post-sampling absorbent mediums on which axillary sweat was collected (de Groot et al., 2020, 2015; Gomes et al., 2023, 2020; Gomes & Semin, 2021; Semin et al., 2024; Smeets et al., 2020). Even though most of this research does not directly assess the quantity of sweat produced as a function of the donor's emotional experience, some interesting findings can be highlighted. When film clips were used to induce the emotional experience of fear in male donors, more sweat was produced than during a resting state (de Groot et al., 2020, 2015; Gomes et al., 2023, 2020; Gomes & Semin, 2021; Semin et al., 2024; Smeets et al., 2020). Interestingly, the same was reported to be true for happiness-inducing sessions through exposure to film clips. Male donors seem to sweat more during happiness-inducing sessions than during rest ones (see de Groot, Smeets, Rowson, et al., 2015). More recently, in a first attempt to demonstrate a direct connection between the emotional state of male donors and the quantity of axillary sweat produced, de Groot et al. (2020) showed that the intensity of the fear state induced by film clips was positively correlated with the quantity of sweat produced. Nevertheless, whether these findings generalize to happiness-inducing conditions or female donors has still to be experimentally assessed in human beings.

Most of the literature has employed just males as sweat donors, often arguing that, as males have larger and more active apocrine glands in the axillary region (Doty et al., 1978), they should be more "efficient" emotional sweat donors. Interestingly, these physiological differences between males and females may have evolutionary roots. Research on primates has shown that sweat (body odors) plays a significant role in communication among conspecifics, particularly in high-arousal contexts (e.g., fear or aggression-related contexts) such as those involving confrontation (e.g., establishing social dominance, harmful encounters), where males are more frequently involved. Congruently, in some species, the release of such body odors, mediated by apocrine glands (for a review, see Drea, 2015), is more pronounced in males than in females. This evolutionary perspective may explain why males have larger and more active apocrine glands than females, supporting the hypothesis that males are more efficient at producing emotional sweat. Notably, despite these arguments, there is little and somewhat contradictory evidence when they were experimentally examined. For instance, regarding the patterns observed in sweat receivers, there are some studies indicating that females may effectively release emotional (e.g., fear) sweat as well (e.g., de Groot et al., 2014a; Radulescu & Mujica-Parodi, 2013; Singh et al., 2018). Nevertheless, only one study has attempted to quantify this production and compare it to male donors under similar conditions. These results from de Groot et al. (2014a) showed a sexual asymmetry in sweat production. Although female donors also produce more sweat in fear than rest-inducing conditions, males released more sweat than female donors in both fear and rest-inducing conditions. However, these results were obtained using a relatively small sample size (13 male and 13 female donors), explored only fear-inducing conditions and did not directly investigate the relation between emotional experience and sweat production.

Taken together, and despite prior efforts to investigate sex-specific differences in emotional sweat production, several key questions about this phenomenon remain unanswered or require further elucidation. Thus, the current study proposes to address the following questions: (i) Do male donors produce greater amounts of sweat compared to female donors, regardless of the emotional condition (i.e. fear, happiness, and rest)? (ii) Does sweat production vary systematically as a function of emotional experience (i.e. fear and happiness vs. rest)? (iii) Is sweat production associated with the donor's self-reported emotional experience in each emotional condition? And, finally, (iv) Is there a sex asymmetry in the link between the intensity of emotional experience and sweat production?

Based on the previously reviewed literature, we hypothesize that male donors will produce more sweat than female donors, irrespective of the type of emotional condition. Additionally, it is predicted that more sweat will be produced in fear conditions compared to rest conditions. However, whether this is also true for the happiness condition compared to the rest condition, or whether happiness results in similar sweat production as fear in both male and female donors remains to be explored. Considering previous findings, we also predict that, for male donors in fear-inducing conditions, sweat production will be directly predicted by self-reported emotional experience. Nevertheless, whether this relation holds for both sexes and across different emotional conditions remains exploratory.

To address our main questions, we analyzed data from a substantial number of donors (N = 334, 185 females) who donated sweat and provided ratings of their subjective emotional experiences under three distinct emotional conditions (i.e., fear, happiness, and rest) as part of various research projects. Please note that, across all the studies from which data were drawn, sweat collection took place at the very beginning of the study protocol and followed the same procedure. It is also important to note that the hypotheses of the current study were partly exploratory, and the conclusions were obtained from a data-driven approach despite being informed by prior research. No strong *a priori* hypotheses were pre-registered, and we do not claim any causal relations. Instead, the primary goal of the current study is to inform future research on emotional communication via sweat by transparently sharing observed data patterns in a large sample of donors, which may provide useful insights and help uncover the complex mechanisms underlying the relation between subjective emotional experience and sweat production in both males and females.

2. Method

2.1. Participants

A total of 149 Portuguese men (age range: 18–35 years; M_{Age} = 23.03; *SD* = 4.18) and 185 Portuguese women (age range: 18–36 years; M_{Age} = 22.37; *SD* = 3.55) provided their informed consent and donated sweat voluntarily in three sweat collection sessions (fear, happiness, and rest) in the context of several distinct research projects. Most of the participants were enrolled in university education. Please note that the sample size was not estimated based on an *a priori* power analysis, nor were any specific stopping rules used. Instead, we pooled the data from several projects involving sweat donors, resulting in a total of 334 participants.

