



How does subjective social status get under the skin? A scoping review of associations with biomarkers of the primary stress systems

Frank Euteneuer^{a,*}, Stefan Salzmann^b, Philipp Süssenbach^c, Linn K. Kuehl^d, Marcel Wilhelm^e

^a Faculty of Human Sciences, Division of Biological Psychology and Neuroscience, Vinzenz Pallotti University, Vallendar, Germany

^b Faculty of Human Sciences, Division of Clinical Psychology and Psychotherapy, Vinzenz Pallotti University, Vallendar, Germany

^c Fachhochschule des Mittelstands (FHM) Bielefeld–University of Applied Sciences, Bielefeld, Germany

^d Clinical Psychology and Psychotherapy, Department of Psychology, Medical School Berlin, Berlin, Germany

^e Division of Clinical Psychology and Psychotherapy, Philipps University of Marburg, Marburg, Germany

ARTICLE INFO

Keywords:

Subjective social status
Autonomic nervous system
Hypothalamic–pituitary–adrenal axis
Stress
Scoping review

ABSTRACT

Socioeconomic disparities in health are well established, and accumulating evidence highlights that subjective social status is a unique predictor of health beyond objective socioeconomic indicators. Theoretical frameworks suggest that psychobiological stress mechanisms are key pathways linking subjective social status to health. However, no comprehensive review has yet synthesized evidence on subjective social status in relation to biomarkers of the primary stress systems. In this scoping review, we systematically identified and mapped studies investigating associations between subjective social status and biomarkers of the hypothalamic–pituitary–adrenal axis and the autonomic nervous system. A total of 25 studies met inclusion criteria. Seventeen studies examined hypothalamic–pituitary–adrenal axis activity, most often focusing on salivary cortisol, while ten studies investigated autonomic markers including heart rate variability, pre-ejection period, blood pressure and heart rate reactivity, catecholamines, or salivary α -amylase. Across both systems, findings were inconsistent. Some evidence links lower subjective social status to blunted diurnal cortisol slopes, altered cortisol reactivity, reduced β -adrenergic receptor responsiveness, or elevated α -amylase, but many studies yielded null or divergent results, suggesting that associations between subjective social status and alterations in primary stress systems are likely contingent on contextual or moderating factors rather than uniform across populations. This review highlights key limitations in the literature, including methodological heterogeneity, understudied biomarkers, small and selective samples, and a lack of longitudinal designs, and it outlines directions for future research. Future studies should prioritize longitudinal designs with harmonized biomarker protocols and larger, more representative samples to enable direct replication across biomarkers and contexts.

1. Introduction

Socioeconomic disparities in health represent one of the most established patterns of social inequality, suggesting that individuals with lower socioeconomic status are at a higher risk for a wide range of physical and mental health outcomes (Adler and Ostrove, 1999; Dougall et al., 2023; Lorant et al., 2003; Pickett and Wilkinson, 2015, 2010). The association between lower socioeconomic status and poor health may be partly explained by absolute differences in objective socioeconomic determinants (i.e., income, education, job position). For example, limited access to health-related factors (e.g., healthcare, protective environmental factors) but also financial strain may result from lower

financial resources (Dougall et al., 2023; Guerra and Eboeime, 2021; Matthews et al., 2010). Moreover, unhealthy behaviors that increase the risk of various diseases and health literacy have been linked to some extent to absolute differences in socioeconomic indicators, in particular to lower levels of education (Coughlin et al., 2020; Kraft and Kraft, 2021; Pampel et al., 2010).

In recent decades, however, several lines of research have highlighted that individuals' relative socioeconomic or social position matters for health above and beyond objective, absolute socioeconomic factors, particularly in richer and more unequal societies (Cheon et al., 2025; Euteneuer, 2014; Hounkpatin et al., 2015; Pickett and Wilkinson, 2015, 2010; Schneider, 2019; Tang et al., 2016). Most studies in this

* Corresponding author at: Faculty of Human Sciences, Division of Biological Psychology and Neuroscience, Vinzenz Pallotti University, Pallottistraße 3, D-56179, Vallendar, Germany.

E-mail address: frank.euteneuer@vp-uni.de (F. Euteneuer).

<https://doi.org/10.1016/j.ijpsycho.2026.113350>

Received 19 December 2025; Received in revised form 13 February 2026; Accepted 19 February 2026

Available online 24 February 2026

0167-8760/© 2026 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

field have employed subjective measures to assess individuals' perceived relative socioeconomic or social position, commonly referred to as subjective socioeconomic or social status (SSS). These assessments typically use visual social ladders (i.e., MacArthur Scales or similar measures), where individuals are asked to rank their socioeconomic or social position relative to a specific reference group (e.g., society of a specific country, local community, school, or workplace) (Adler et al., 2000; Cohen, 1999; Goodman et al., 2001). Thus, SSS is thought to reflect individuals' appraisals of their social status relative to others, grounded in social comparisons (Adler et al., 2000; Cohen, 1999; Festinger, 1954; Goodman et al., 2001; Hounkpatin et al., 2015). The most widely used version of these ladders explicitly instructs individuals to rate their social position in terms of objective socioeconomic indicators such as income, education, and occupation compared to others in the society of their country, also referred to as "societal SSS" (Adler et al., 2000). Another frequently used version asks individuals to rank their social position in comparison to members of their self-defined "community" (Cohen, 1999), in most cases without explicitly referring to traditional socioeconomic anchors, which has been referred to as "community SSS" (Zell et al., 2018).

Although SSS shows moderate overlap with objective indicators of socioeconomic status (i.e., income, education, and occupation) in a wide range of studies (Cundiff and Matthews, 2017), SSS has been found to be related to poor health outcomes (e.g., cardiovascular disease, diabetes, dyslipidemia, depression, self-rated health) beyond objective, absolute socioeconomic measures (Cundiff et al., 2020; Cundiff and Matthews, 2017; Euteneuer, 2014; Hoebel and Lampert, 2018; Scott et al., 2014; Tang et al., 2016). Longitudinal studies have also demonstrated that lower SSS uniquely predicts reduced physical functioning, frailty, lower health-related quality of life, depressive symptoms, short sleep duration, inflammation, chronic conditions, and mortality (Demakakos et al., 2018; Euteneuer et al., 2021; Euteneuer and Süßenbach, 2021; Jones et al., 2023; Kim et al., 2021; Madigan and Daly, 2023; Maharani et al., 2024; O'Leary et al., 2021). Considering that SSS may capture a cognitive averaging of objective socioeconomic information but also other status-related information (e.g., past and future prospects), it has been argued that SSS partly mediates associations between objective socioeconomic status and health outcomes (Cundiff and Matthews, 2017; Euteneuer et al., 2021; Euteneuer and Süßenbach, 2021; Singh-Manoux et al., 2005).