As in previous studies (e.g., de Groot et al., 2015; Gomes et al., 2020), all participants were Caucasian, heterosexual, and reported not to have used in the past six months products with nicotine and alcohol or other drugs in quantities or frequencies that would qualify for an addiction disorder. At the time of the sessions, none of the participants reported suffering from any medical conditions known to influence emotion, sweat production, or temperature regulation (e.g., anxiety, depression, head trauma, epilepsy, cancer, hyperhidrosis). Additionally, no participant reported being on medication intake. Regarding women, 97 out of 185 reported using hormonal contraceptives, but hormonal contraceptive use had no effect on sweat production (M_{users} = 157.19 mg, *SD* = 141.58, 95 % CI [128.65, 185.72]; $M_{non\text{-}users}$ = 175.87 mg, *SD* = 163.16, 95 % CI [141.30, 210.44]), [$t(183) = 0.83$, $p = .406$, $d = 0.12$]. Moreover, except for two males, participants did not have evidence of clinical symptoms of depression or anxiety. Depression levels (males: *M* = 5.73, *SD* = 5.36, range= 0–38; females: *M* = 6.55, *SD* = 5.41, range = 0–27) were measured via the Beck Depression Inventory-II (Total score ≤ 29; Beck et al., 1996). Trait anxiety (Males: *M* = 30.96; *SD* = 6.54; range = 21–56; Females: *M* = 31.97; *SD* = 5.32; range = 21–44) was measured by the State and Trait Inventory for Cognitive and Somatic Anxiety (score ≤ 51; Grös et al., 2007).

Each participant received monetary compensation for their time (50€).

All procedures for sweat collection were reviewed and approved by the host institution's ethics committee and complied with the American Psychological Association's standards.

2.2. Materials and measures

2.2.1. Emotional induction film clips

Different sets of film clips were used for each session to induce fear, happiness, and resting states necessary for the sweat collection. Notably, using film clips is thought to be a valid method to induce emotional states in experimental settings (see Siedlecka & Denson, 2018; Westermann et al., 1996) and is a standard methodology in the research field to sample emotion-related sweat (e.g., de Groot et al., 2012, 2014b, 2015; Gomes et al., 2023, 2020; Gomes & Semin, 2021; Silva et al., 2020).

Following the procedures employed in previous research (e.g., de Groot et al. 2015), a set of short horror film clips was used to induce fear-related states, comedy clips were chosen to induce happiness-related states, and short nature and wildlife documentaries with neutral content were utilized to lead the donor to a rest state. The clips employed in each session were selected based on a pilot study in a population similar to our sweat donor population, to ascertain that fear, happiness, and rest states were induced during the exposure to the clips. The clips used in the fear-inducing session included parts of commercial horror movies as *The Nun* (4 min 54 s), *Mamma* (7 min 40 s), *Sinister* (2 min 7 s), *The Descent* (2 min 41 s), *The Grudge* (2 min 10 s), *REC 1* (2 min 53 s), *Insidious* (4 min 55 s), and *A Tale of Two Sisters* (7 min 30 s). Regarding the happiness-inducing session clips were retrieved from the movies *Home Alone* (6 min 23 s), *Mr. Bean's Holiday* (12 min 45 s), *What Women Want* (3 min 47 s), *Sister Act* (2 min 30 s), *Three Fugitives* (2 min 24 s), and *Madagascar* (1 min 42 s). For the rest session, the clips were selected from documentaries, including *Solar Eclipse* (2 min 37 s), *The Secret Life of Birds* (4 min 25 s), *The Transit of Venus* (3 min 2 s), *Equator: Battle for the Light* (2 min 12 s), *Do We Need the Moon?* (2 min 9 s), *Discovery Decade* (1 min 42 s), *Portugal Earth* (3 min 8 s), and *Woolly Mammoth* (3 min 36 s). Some nature scenery clips retrieved from *YouTube* (11 min 40 s) were also included in the rest condition.

2.2.2. Self-report emotional ratings

As in Gomes et al. (2020, 2023), participants provided ratings of how intensely they felt angry, fearful, disgusted, happy, sad, surprised, amused, calm, and neutral (see also de Groot et al. 2015). These ratings were collected using sliders on a scale from 0 (Not at all) to 100 (Very Much). Participants reported their emotional state before and after the session indicating how they felt during the session. To analyze participants' self-reported emotional experience during each session, we computed a differential index by subtracting pre-session ratings from post-session ratings (akin to a baseline correction procedure). The mean and standard deviation for each emotional rating by donor's sex and emotion-inducing session can be consulted in the Supplementary materials (see Table S1).

2.2.3. Room temperature measurement

To ensure consistent temperature conditions during all sweat collection sessions, the rooms (measuring 125 cm in width and 150 cm in length) were climatized to achieve an average temperature of 23ºC. To monitor potential temperature fluctuations due to malfunctioning of the climatization system, we used a thermometer (VWR traceable digital thermometer – Avery L7162) to record the room temperature at the beginning of each session. Indeed, a problem in the climatization system was detected, leading to some degree of variation in room temperature (*M* = 23.80 ºC; *SD* = 2.37; range = 17–30 ºC). Thus, we: (1) included this variable as a covariate in our analysis to control its influence on sweat production, since our focus was on the production of emotion-induced sweat; (2) conducted additional analyses filtering our data to include only a temperature range of 21–25 °C (i.e., ± 2 °C around our target of

23 °C). As the observed data pattern was similar, we decided to keep the analysis with the full sample in the manuscript. Results from the analyses using the restricted temperature range are reported in the Supplementary materials.

2.2.4. Sweat production

Non-woven absorbent 10 × 10 cm sterile absorbent pads (70 % viscose, 30 % polyester; Wells, Sonae SA, Portugal) were placed under the left and right armpits of the participants to sample the sweat in each emotional condition. To measure the volume of sweat produced during each session, the pads were weighed on a *Precisa* scale (model: BJ 100M; precision: 0.001 g) before being placed in the participants' armpits and after the emotion-inducing session. Sweat production was calculated by subtracting the pad's weight before the sweat collection session from its weight after the session.

2.3. Sweat sampling procedure

Participants were recruited through both in-person and online advertisements. They first completed an online screening questionnaire hosted on the Qualtrics platform to determine their eligibility for sweat donation. Those who qualified were contacted by an experimenter of the same sex and invited to attend an instructional session. During this session, participants were provided with detailed information about the hygiene and dietary guidelines they needed to follow for 48 h before and on the day of the sweat collection to avoid sweat contamination from food, physical activity, personal care products, or sexual activity. In line with previous research (e.g., de Groot et al. 2015; Gomes et al., 2023, 2020; Gomes & Semin, 2021; Silva et al., 2020), they were instructed to shave their armpits 48 h before collection, only use fragrance-free personal care products (no perfume or aftershave use was allowed), to wear a given deodorant (Sanex Roll-On 0 % without perfume), and shower every morning with a specific shower gel (Urtekram no perfume Organic). These products were provided to the participants in the instructional session. Additionally, participants were asked to avoid consuming alcohol and highly odorous foods (e.g., garlic, vinegar, chili, asparagus), engaging in sexual intercourse, or performing intense exercise. To ensure adherence to the restrictions, participants were asked to complete an activity sheet, reporting what they ate and the activities they engaged in during the 48 h before the sweat collection. On the day of collection, they were instructed not to use any personal care products and to refrain from eating or drinking anything except water for two hours before the collection began. Any identified breach of the sweat collection protocol resulted in the session being rescheduled by the experimenter.

During each collection session, participants washed their armpits with water and dried them using a paper towel, all under the experimenter's supervision. The experimenter, wearing latex gloves, then attached a pre-weighed pad to each participant's armpit. An additional external pad, secured with hypoallergenic tape, was used to hold the collection pad close to the armpit skin, ensuring that only the external pads made contact with the sampling pads. Afterward, participants were provided with sterilized t-shirts and sweatshirts to wear. Once the preparation was complete, participants were led to a temperature-controlled room. After completing the self-reported emotional ratings and putting on noise-canceling headphones, the lights were turned off, and they watched film clips for approximately 30 min. The order of the sessions (i.e., fear, happiness, and rest) was counterbalanced across participants.

After the session, participants completed the self-reported emotional ratings once again. The experimenter, wearing latex gloves, first stored the external pads separately and then removed the sampling pads from the participants' armpits, weighing them. The pads were placed in amber vials and stored at − 80 °C for future use.

In general, each session took place approximately one week after the previous one. After completing the instructional session and three collection sessions, participants were thanked, debriefed, and received their monetary compensation.

2.4. Data preparation and statistical analysis

The data and code for the analyses are available at https://osf.io/2bznk/files/osfstorage?view_only=e37c0155d99f4b0f87998f4968c0e63f

2.4.1. Data-driven, data reduction of emotional experience ratings

As a starting point, a Principal Component Analysis (PCA; Lattin et al., 2004) was performed to reduce the dimensionality of the nine baseline-corrected emotional ratings, in order to identify a smaller set of components that capture most of the variance in the original variables for use in subsequent analyses. This dimensionality reduction approach led to a more concise representation of participants' overall emotional experiences across the three emotion-inducing conditions.

Firstly, sadness (mean absolute r value = .14, range = − .15 to .26) and surprise (mean absolute r value = .18, range = − .26 to .33) ratings were excluded from the PCA because they exhibited only modest correlations with the other emotional ratings (see Field et al., 2012). Then, we assessed the sample adequacy for a PCA (KMO >.70; Dziuban & Shirkey, 1974; Kaiser, 1974), and confirmed also that the sample correlation matrix is factorable and, therefore, suitable for the analysis (Barlett's test p-value < .05; Bartlett, 1950). Additionally, no significant multicollinearity or singularity problems were found (determinant of the correlation matrix > 0.0001; Field et al., 2012).

The number of principal components to extract was determined using: (1) the scree plot (Cattell, 1966); (2) Kaiser's rule (Kaiser, 1974); (3) Horn's parallel analysis (Horn, 1965); and (4) explained variance (Hair et al., 1995). Two components were extracted. The first principal component accounted for nearly one-third of the variance (32 %), while the second principal component accounted for 29 % of the remaining variance. To ease the interpretation of the two-component solution, an oblique rotation (*oblimin*) was applied. Factor scores from each component were then derived to be used in subsequent analyses based on component loadings greater than the cutoff score of .40 (Field et al., 2012). As shown in Table 1, the first component, labeled "Negative Affect", displayed positive loadings for "fear", "disgust", and "anger" along with negative loadings for "neutrality" and "calm". The second component, labeled "Positive Affect," exhibited high positive loadings for "amusement" and "happiness" but negative loadings for "fear" and "neutrality". Furthermore, the two components showed only a weak negative correlation. (r = -.15), indicating they represent, to some extent, empirically distinct aspects of emotional experience.

PCA was conducted on the correlation matrix in R (R Core Team, 2024) using the *psych* package (William Revelle, 2024). Factor (or solution) rotation was performed using the *GPArotation* package (Bernaards & Jennrich, 2005). For additional information about this analysis, please refer to the Supplementary materials.

Table 1
Loadings, uniqueness, and variance accounted for by principal components.