But what are the proposed mechanisms by which SSS affects health? Several putative, interacting cognitive, affective, behavioral, and biological pathways have been suggested (Cheon et al., 2025; Dougall et al., 2023; Euteneuer, 2014; Hoebel and Lampert, 2018; Matthews et al., 2010; Pickett and Wilkinson, 2015; Tang et al., 2016; Wetherall et al., 2019). It has frequently been argued that these pathways involve stress-related psychobiological mechanisms, based on the notion that social comparisons and a perceived lower relative position can act as stressors (Cundiff and Matthews, 2017; Korzan and Summers, 2021). Theoretically, lower SSS may be accompanied by experiences and perceptions of social exclusion, relative deprivation, and loss of social power (Jiang and Chen, 2020; Kraus et al., 2009; Sagioglou and Hommerich, 2024), which may pose a threat to fundamental human needs such as belonging, control, self-esteem, and meaningful existence (Godwin et al., 2014; Williams, 2007). As a result, individuals may experience feelings of sadness, shame, anger, or anxiety (Godwin et al., 2014; Matthews et al., 2010; Williams, 2007), which may activate the body's primary stress systems—the hypothalamic–pituitary–adrenal (HPA) axis and the autonomic nervous system (ANS). This, in turn, may lead to downstream physiological consequences, including immunological alterations, endocrine dysregulation, and cardiovascular changes (Beekman et al., 2016; Kroll et al., 2019; Pieritz et al., 2017; Prendergast and Schubert, 2020; Radke et al., 2018; Slavich et al., 2010; Zwolinski, 2012). In this regard, studies on nonhuman species suggest that the social environment is less controllable and predictable for low-ranking subordinates, leading to hypervigilance to threats and stress-related

biological alterations (Gilbert, 2006; Sanz et al., 2020; Sapolsky, 2005; Shively, 1998; Snyder-Mackler et al., 2016; Tung et al., 2012). While stress-associated biological responses are initially adaptive, they may ultimately result in adverse health consequences in the long run when stress responses are excessive, prolonged, or poorly regulated (Korzan and Summers, 2021; Sapolsky, 2005).

In addition to direct stress-associated psychobiological pathways in the relationship between SSS and health, there may also be indirect pathways involving changes in health and risk behaviors such as smoking, alcohol consumption, unhealthy eating, poor sleep, reduced physical activity, and risky coping strategies (Camelo et al., 2013; Cheon et al., 2025; D'Hooge et al., 2018; Euteneuer and Süßenbach, 2021; Frerichs et al., 2014; Goon et al., 2024; Reitzel et al., 2013; Zell et al., 2018). Activation of the body's primary stress axes (i.e., HPA axis and ANS) can impair emotion regulation and self-control, thereby increasing the likelihood of these maladaptive health behaviors. Conversely, poor health behaviors may further dysregulate stress-responsive systems, potentially reinforcing this cycle over time (Arnsten, 2009; Mandelli et al., 2022; O'Connor et al., 2021; Packard et al., 2016). Although longitudinal studies explicitly examining these indirect pathways in the context of SSS are lacking, it is well established that various stress-related biological changes are associated with health and risk behavior patterns (Kraft and Kraft, 2021; Mandelli et al., 2022; O'Connor et al., 2021).

Although theoretical frameworks consistently highlight stress as a key pathway linking SSS to health outcomes (Cundiff et al., 2020; Cundiff and Matthews, 2017; Euteneuer, 2014; Hoebel and Lampert, 2018), no comprehensive review has examined SSS in relation to putative alterations in biological stress systems. One recent meta-analysis suggests that experimentally induced reductions in perceived social rank are associated with heightened cardiovascular reactivity, when manipulations are based on socioeconomic factors (Williams et al., 2025). While such experimental manipulations are essential for clarifying potential causal links between short-term changes in SSS and acute stress responses, they may be limited in capturing more enduring, chronic biological correlates of real-life SSS and were therefore not considered in the present scoping review, which focuses on real-life associations. Here, we systematically identify and synthesize studies investigating associations between SSS and peripheral biomarkers of stress, and aim to identify research gaps. We focus on the two primary biological stress systems: the HPA axis and the ANS (O'Connor et al., 2021).

2. Methods

Based on preliminary considerations, we anticipated considerable conceptual and methodological variation across studies, particularly regarding biomarker assessment and study populations. We therefore selected a broad scoping review approach to explore the extent and nature of existing research, rather than conducting a narrowly focused systematic review. The present scoping review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA-ScR) extension guidelines for scoping reviews (Tricco et al., 2018).

2.1. Eligibility criteria

We included studies in individuals aged 18 years and over that report associations of SSS with potentially stress-sensitive biomarkers of the HPA axis and the ANS. Regarding SSS, studies were eligible if they assessed an individual's perceived social position relative to a reference group (e.g., society, community, workplace, or neighborhood). Studies were included regardless of whether SSS was assessed in reference to traditional socioeconomic indicators (e.g., income, education, and occupation) or more broadly, without explicit reference to these socioeconomic anchors. With respect to stress-related biomarkers, articles

were included if they met the following criteria:

- (i) HPA axis: included at least one measure of cortisol, adrenocorticotrophic hormone (ACTH), or corticotropin-releasing hormone (CRH), or dehydroepiandrosterone (DHEA).
- (ii) ANS: included at least one measure of heart rate variability (HRV), norepinephrine, epinephrine, α -amylase, pre-ejection period (PEP), or electrodermal activity (EDA), heart rate (HR) reactivity, or blood pressure (BP) reactivity.