	Component		
	Negative Affect	Positive Affect	Uniqueness
Fear	0.71	− 0.40	0.25
Disgust	0.57		0.52
Anger	0.46		0.71
Amusement		0.90	0.21
Happiness		0.84	0.25
Calm	− 0.75		0.42
Neutrality	− 0.78	− 0.42	0.30
Component	SS Loadings	% of Variance	Cumulative %
Negative Affect	2.29	33 %	33 %
Positive Affect	2.05	29 %	62 %

Note: Loadings < .40 are not displayed.

2.4.2. Sex differences in sweat production and emotional experience

To examine sex-specific differences in emotional experience, sweat production, and the association between emotional experience and sweat production, five linear mixed-effects models (LMMs) were estimated using the *nlme* package in R (Pinheiro et al., 2025). LMMs are well-suited for handling repeated measures and addressing violations of the sphericity assumption in repeated-measures ANOVA (Gelman & Hill, 2006).

The first two models examined sex-specific differences in the extent to which negative and positive affect were experienced during fear, happiness, and rest conditions – factors that are likely to influence sweat production. These models included either negative affect or positive affect (PCA-derived continuous scores) as dependent variables, and the fixed effects of Sex (male or female) and Condition (fear, happiness, or rest), as well as their interaction.

The third model was planned to examine sex-specific differences in sweat production during fear, happiness, and rest conditions. Here, a log-transformed sweat production (measured in milligrams; mg) variable was used as the dependent variable. Log transformation was applied due to violations of the assumptions of normality and homoscedasticity, as confirmed by inspection of residual diagnostics. This model also included the fixed effects of Sex (male or female) and Condition (fear, happiness, or rest), as well as their interaction. Notably, in this model, displayed estimated marginal means regarding sweat production were back-transformed from the log scale to the original scale (mg) using the *bias.adjust* option in the *emmeans* package (Lenth, 2025) to ease interpretability.

The last two models examined sex-specific differences in the association between emotional responses and sweat production. Once again, a log transformation of sweat production (in milligrams) was used as the dependent variable. The models included the fixed effects of Sex (male or female) and Condition (fear, happiness, or rest), as well as emotional responses – either negative affect or positive affect (PCA-derived continuous scores) –, along with all interactions between these variables.

Room temperature at the beginning of the sweat collection was included as covariate in all models using sweat production as the dependent variable to account for its potential influence on perspiration.

All models included an unstructured within-participant covariance matrix specified with corSymm (form $= \sim 1 \mid$ PartID), as specified in the *nlme* package (Pinheiro et al., 2025). The selection of random effects for all models followed the approach of Matuschek et al. (2017), which emphasizes balancing statistical power and Type I error by selecting the most complex model supported by the data. In all cases, the most parsimonious model involved just random intercepts by participant to account for individual mean variability.

All models were estimated via restricted maximum likelihood (REML).

The significance of fixed effects was assessed using t-tests with Satterthwaite approximations for degrees of freedom. Post-hoc comparisons were performed using the *emmeans* package (Lenth, 2025) and adjusted for multiple comparisons using the Bonferroni method.

3. Results

3.1. Sex differences in emotional experience during fear, happiness, and rest

Regarding sex and condition differences in negative affect, the model ($R^2_{Marginal} = .45$; $R^2_{Conditional} = .52$) revealed a significant main effect of Condition [$F(2, 663) = 401.24$, $p < .001$]. As expected, post-hoc comparisons indicated that the fear condition increased negative affect ($M =$ 0.91, $SE = 0.04$, 95 % CI [0.82, 0.99]) compared to both the happiness ($M = -0.23$, $SE = 0.04$, 95 % CI [-0.31, $-$ 0.15]) and rest ($M = -0.68$, $SE =$ 0.04, 95 % CI [-0.76, $-$ 0.60]) conditions. In turn, the rest condition elicited a greater reduction in negative affect compared to the happiness condition (all p's $< .001$) (see Fig. 1A). No additional main effects or interactions were significant (all p's $> .05$).

Concerning sex and condition differences in positive affect, the model ($R^2_{Marginal} = .39$; $R^2_{Conditional} = .44$) revealed a significant main effect of Condition [$F(2, 663) = 321.98$, $p < .001$]. This effect was qualified by a significant Sex × Condition interaction [$F(2, 663) = 8.84$, $p < .001$]. As expected, post-hoc comparisons indicated that the happiness condition increased positive affect ($M = 0.81$, $SE = 0.04$, 95 % CI [0.72, 0.89]) compared to both the rest ($M = -0.15$, $SE = 0.04$, 95 % CI [-0.23, $-$ 0.06]) and fear ($M = -0.65$, $SE = 0.04$, 95 % CI [-0.74, $-$ 0.57]) conditions. The fear condition elicited a greater reduction in positive affect compared to the rest condition (all p's $< .001$) (see Fig. 1B). Both males and females exhibited an increase in positive affect during happiness (Males: $M = 0.73$, $SE = 0.06$, 95 % CI [0.61, 0.86]; Females: $M = 0.88$, $SE = 0.06$, 95 % CI [0.77, 1.00]) compared to both the fear (Males: $M = -0.48$, $SE = 0.06$, 95 % CI [-0.61, $-$ 0.36]; Females: $M = -0.82$, $SE = 0.06$, 95 % CI [-0.93, $-$ 0.71]) and rest (Males: $M =$ -0.16, $SE = 0.06$, 95 % CI [-0.29, $-$ 0.04]; Females: $M = -0.13$, $SE = 0.06$, 95 % CI [-0.25, $-$ 0.02]) conditions, as well as a greater reduction in positive affect during fear compared to the rest condition (all p's $< .01$). Moreover, post-hoc comparisons indicated that the Sex × Condition interaction was also driven by sex differences in fear-induced reductions of positive affect: females exhibited a greater reduction in positive affect compared to males during fear ($p = = .002$) (see Fig. 1B). No additional main effects or interactions were significant (all p's $> .05$).

3.2. Sex differences in sweat production during fear, happiness, and rest

The model examining sex-specific differences in sweat production across emotion-inducing conditions ($R^2_{Marginal} = .08$; $R^2_{Conditional} = .53$) revealed a statistically significant main effect of Sex [$F(1, 332) = 9.25$, $p = = .003$], indicating that males ($M = 172.33$ mg, $SE = 13.88$, 95 % CI [147.07, 201.92]) produced more sweat, on average, than females ($M =$ 124.22 mg, $SE = 8.98$, 95 % CI [107.76, 143.21]). Additionally, a significant main effect of Condition was found [$F(2, 663) = 28.17$, $p < .001$]. Post-hoc comparisons showed that sweat production was greater during fear ($M = 196.26$ mg, $SE = 13.07$, 95 % CI [172.17, 223.72]) than during happiness ($M = 136.23$ mg, $SE = 9.07$, 95 % CI [119.51, 155.29]) or rest ($M = 117.15$ mg, $SE = 7.80$, 95 % CI [102.77, 133.54]) (all p's $< .001$), with no difference between happiness and rest ($p > .05$). A marginally significant interaction Sex × Condition was also observed [$F(2,663) = 2.78$, $p = .063$]. Although this interaction did not reach the threshold for statistical significance, we conducted post-hoc comparisons to explore potential differences in sweat production between males and females across emotions, given the relevance of these results to answering our research questions. The post-hoc comparisons revealed that males exhibited significantly greater fear-induced sweat production ($M = 253.50$ mg, $SE = 25.12$, 95 % CI [208.60, 308.07]) than females ($M = 151.94$ mg, $SE = 13.52$, 95 % CI [127.54, 181.00]) ($p = .002$; see Fig. 2).

3.3. Sex differences in the link between emotional experience and sweat production

As in the previously reported model, this model examining sex and condition differences in the association between negative affect and sweat production ($R^2_{Marginal} = .09$; $R^2_{Conditional} = .53$) also revealed a significant main effect of Sex [$F(1, 332) = 9.34$, $p = = .002$] and Condition [$F(2, 657) = 10.50$, $p < .001$]. Additionally, this model revealed a significant main effect of Negative Affect [$F(1, 657) = 36.88$, $p < .001$], which was qualified by a significant two-way Negative Affect × Sex interaction [$F(1, 657) = 8.51$, $p = = .004$], that, in turn, was qualified by a significant Negative Affect × Sex × Condition interaction [$F(2, 657) = 5.78$, $p = = .003$]. Inspection of the simple slopes indicated that, during fear, greater Negative Affect was associated with an increase in sweat production in males ($b = .27$, $SE = .08$, $p < .001$, 95 % CI

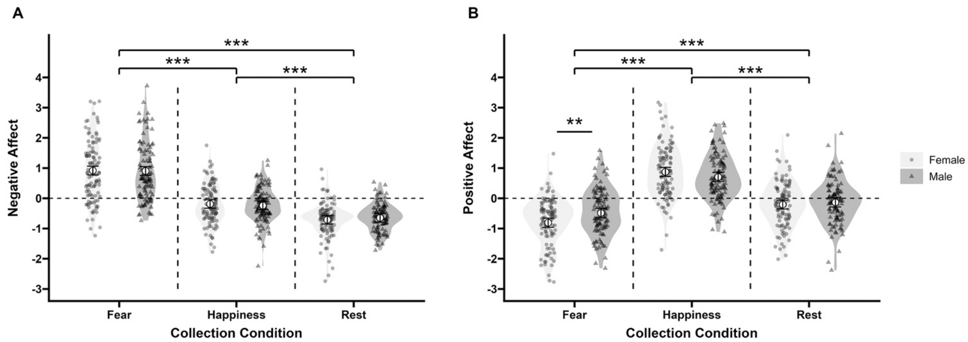

Fig. 1. Emotional (baseline-corrected) responses across conditions, as a function of sex: **(A)** Greater increase in negative affect was found in the fear condition compared to both happiness and rest, and a greater reduction in negative affect was found in the rest condition. **(B)** Males and females exhibited a greater increment in positive affect during happiness compared to fear and rest, and a greater reduction in positive affect was found during fear compared to rest. A greater reduction in positive affect was also observed in females compared to males during fear condition. Error bars represent 95 % confidence intervals of the estimated marginal means. ** $p < .01$, ***$p < .001$.

Fig. 2. Sweat production during fear, happiness, and rest, as a function of sex: Greater sweat production was found in males relative to females during fear. Error bars represent 95 % confidence intervals of the estimated marginal means. ** $p < .01$, ***$p < .001$.

[.11,.43]), but not in females (b=-.09, SE = .07, p = = .202, 95 % CI [-.24,.05]) (Fig. 3). Neither males nor females showed significant associations between Negative Affect and sweat production during happiness or rest conditions (all p's > .05). A full graphical representation of this three-way interaction (i.e., including also both the happiness and rest-inducing conditions) can be consulted in the Supplementary materials (see Figure S3). No additional main or interaction effects were significant in this model (all p's > .05).