The scoping review framework allowed us the flexibility to include heterogeneous studies, regardless of whether they assessed basal or stimulated biomarkers, short-term or long-term measures, used specific methods or samples, or followed different study designs. However, in terms of ANS biomarkers, resting HR and resting BP measures were not included. Although HR and BP indices are influenced by the ANS, we were primarily interested in measures that reflect closer aspects of autonomic regulation, such as reactivity to a stressor (Dauphinot et al., 2010; Di Raimondo et al., 2016; Lodhi et al., 2019; O'Connor et al., 2021; Zhang et al., 2012). Clinical BP outcomes (e.g., hypertension diagnosis) were also not considered a valid proxy for stress-related autonomic functioning, as they may instead reflect long-term cardiovascular changes influenced by multiple physiological and behavioral factors (Di Raimondo et al., 2016; Oparil et al., 2018). Moreover, we did not consider studies that only report composite indices of a wide range of biomarkers, since these do not allow conclusions about specific stress systems or individual biomarkers.

The exact mechanisms of stress-related biological systems and the interplay of biological factors considered in this review have been discussed in detail elsewhere (Ahmed et al., 2023; Albinet et al., 2024; Nater et al., 2013; O'Connor et al., 2021; Shaffer and Ginsberg, 2017). While we categorize biomarkers broadly under the HPA axis and the ANS, explanations of individual biomarkers and their physiological relevance, particularly in light of the specific measurement methods used, are provided in the results section. This approach improves the interpretability of findings and allows for contextualization based on the functional significance of each biomarker.

2.2. Search method

We searched the PubMed and PsycINFO databases for studies due to their complementary coverage of biomedical and psychological literature. As shown in Table 1, the search terms were grouped into four concepts: (i) subjective socioeconomic status, (ii) biomarkers of HPA axis, (iii) biomarkers of ANS, and (iv) umbrella terms. No lower publication date limit was applied, and the search was continued until June 15th, 2025. To ensure the feasibility of the search process, we excluded grey literature and non-English publications—an approach that aligns with common practice in scoping reviews (Pham et al., 2014).

2.3. Study selection

Fig. 1 presents the PRISMA flow diagram (Page et al., 2021), providing detailed information about the search process and the reasons for exclusion. A total of 453 records were identified through PubMed and PsycINFO database searches, with 331 records screened after the removal of 122 duplicates. Two reviewers (F.E. and M.W.) independently screened titles and abstracts for eligibility. When eligibility was uncertain, the reviewers discussed discrepancies to reach a consensus. In total, 154 records were excluded during the screening stage, as they focused on research involving nonhuman animals. Subsequently, 177 full-text reports were retrieved and assessed for eligibility. Following the full-text review, 157 records were excluded, leaving 20 reports comprising 21 studies that met the final inclusion criteria from the database search. In addition, manual citation searching within the included reports and reference list screening were applied by the two

Table 1
Search terms.

Concept	Search terms
Subjective socioeconomic status	("subjective socioeconomic status" OR "subjective socioeconomic position" OR "subjective socioeconomic standing" ¹ OR "subjective social status" OR "subjective social position" OR "subjective social standing" OR "self-rated socioeconomic status" OR "self-rated socioeconomic position" ¹ OR "self-rated socioeconomic standing" ¹ OR "self-rated social status" OR "self-rated social position" ¹ OR "self-rated social standing" ¹ OR "perceived socioeconomic status" OR "perceived socioeconomic position" ¹ OR "perceived socioeconomic standing" ¹ OR "perceived social status" OR "perceived social position" OR "perceived social standing" OR "relative socioeconomic status" OR "relative socioeconomic position" OR "relative socioeconomic standing" OR "relative social status" OR "relative social position" OR "relative social standing" OR "social rank" OR "socioeconomic rank")
Biomarkers of HPA axis	AND ("hypothalam*–pituitary–adrenal" OR "HPA" OR "cortisol" OR "adrenocorticotrophic hormone" OR "ACTH" OR "glucocorticoid" OR "corticotropin-releasing hormone" OR "CRH" OR "CRF" OR "dehydroepiandrosterone" OR
Biomarkers of ANS	"heart rate" OR "HRV" OR "respiratory sinus arrhythmia" OR "pre-ejection period" OR "cardiovascular" OR "vagal" OR "sympathetic" OR "parasympathetic" OR "autonomic nervous system" OR "ANS" OR "cardiovascular" OR "cardiac" OR "blood pressure" OR "epinephrine" OR "norepinephrine" OR "adrenaline" OR "noradrenaline" OR "amylase" OR "skin conductance" OR "electrodermal activity" OR "galvanic skin" OR
Umbrella terms	"stress biology" OR "biological stress" OR "allostatic load" OR "biomarkers")

Notes. Title and abstract search. ACTH = adrenocorticotrophic hormone, ANS = autonomic nervous system, CRF = corticotropin-releasing factor, CRH = corticotropin-releasing hormone, HPA = hypothalamic–pituitary–adrenal, HRV = heart rate variability.

¹ Phrase variants were initially considered but excluded from the final search strings, as they returned no results.

* Acts as a truncation symbol to capture word-stem variants (e.g., hypothalam* retrieves hypothalamic and hypothalamus).

reviewers (F.E. and M.W.). Four additional reports were sought for retrieval, and retrieved full texts were assessed against the predefined inclusion criteria. The inclusion of these four reports comprising four studies brought the total number of studies included in the scoping review to 25.

2.4. Data extraction

Based on common variables extracted in previous scoping reviews in the field of biological stress research (e.g., Immanuel et al., 2023; Rinne et al., 2023; Scholaske et al., 2021), two authors (F.E. and M.W.) developed a data extraction form. The form was tested and revised as necessary by applying it to the included studies to ensure that all variables could be extracted consistently and that the form was practical to complete. The following variables were extracted: (a) study information (author, year), (b) sample characteristics, (c) study design, (d) measure of SSS, (e) biomarker outcome (including assessment methods), (f) type of statistical analyses testing associations of SSS with biomarkers and covariates (if applicable), and (g) main findings regarding SSS.