The similar model incorporating Positive Affect ($R^2_{Marginal}$ = .08; $R^2_{Conditional}$ = .53) also revealed a significant main effect of Sex [F(1, 332) = 9.23, p = .003] and Condition [F(2, 657) = 21.90, p < .001], as evidenced in the models reported above. Moreover, this model revealed a significant main effect of Positive Affect [F(1, 657) = 14.79, p < .001], which was qualified by a significant Positive Affect × Sex interaction [F(1, 657) = 5.10, p = .024]. Inspection of the simple slopes indicated that an increment in Positive Affect was associated with lower sweat production in males (b = -.14, SE = .06, p = .016, 95 % CI [-.25, − .03]), but not in females (b = -.00, SE = .05, p = .997, 95 % CI [-.09,.09]) (Fig. 4). No additional interaction effects were statistically significant in this model (all p's > .05).

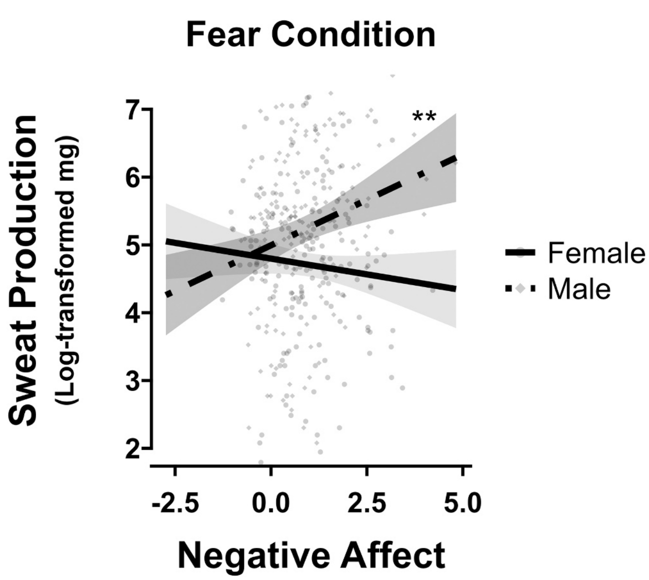

Fig. 3. Three-way interaction between negative affect, sex, and emotion, here represented the sweat production during the fear condition. The figure illustrates the association between negative affect (PCA-derived scores) and sweat production (log-transformed) during fear, as a function of sex. Sweat production increases with negative affect in males, but not in females. The shaded areas around the regression lines represent 95 % confidence intervals. ** $p < .01$.

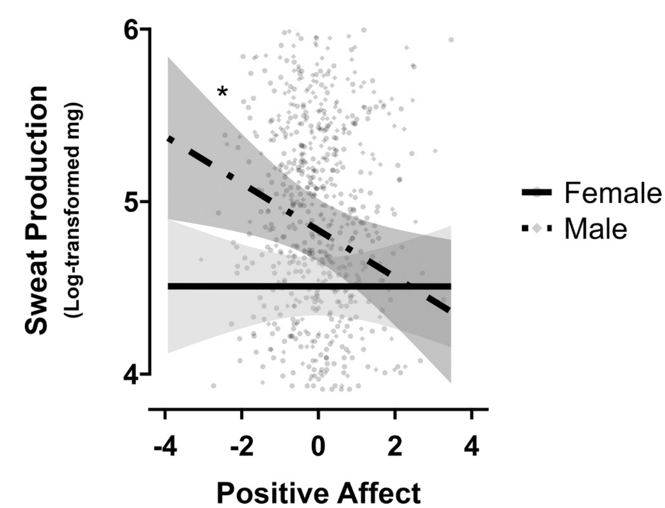

Fig. 4. Two-way interaction between positive affect and sex on sweat production across conditions. The figure illustrates the association between positive affect (PCA-derived scores) and sweat production (log-transformed), as a function of sex. Sweat production decreased with positive affect in males, but not in females. The shaded areas around the regression lines represent 95 % confidence intervals. * $p < .05$.

4. Discussion

While sweating is primarily recognized for its role in thermoregulation (e.g., Baker, 2019), accumulating evidence suggests it also carries information from donor to receiver, including emotion-related one (e.g., de Groot, Semin, & Smeets, 2017). Despite the existing number of studies on responses to emotion-induced sweat (e.g., de Groot et al., 2014b, 2015; Gomes et al., 2020, 2023; Gomes & Semin, 2021; Semin et al., 2024), few have focused on sweat production itself (e.g., de Groot et al., 2021) – a potentially important aspect for the success of information transfer, especially in ecological contexts, as further discussed below. This study, the largest to date with a cohort of 334 sweat donors, examined several fundamental questions and assumptions in the literature regarding emotional sweat production. Namely, (i) whether a sex asymmetry exists in sweat production; (ii) if distinct emotional states result in distinct amounts of produced sweat; (iii) if the amount of sweat can be linked to the donor's subjective emotional experience across different emotion-inducing conditions; and (iv) whether this relation differs systematically between males and females. While some of our findings are consistent with previous literature (see, for instance, de Groot et al., 2014a), our data also revealed novel aspects of emotional sweat production that have not been previously documented.

Firstly, consistent with previous work (e.g., de Groot et al., 2014a), our results showed (i) a sex asymmetry in sweat production, with males producing more sweat than females overall – a finding explained primarily by fear-related sweat production, as observed in post hoc comparisons following a marginally significant interaction between the donor's sex and emotional condition. Likewise, our findings are consistent with most of the literature (e.g., de Groot et al., 2014b, 2015; Gomes et al., 2020, 2023; Gomes & Semin, 2021) confirming that (ii) fear states lead donors – primarily male donors – to produce significantly more emotion-related sweat than during rest states. From a physiological perspective, this data trend may be explained by differences regarding apocrine sweat glands between males and females (Doty et al., 1978). In fear-related sessions, the increased sweat production likely corresponds to heightened apocrine gland activity (Parma et al., 2017), which is known to respond to adrenergic and sympathetic stimulation under emotional and high arousal states (e.g., Lindsay et al., 2008; Nakazato et al., 2004; Shelley & Hurley, 1953; Wilke et al., 2007). Given that males reportedly have larger and more active apocrine glands in the armpit region than females, it comes as no surprise that fear – a high-arousal, negative emotional state (e.g., Jang et al., 2020) – triggers more axillary sweat production particularly in males (see also de Groot et al., 2014a).

Importantly, contrary to previous work, our findings show that this sex asymmetry does not hold for happiness-related sweat production, which did not differ from rest states, neither for male (as shown in de Groot, Smeets, Rowson, et al., 2015) nor for female donors. Notably, an important methodological difference between de Groot, Smeets, Rowson, et al. (2015) and the current study may account for this observed discrepancy. In the study by de Groot, Smeets, Rowson, et al. (2015), the happiness-inducing sessions involved sweat donors watching comedy film clips in groups of three, a design intended by the authors to enhance the effectiveness of the emotion-induction procedure. In contrast, our study sampled sweat in an individual setting to maintain consistency across all three emotion-inducing conditions. This methodological distinction may have led to a less intense happiness induction in our study, resulting in decreased amounts of sweat produced under these specific conditions – an argument reinforced by inspection of Fig. 3 in de Groot, Smeets, Rowson, et al. (2015). It is perceptible from the figure that sweat donors (only males), using a 1–7 Likert scales to rate their subjective happiness and amusement feelings after the sessions, reported mean scores around 6 and 6.5 (respectively), which are close to the maximum of the scale. In contrast, our data (see Table S1 in Supplementary materials) show post-session emotion ratings for happiness and amusement that are much closer to the scale's midpoint (61.80 and 61.47, respectively; 0–100 sliders), supporting the argument that the happiness induction in our study was less intense.

This suggests that the social environment may be an important factor in enhancing the intensity of positive emotion induction, with emotion intensity potentially being critical for the ability to produce emotion-related sweat. Consistent with this idea, research suggests that emotional experiences related to happiness can be modulated by the presence of others (e.g., Donoghue et al., 1983) and may be shaped by group processes as well (e.g., Van Kleef, 2014). Thus, together with those findings reported by de Groot, Smeets, Rowson, et al. (2015), our results provide preliminary evidence that the presence of others, by being critical to increase the intensity of the induction of positive emotional states (and hypothetically, arousal), should be an important fact to consider when the production of happiness-related sweat is of interest. In fact, although speculative, and assuming that happiness-related sweat is produced through a physiological mechanism similar to the previously proposed for fear sweat, one possible explanation for our findings is that participants in our solo condition may not have reached a sufficiently high level of arousal to trigger detectable higher sweat production in the happiness condition. As a result, we observed no significant differences between the happiness and rest conditions, neither in males nor in females. This contrasts with the group condition in de Groot, Smeets, Rowson, et al. (2015), where increased arousal may have occurred, and differences between happiness and rest-related sweat production are clearly observed in their donors (only males). While further research is needed to directly examine the role of group context in inducing positive emotions and its relation to emotional sweat production, our findings provide valuable insights for future research. Specifically, they suggest group conditions as an important strategy for more effectively sampling happiness-related sweat.

Additionally, although males generally tend to sweat more than females, even under non-emotional conditions (e.g., Ichinose-Kuwahara et al., 2010), no sex differences were observed during the rest-inducing sessions in our study. Importantly, this rest-inducing condition was designed to minimize emotion-related sweat production, with the sweat produced during rest likely related to thermoregulation. Therefore, the lack of observed differences may be due to the control procedures for room temperature.

Moreover, the current study extends previous research by showing that (iii) sweat production can be directly linked to (iv) males', but not to females', self-reported negative emotional experience during fear. That is, the higher the negative affect reported by males in the fear-inducing condition, the higher the quantity of sweat produced. Importantly, this relation was not observed for the other emotion-inducing conditions. In the case of female donors, none of these relations proved to be significantly different from zero. Interestingly, the distinctive findings between males and females described above cannot be attributed to differences in the intensity of subjective emotional experiences, as male donors did not report higher levels of negative affect than female donors. Nevertheless, males appear to have the capacity to encode the intensity of their negative affect, and hypothetically the arousal level, in the quantity of sweat produced (see also de Groot et al., 2020) – a phenomenon not observed in female donors.

From our perspective, this sex asymmetry can result from the previously mentioned physiological differences in terms of the features and activity of the apocrine glands between males and females. As discussed in the introduction, in several primate species, olfactory communication plays an important role with male primates' sweat carrying important arousal-related information, such as social hierarchy and dominance behaviors (e.g., confrontation; see, for instance, Drea, 2015). This may explain, at least in part, why males have a higher density and more active apocrine glands, as males are more likely to exhibit these types of behaviors. As a result, males appear to have a greater physiological ability than females to encode arousal levels – in our study, the intensity of negative affect – through sweat production during fear conditions.

This arousal-related explanation can also be extended to the observed overall negative association between positive affect and sweat production in male donors. It is possible that our individual happiness sampling condition, due to the aforementioned low intensity, led to reduced, instead of increased, arousal levels during exposure to comedy-related film clips. Thus, although donors have reported an increased positive affect during the happiness-related session, this could have been translated into a state of higher relaxation rather than a higher arousal, and consequently reduced sweat production. Nevertheless, this argument requires further investigation in future studies employing more direct and objective measures to directly assess donors' emotional experience and arousal (e.g., skin conductance level, heartbeat rate), a limiting factor in the current work.