3. Results

3.1. Characteristics of included studies

As described in the Methods section, the search strategy identified 25 studies that were included in the scoping review. A detailed summary of

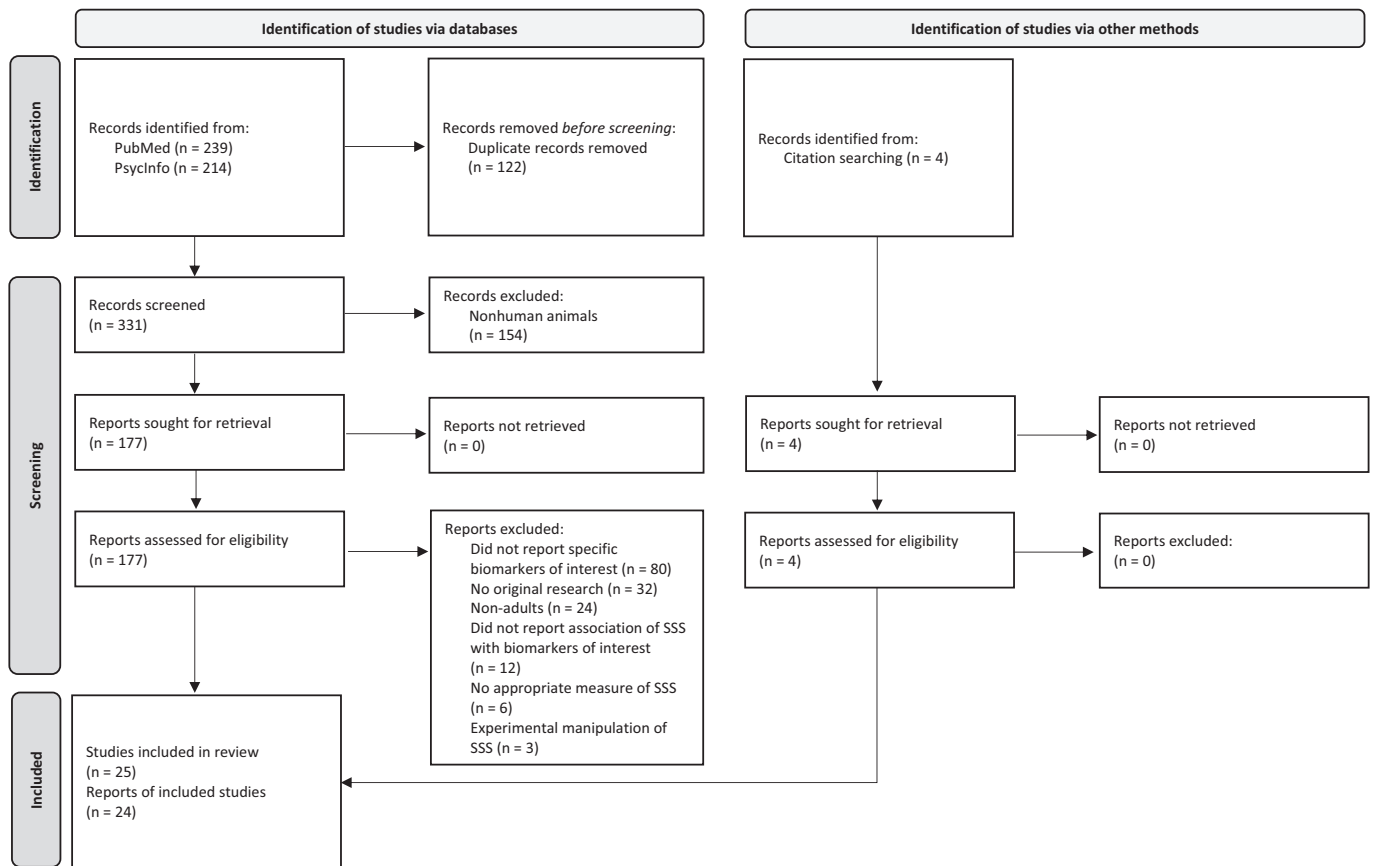


Fig. 1. PRISMA flow diagram for the scoping review process.

study characteristics, methods, and main findings is presented in Table 2 for the HPA axis and in Table 3 for ANS biomarkers.

For studies examining the association between SSS and HPA axis biomarkers ($n = 17$), publication dates ranged from 2000 to 2024. Data were provided from the USA ($n = 8$), Spain ($n = 5$), Germany ($n = 1$), the Republic of Honduras ($n = 1$), Taiwan ($n = 1$), and the United Kingdom ($n = 1$). The samples consisted of middle-aged and/or older adults ($n = 8$), young adults and/or late adolescents ($n = 3$), undergraduate students ($n = 2$), adults from the general population ($n = 1$), adult women only ($n = 1$), employed and unemployed adults ($n = 1$), and young adult men ($n = 1$). Among studies addressing the HPA axis, salivary cortisol was the most frequently analyzed biomarker (in 82.4% of studies), assessed as awakening levels ($n = 5$), the cortisol awakening response (CAR) ($n = 5$), diurnal profiles and/or total secretion ($n = 6$), and in relation to induced stress ($n = 5$). Findings on the associations of SSS with salivary DHEA in response to a stressor ($n = 1$), urinary cortisol ($n = 1$), blood DHEA-sulfate ($n = 1$), hair cortisol ($n = 2$), and hair DHEA ($n = 1$) were also reported. With respect to SSS, all examined studies employed cross-sectional designs ($n = 17$), in some cases with repeated biomarker assessments. Longitudinal studies, in which both SSS and biomarkers of the HPA axis are repeatedly assessed, are currently lacking.

Among studies examining the association between SSS and ANS biomarkers ($n = 10$), publication dates ranged from 2012 to 2024. Data originated from the USA ($n = 8$), Switzerland ($n = 1$), and Taiwan ($n = 1$). The samples consisted of adults from the general population ($n = 2$), adult men only ($n = 1$), police officers ($n = 1$), male police officers ($n = 1$), male students ($n = 2$), middle-aged and older adults ($n = 1$), as well as young adults and/or late adolescents ($n = 2$). Studies on ANS biomarkers included HRV measures ($n = 5$), assessed in response to induced stress ($n = 2$), anger recall ($n = 1$), faces depicting low, average, or high financial status ($n = 1$), as well as HRV at rest ($n = 1$). Cardiac reactivity was also analyzed by changes in HR (stress task: $n = 4$, anger recall: $n =$

1), BP (stress task: $n = 1$, anger recall: $n = 1$), PEP (faces depicting low, average, or high financial status: $n = 1$), cardiac output (stress task: $n = 1$), and by measuring the responsiveness of β -adrenergic receptors (isoproterenol stimulation test: $n = 1$). In addition to cardiovascular ANS measures, SSS was examined in relation to diurnal activity of salivary α -amylase ($n = 1$) and urinary epinephrine and norepinephrine ($n = 1$). As for SSS and biomarkers of the HPA axis, all study designs in relation to the association between SSS and ANS biomarkers were cross-sectional ($n = 10$).