Importantly, the lack of a relation between emotional intensity and sweat production in females does not mean that their sweat does not carry fear-related information. In fact, research has shown that female receivers exhibit facial electromyography patterns congruent with fear (i.e., increased activity of the *medial frontalis*) when exposed to fear-related sweat sampled from either male or female donors (de Groot et al., 2014a). Instead, our findings indicate solely that female donors do not encode the intensity of their emotional experience in the quantity of sweat produced. Despite this, females, as receivers, seem to be more sensitive than males to high arousal-related sweat (e.g., fear- or aggression-induced; de Groot et al., 2014a; Pause et al., 2020), particularly when sampled from male donors (Pause et al., 2020). This suggests an intriguing asymmetry in chemical communication regarding human beings. Even though males are physiologically more capable of encoding emotional intensity in sweat production, the emotion-related information (not emotion intensity; see de Groot et al., 2021) appears to be better captured by female receivers, especially when it comes from male donors. This was considered by Pause et al. (2020) as highly adaptive for defense and survival purposes, as arousal-related sweat from males may be more associated with physical harm than sweat from females.

An important question that arises is: What is the significance of encoding emotional intensity through the amount of sweat produced for this communication phenomenon? As shown by de Groot et al. (2021), female receivers seem not to react differently to male fear-related sweat sampled during high (vs. low) intensity fear situations, evidencing that, although more sensitive, they cannot decode the donors' fear intensity. The authors argued for "dose-invariant effects" of fear sweat, suggesting that human olfaction engages in a binary on/off mechanism when emotion communication is at stake. In other words, once the fear chemical message is received, the behavioral, physiological, and neural changes in female receivers would be similar, regardless of the emotional intensity, and consequently, the quantity of sweat produced by the donor. This indicates that encoding fear intensity in sweat production is not relevant for the "quality" of the carried message. However, as we argue below, the quantity of sweat can be particularly relevant to the success of information transfer.

In accordance with our data and as shown by the same authors in a distinct publication using the same sweat samples (de Groot et al., 2020), male donors who experienced more intense fear also produced more sweat. This fear sweat, in turn, emitted more volatiles (assessed using a photoionization detector) for longer periods of time when compared to sweat collected from donors who experienced less intense fear and consequently produced less sweat. Therefore, encoding fear intensity in sweat production appears to cause more volatiles to be released for longer durations, which could improve the success rate of information transfer. This argument is partly supported by data from the same authors (de Groot et al., 2021), who showed that the effects of fear (vs. rest) sweat were much stronger during the trials occurring in the first (vs. second) half of the experiment because the volatiles released by the fear sweat were reduced in the second half of the experiment, as confirmed in pilot tests using a photoionization detector. Nevertheless, future research is needed to directly test the idea that producing more sweat during more intense fear responses helps preserve its information-transfer ability over longer periods, increasing the chances of communication. This line of research would confirm the hypothetical advantage of encoding emotional intensity in sweat production discussed here. That is, male sweat produced during high intensity emotion-related situations may be more effective not due to the 'quality' of the information it carries, but due to its higher volatile quantities that would increase the chances of information transfer.

Additionally, confirming this idea – beyond its theoretical value – would also have significant methodological implications, particularly given the lengthy experimental setups often used in this field. For example, data from extended experimental procedures showing that females are more sensitive to male sweat than to female sweat may reflect the fact that males typically produce more sweat. This could cause the chemical signals in the olfactory stimuli to persist longer, resulting in stronger average effects (i.e., more trials yielding the expected outcome) compared to those from female sweat. However, this remains speculative until directly examined in future studies.

In conclusion, the current study further elucidates the mechanisms of emotional sweat production using a large sample of donors, highlighting sex asymmetries and potential contextual dependencies that are important to consider in future studies involving emotion-related sweat sampling. Males not only produce more sweat than females, especially in fear-related situations, but also appear capable of encoding the intensity of fear through sweat production – a trait not observed in females. These findings further emphasize the role of physiological differences and arousal in sweat production and suggest an evolutionary-based mechanism for transmitting information. Furthermore, these results are an important step toward understanding how emotional intensity and, consequently, sweat production contribute to the success of emotion-related chemosensory communication, raising the hypothesis that fear (arousal)-related sweat from male donors in high intensity emotional states might be more effective in conveying messages due to the higher number of volatiles released for longer periods.

CRediT authorship contribution statement

Jorge S. Martins: Writing – review & editing, Visualization, Formal analysis, Data curation. **Gün R. Semin:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Nuno Gomes:** Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Miguel F. Benrós:** Writing – original draft, Visualization, Resources, Methodology, Funding acquisition, Formal analysis, Data curation.

Declaration of Generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work, the authors used Grammarly in order to correct typographical errors and improve fluency. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Author Note

NG and GRS planned the research. NG and MFB executed it. NG, MFB, and JSM prepared and analyzed the data. NG, MFB, JSM, and GRS wrote the manuscript. All authors declare no conflicts of interest to report regarding the findings of this study.

The data and code for the analyses are available at https://osf.io/2bznk/files/osfstorage?view_only=e37c0155d99f4b0f87998f4968c0e63f.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nuno Gomes reports financial support was provided by Foundation for Science and Technology. Miguel F. Benros reports financial support was provided by Foundation for Science and Technology. Gun R. Semin reports financial support and equipment, drugs, or supplies were provided by Horizon Europe. Nuno Gomes reports financial support and equipment, drugs, or supplies were provided by Horizon Europe. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2025.109125.

Data availability

Data is available through an anonymous OSF link found in the methods section.

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