3.2. HPA axis

The HPA axis is a central component of the body's neuroendocrine primary stress system. Upon activation by psychological or physiological stressors, the hypothalamus releases CRH, stimulating the pituitary gland to secrete ACTH, which in turn prompts the adrenal cortex to produce glucocorticoids, primarily cortisol. In this sense, cortisol is a key downstream output of HPA axis activity, helping to mobilize energy, modulate immune responses, and maintain homeostasis. The dynamics of HPA axis activation can be assessed using different biomarkers, including cortisol measured in saliva, blood, urine, or hair, as well as DHEA, an adrenal steroid co-released with cortisol that exerts partly anti-glucocorticoid effects. These markers vary in temporal sensitivity, capturing acute reactivity, diurnal patterns, or long-term cumulative exposure (Nater et al., 2013; O'Connor et al., 2021; Ring, 2025).

3.2.1. Cortisol

The glucocorticoid hormone cortisol is widely used as a biomarker in psychobiological stress research. Cortisol functions as the main effector hormone of the HPA axis. The HPA axis is controlled via negative feedback, in which central receptors monitor circulating cortisol and adjust secretion accordingly. Repeated or sustained activation of the

Table 2
Synthesis of included studies for HPA axis biomarkers (n = 17).

Study	Sample	Measure of subjective social status	Biomarker outcome	Types of statistical analyses testing associations of SSS with biomarkers; covariates included in models (if applicable)	Main findings regarding SSS
Adler et al., 2000	Women (USA), N = 157, mean age = 37.4 (SD = 4.8); subsample for salivary cortisol adaptation, N = 59	SSS relative to others in the society, in terms of income, education, and occupational standing	Salivary cortisol adaptation to challenge: three laboratory stress sessions (mental stress and speech) over 3 consecutive days in the late afternoon (8 samples each session)	Analysis of variance, IV: three adaptation groups, i) habituators with higher cortisol on day 1 than day 2 or 3 (i.e., healthy adaptation), ii) nonhabitua-tors with levels of cortisol on day 2 or 3 equal to or higher than on day 1, iii) low reactors with little response on any day with cortisol levels staying at about 0.10 µg/dl throughout the sessions; DV: SSS (separate additional analysis with objective SES using a composite measure of education, income, and occupation)	SSS in the society of nonhabitua-tors was sign. lower than in low reactors or habituators; cortisol adaptation groups did not significantly differ in objective SES
Agbedia et al., 2011	Older adults (USA), in part with chronic medical conditions, N = 98, mean age = 66.8 (SD = 5.6), female (%) = 70.0	SSS relative to others in the society, in terms of income, education, and occupational standing	Salivary cortisol: awakening level, CAR, AUC (total diurnal cortisol secretion), and rate of cortisol decline over the day (4 samples: 0 and 30–60 min after wake-up, before dinner, before bedtime)	Linear regression models, IV: two groups (high SSS = upper 5 rungs, low SSS = lower 5 rungs), DV: individual analyses for each cortisol measure; unadjusted models and adjusted models with age, sex, BMI, and education	Older adults with lower SSS in the society showed a sign. more blunted rate of cortisol decline over the day than individuals with higher SSS in unadjusted and adjusted models; no sign. results for awakening level, CAR, and AUC
García et al., 2017	Residents of Utila (Honduras), N = 57, mean age = 39.4 (SD = 12.1), male mean age = 39.3 (SD = 15.0), female (%) = 68.4	SSS relative to others on the island, in terms of respect in the community, money and occupational standing	Salivary cortisol over two consecutive days: AUC (total diurnal cortisol secretion), slope of cortisol decline (2 × 3 samples: 30 min, 2 h, and 8 h after wake-up)	Generalized linear models, IV: SSS, DV: each cortisol measure; adjusted for age and sex with additional models adjusted for objective SES (composite measure of education, income, and occupational rank)	No sign. associations of SSS on the island with AUC and slope of cortisol decline
Geiger et al., 2019	Sample of employed and unemployed adults (Germany), N = 36, mean age = 33.3, female (%) = 66.7	SSS relative to others in the neighborhood (no socioeconomic anchors); SSS relative to others family members and friends (no socioeconomic anchors)	Salivary cortisol over two consecutive days: CAR, CAR recovery (2 × 4 samples: 0, 30, 45, and 60 min after wake-up)	Linear regression models, IV: individual analyses for each SSS measure; DV: individual analyses for CAR and CRA recovery; adjusted for age, sex, and employment status	No sign. associations between SSS in the neighborhood and SSS relative to family members and friends with CAR or CAR recovery
Gersten et al., 2015	Middle-aged and older adults (Taiwan) participating in the 2000 wave of the Social Environment and Biomarkers of Aging Study (SEBAS), N = 930, mean age = 66.3 (SD = 8.0), female (%) = 43.0	SSS relative to others in the society, in terms of income, education, and occupational standing; SSS relative to others in the community (no socioeconomic anchors)	Total urinary cortisol and blood DHEA-sulfate: 12-h overnight sample	Linear regression models, IV: individual analyses for each SSS measure; DV: urinary cortisol, and blood DHEA-sulfate; adjusted for age, sex, medication use, diet, exercise, alcohol consumption, betel quid chewing and smoking with additional models adjusted for objective SES (measures of education and occupation)	No sign. associations between SSS in the society and SSS in the community with urinary cortisol and blood DHEA-sulfate
Hidalgo et al., 2021	Older adults (Spain), N = 140, mean age = 64.7 (SD = 2.7), female (%) = 50.7	SSS relative to others in the society, in terms of income, education, and occupational standing	Salivary cortisol over two consecutive days: awakening level, CAR, total cortisol during the first 45 min, wake-to-bed cortisol slope, bedtime cortisol (2 × 4 samples: 0, 30, and 45 min after wake-up, before bedtime)	Correlations	No sign. associations of SSS in the society with awakening cortisol level, CAR, total cortisol during the first 45 min, wake-to-bed cortisol slope, and bedtime cortisol
Hooker et al., 2018	Undergraduate students (USA) ≥18 years, N = 115, mean age = 19.6 (SD = 2.1), female (%) = 54.8	SSS relative to others in the society, in terms of income, education, and occupational standing	Salivary cortisol reactivity and recovery: changes from baseline to post-stressor (Trier Social Stress Test), to a recovery period (5 samples: baseline, immediately after speech, as well as 10, 25, and 40 min after the end of speech)	Multilevel model, IV: SSS, social support (moderator); DV: cortisol response; adjusted for sex	Sign. interaction: undergraduates with lower SSS in the society and lower perceived social support exhibited sign. greater cortisol responses during recovery than those who reported higher SSS and lower support; when support was high, those who reported higher and

(continued on next page)

Table 2 (continued)

Study	Sample	Measure of subjective social status	Biomarker outcome	Types of statistical analyses testing associations of SSS with biomarkers; covariates included in models (if applicable)	Main findings regarding SSS
Hooker et al., 2020	Undergraduate students (USA) ≥ 18 years, $N = 128$, mean age = 19.9 (SD = 1.7), female (%) = 48.1	SSS relative to others in the society, in terms of income, education, and occupational standing	Salivary cortisol over two consecutive days: average diurnal cortisol across timepoints and days, quadratic and linear rates of change in diurnal cortisol (2×7 samples throughout each day)	Correlations/multilevel models, IV: social support, SSS (moderator); DV: change in diurnal cortisol; multilevel models were adjusted for sex, BMI, hours since awakening with additional models adjusted for parental education and negative events on the previous day	lower SSS exhibited similar cortisol responses Sign. interaction: across all models, a flatter slope in diurnal cortisol was most prominent in undergraduates with higher SSS in the society and more social support than usual on the previous day (within-person support), students lower in SSS generally exhibited flatter slopes; No sign. overall association between SSS and average diurnal cortisol
O'Brien et al., 2017	Young adults (USA), $N = 180$, mean age = 22.2 (SD = 3.4), female (%) = 52.0	SSS relative to others in the community (no socioeconomic anchors)	Hair cortisol: 3-month period	Correlations/linear regression models: IV: SSS; DV: hair cortisol; regressions adjusted for age and sex	No sign. associations of SSS in the community with hair cortisol
Prall et al., 2017	Younger male adults (USA), $N = 27$, mean age = 21.6 (SD = 2.7)	SSS relative to others in the society, in terms of income, education, and occupational standing	Responses of salivary cortisol and DHEA: Overall increases (AUC _i) from baseline to post-stressor (modified Trier Social Stress test), to a post-stress period (4 samples: baseline, immediately after the task, as well 10 and 20 min after the end of the task)	Correlations/linear regression models: IV: SSS; DV: AUC _i for each endocrinological marker; adjusted for age	Adults with lower SSS in the society exhibited lower responses in cortisol and DHEA in unadjusted analyses (findings for cortisol became non-sign. when adjusting for age)
Pulopulos et al., 2016	Middle-aged and older adults (Spain), $N = 86$, mean age = 64.4 (SD = 3.9), female (%) = 52.3	SSS relative to others in the society, in terms of income, education, and occupational standing	Salivary cortisol over two consecutive days: awakening level, CAR (2×3 samples: 0, 30, and 45 min after wake-up)	Correlations	No sign. associations of SSS in the society with CAR and awakening cortisol
Rahal et al., 2020	Late adolescents (USA) ≥ 18 years, $N = 87$ (in high-school: $N = 50$, one year after high school: $N = 37$), mean age = 18.4, female (%) = 57.5	SSS (i.e., family's standing) relative to others in society, in terms of income, education, and occupational standing	Salivary cortisol reactivity and recovery: changes from baseline to post-stressor (Trier Social Stress Test), to a recovery period (6 samples: baseline, immediately after the task, as well as 15, 30, 45, and 60 min after the end of task)	Multilevel model, IV: SSS; DV: cortisol response; adjusted for gender, ethnicity, and high school status (enrolled/ graduated) with additional models adjusted for family income and parental education	Late adolescents with lower family SSS in the society exhibited sign. greater cortisol reactivity and higher (i.e., faster) rates of cortisol recovery
Weiss and Weiss, 2016	Older adults (USA) participating in the National Survey of Midlife Development in the US 2 (MIDUS 2, 2004–2006) and the Biomarker Project (2004–2009), $N = 389$, mean age = 70.8 (SD = 6.5), female (%) = 53.6	SSS relative to others in the society, in terms of income, education, and occupational standing	Salivary cortisol reactivity: changes from baseline to 44 min after cognitive stressors (mental arithmetic and Stroop color-word matching), AUC with respect to an increase and decrease after baseline (AUC _i) (4 samples: baseline, immediately after the second task, as well as 14 and 44 min after the end of the tasks)	Linear regression models, IV: SSS, essentialist beliefs about cognitive aging (moderator); DV: cortisol reactivity (adjusted for baseline cortisol), AUC _i ; additional models adjusted for age, gender, education, subjective health, BMI, cognitive functioning, session start time, and time of last meal	Sign. interaction: older adults with low SSS in the society and high essentialist beliefs showed significantly elevated cortisol reactivity and AUC _i ; no sign. overall associations of SSS with cortisol reactivity or AUC _i
Wright and Steptoe, 2005	Older adults (UK), divided into groups with lower and higher SSS (based on a cut point of 5 on a 10-rung SSS scale); subsample with lower SSS: $N = 24$, mean age = 71.4 (SD = 4.0+), female (%) = 45.8, subsample with higher SSS: $N = 57$, mean age = 70.5 (SD = 4.2), female (%) = 52.6	SSS relative to others in the society, in terms of income, education, and occupational standing	Salivary cortisol: CAR (5 samples: 0, 10, 20, 30, and 60 min after wake-up), only compliant participants were included	Repeated measures analysis of variance, IV: SSS groups, DV: CAR; additional analysis of covariance adjusted for gender, BMI, waist/hip ratio, smoking status, and time of waking, IV: SSS groups, DV: change in cortisol from waking to 30 min after wake-up (separate additional analysis with objective SES using education groups)	Older adults with lower SSS in the society exhibited a sign. larger CAR than those with higher SSS across all analyses; objective SES was not sign. associated with CAR
Zapater-Fajari et al.,	Young adults (Spain), $N = 75$, mean age = 22.2 (SD = 3.8), female (%) = 50.7	SSS relative to others in the society, in terms of income, education, and occupational standing	Salivary cortisol over two consecutive days: awakening level, diurnal cortisol slope (2 samples:	Correlations	No sign. associations of SSS in the society with awakening cortisol and diurnal cortisol slope

(continued on next page)

Table 2 (continued)

Study	Sample	Measure of subjective social status	Biomarker outcome	Types of statistical analyses testing associations of SSS with biomarkers; covariates included in models (if applicable)	Main findings regarding SSS
2022 (study 1) Zapater-Fajarf et al., 2022 (study 2)	Middle-aged adults (Spain), N = 35, mean age = 59.6 (SD = 2.8), female (%) = 54.3; older adults (Spain), N = 38, mean age = 69.1 (SD = 3.1), female (%) = 39.5	SSS relative to others in the society, in terms of income, education, and occupational standing	after wake-up, before bedtime) Salivary cortisol over two consecutive days: awakening level, diurnal cortisol slope (2 samples: after wake-up, before bedtime)	Correlations	No sign. associations of SSS in the society with awakening cortisol and diurnal cortisol slope
Zapater-Fajarf et al., 2024	Middle-aged and older adults (Spain), N = 119, mean age = 67.4 (SD = 5.3), female (%) = 61.3	SSS relative to others in the society, in terms of income, education, and occupational standing	Hair cortisol, DHEA, and cortisol to DHEA ratio: 3-month period	Correlations	No sign. associations of SSS in the society with cortisol, DHEA, and cortisol to DHEA ratio in the hair

Notes. ANS = autonomic nervous system, AUC = area under the curve, BMI = body mass index, CAR = cortisol awakening response, DHEA = dehydroepiandrosterone, DV = dependent variable, HPA = hypothalamic–pituitary–adrenal, IV = independent variable, SES = socioeconomic status, SSS = subjective social status.

HPA axis can, however, produce chronically elevated cortisol output and maladaptive response patterns, which may contribute to a broad range of poor mental and physical health outcomes (Adam et al., 2017; Nater et al., 2013; O'Connor et al., 2021; Ring, 2025). Cortisol is most frequently analyzed in saliva, which also applies to the studies included in this review, as noted above. Salivary cortisol is used to examine key components of diurnal cortisol rhythm. These components involve the basal awakening level (i.e., a single-point measure), the rapid increase in cortisol levels across the first 30 to 45 min after morning awakening (i.e., CAR), the gradual decline in cortisol levels over the course of the day, referred to as the diurnal cortisol slope, and the average levels of cortisol across the day (Adam et al., 2017; O'Connor et al., 2021; Pruessner et al., 1997; Ring, 2025).

3.2.1.1. CAR & salivary cortisol awakening levels. With regard to the post-wake salivary cortisol increase, both low and high CARs have been associated with chronic stress, with mixed findings for specific putative psychosocial stressors, including low socioeconomic status (Dowd et al., 2009; Miller et al., 2007; O'Connor et al., 2021; Steptoe and Serwinski, 2016). It has been speculated that divergent findings may reflect that a higher CAR is more prominent under conditions requiring individuals to actively cope with daily demands, whereas a lower CAR may be associated with prolonged stressful conditions that cannot be addressed through active coping strategies, although other explanations have also been proposed (O'Connor et al., 2021; Steptoe and Serwinski, 2016). Among the five included studies that examined associations between SSS and the CAR, only one study found a significant effect: older adults with lower SSS relative to society (i.e., in the UK) exhibited a larger CAR than those with higher SSS (Wright and Steptoe, 2005). In contrast, all other studies reported null findings. These included studies assessing SSS relative to society in middle-aged and/or older adults in the USA (Agbedia et al., 2011) and in Spain (Hidalgo et al., 2021; Pulopulos et al., 2016), as well as studies measuring neighborhood SSS and SSS relative to family and friends in employed and unemployed adults in Germany (Geiger et al., 2019). Basal awakening levels of salivary cortisol, sometimes also used as an indicator of HPA axis activation (i.e., higher levels are often interpreted as reflecting higher HPA axis activity), showed no significant associations with SSS across five studies (Agbedia et al., 2011; Hidalgo et al., 2021; Pulopulos et al., 2016; Zapater-Fajarf et al., 2022).

3.2.1.2. Diurnal salivary cortisol. With regard to the diurnal salivary cortisol slope, a blunted decline (i.e., a flatter slope) has been linked to chronic stress and adverse health outcomes (Adam et al., 2017; Adam and Kumari, 2009; O'Connor et al., 2021; Ring, 2025). Among the six included studies that examined associations between SSS and salivary

cortisol levels across the diurnal course, one study reported that older adults with lower SSS in society (i.e., in the USA) showed a blunted decline in cortisol levels over the course of the day (Agbedia et al., 2011). Another study did not find a main effect of SSS, but reported an interaction between societal SSS and daily social support in relation to the diurnal cortisol slope. Among US undergraduate students higher in SSS, receiving more support than usual was associated with a blunted slope, whereas receiving less support was associated with a steeper, more adaptive slope. In contrast, students lower in SSS generally exhibited flatter slopes, with the most pronounced blunting when they reported low support (Hooker et al., 2020). The four remaining studies did not report any significant associations between SSS and the diurnal slope. These included studies assessing SSS relative to society in adults in Utila, Honduras (García et al., 2017) and in young, middle-aged, and older adults in Spain (Hidalgo et al., 2021; Zapater-Fajarf et al., 2022). Of the six studies that investigated associations between SSS and salivary cortisol levels across the diurnal course, two additionally examined total salivary cortisol output across the day (i.e., area under the curve) as an integrated indicator of HPA axis activation, but both reported null findings (Agbedia et al., 2011; García et al., 2017).

3.2.1.3. Reactivity of salivary cortisol under laboratory conditions. Research on salivary cortisol responses to acute laboratory stress has been guided by the assumption that altered physiological stress responses can index vulnerability to long-term health risk (Dickerson and Kemeny, 2004; McEwen, 1998; O'Connor et al., 2021; Obrist, 1981). Although findings are not fully consistent, it has been proposed that greater exposure to real-life stressors may be linked initially to heightened cortisol responsiveness in the laboratory, with a shift toward hyporeactivity (i.e., blunted responses) as exposure to real-life stressors persists (Bunea et al., 2017; Creswell et al., 2025; Fries et al., 2005; Lê-Scherban et al., 2018; McEwen, 1998; Ring, 2025). In addition, prolonged stress exposure may alter HPA-axis dynamics, yielding impaired recovery after stress and changed habituation patterns to repeated laboratory stressors (Barthel et al., 2025; Bunea et al., 2017; Lê-Scherban et al., 2018; Ring, 2025). Among the five included studies that examined associations of SSS with salivary cortisol in the context of acute laboratory stressors, findings were mixed. One study reported that late adolescents with lower family SSS in the USA exhibited greater cortisol reactivity but also faster cortisol recovery in response to social stress (Rahal et al., 2020). Two additional studies also reported associations between societal SSS in the USA and higher salivary cortisol in response to cognitive and social stress, but only when moderating variables were taken into account, such as lower social support in undergraduates (Hooker et al., 2018) and stronger essentialist beliefs in older adults (Weiss and Weiss, 2016). In contrast, another study of younger male

Table 3
Synthesis of included studies for ANS biomarkers (n = 10).

Study	Sample	Measure of subjective social status	Biomarker outcome	Type of statistical analyses testing associations of SSS with biomarkers; covariates included in models (if applicable)	Main findings regarding SSS
Akinola and Mendes, 2014 (study I)	Male police officers (USA), N = 81, mean age = 40.8 (SD = 8.7)	SSS relative to others in the society, in terms of income, education, and occupational standing; SSS relative to people at the police department in terms of income, education, and occupational standing	Cardiac reactivity: changes in HR and cardiac output from baseline to a social stress task	Correlations, unadjusted and adjusted for age and race	Police officers with lower SSS at the police department exhibited sign. lower cardiac output and HR reactivity (findings for HR reactivity became non-sign. in adjusted analysis); no sign. association of SSS in the society with cardiac reactivity
Cundiff et al., 2019	Male community sample (USA), N = 307, mean age = 32	SSS relative to others in the society, in terms of income, education, and occupational standing; SSS relative to others in the community (no socioeconomic anchors)	Cardiac reactivity: changes in HR, HF-HRV, SBP, and DBP from baseline to an anger recall task	Correlations	No sign. associations between SSS in the society and SSS in the community with changes in HR, HF-HRV, SBP, and DBP during anger recall
Cloutier et al., 2013	Male undergraduate students (USA), N = 46, mean age = 20.4 (SD = 3.1)	SSS relative to the university undergraduate population of the Chicago area, in terms of financial status and wealth	Cardiac reactivity: changes in HF-HRV and PEP from baseline to stimuli blocks presenting faces assigned with either a low, average, or high financial status	Linear regression models, IV: SSS; DV: individual analyses for changes in HF-HRV and PEP; adjusted for age and income	In contrast to undergraduates with lower SSS in the university undergraduate population, those with higher SSS showed sign. reduced PEP when viewing low- and medium status faces as compared to high-status faces, and sign. lower HF-HRV response when viewing high- and medium-status faces relative to low-status faces
Eisen et al., 2024	Male students (USA), N = 64, mean age = 22.7 (SD = 3.4)	SSS relative to others in the society, in terms of income, education, and occupational standing	Cardiac recovery: changes in HR, LF/HF-HRV, RMSSD, and indexes of sympathetic and parasympathetic tone from baseline to a recovery period (after the Trier Social Stress Test and exposure to a nature or an office virtual reality environment)	Linear regression models, IV: environment group, SSS, environment × SSS interaction; DV: individual analyses for changes in each cardiac outcome	No sign. associations between SSS in the society and cardiac recovery (i.e., HR and several HRV indicators) after virtual nature environment exposure (vs. office environment exposure)
Euteneuer et al., 2012	Adults (USA), N = 93, mean age = 35.1 (SD = 9.3), female (%) = 42.6	SSS relative to others in the society, in terms of income, education, and occupational standing; SSS relative to others in the community (no socioeconomic anchors)	In vivo β-adrenergic receptor responsiveness: dose of isoproterenol, which is necessary to increase HR by 25 beats/min (i.e., chronotropic 25 dose)	Correlations/linear regression models, IV: individual analyses for each SSS measure; DV: β-adrenergic receptor responsiveness; adjusted for age, sex, ethnicity, BMI, exercise, smoking status, and objective SES (two-factor index of education and occupation)	β-Adrenergic receptor responsiveness was sign. reduced in adults with lower SSS in the society and in those with lower SSS in the community (findings for SSS in the society became non-sign. in the fully adjusted model)
Gersten et al., 2015	Middle-aged and older adults (Taiwan) participating in the 2000 wave of the Social Environment and Biomarkers of Aging Study (SEBAS), N = 930, mean age = 66.3 (SD = 8.0), female (%) = 43.0	SSS relative to others in the society, in terms of income, education, and occupational standing; SSS relative to others in the community (no socioeconomic anchors)	Total urinary epinephrine and norepinephrine: 12-h overnight samples	Linear regression models, IV: individual analyses for each SSS measure; DV: individual analysis for urinary epinephrine and norepinephrine; all analyses adjusted for age, sex, medication use, diet, exercise, alcohol consumption, betel quid chewing and smoking with additional models adjusted for objective SES (measures of education and occupation)	Adults with lower SSS in the society exhibited sign. lower levels of urinary norepinephrine (findings became non-sign. when adjusting for objective SES); no sign. association of SSS in the community with urinary norepinephrine; no sign. associations of SSS measures with urinary epinephrine
Habersaat et al., 2018	Police officers (Switzerland), N = 56, mean age = 39.5 (SD = 8.1), female (%) = 16.1	SSS relative to others in the society, in terms of income, education, and occupational standing; SSS relative to others in the community (no socioeconomic anchors); SSS relative to others at the police (no socioeconomic anchors); SSS relative to	Diurnal activity of salivary alpha-amylase: samples at 0, 15, and 30 min after wake-up, before mealtime at midday, before mealtime in the evening, before bedtime	Multilevel model, IV: individual analyses for each SSS measure; DV: diurnal measures of salivary alpha-amylase; adjusted for smoking status, BMI and type of police division	Police officers with lower SSS in the police exhibited sign. higher wake-up levels of salivary alpha-amylase, followed by a steep decrease and higher levels during the second part of the day; no sign. associations of other SSS measures (i.e., society, community, friends) with

(continued on next page)

Table 3 (continued)

Study	Sample	Measure of subjective social status	Biomarker outcome	Type of statistical analyses testing associations of SSS with biomarkers; covariates included in models (if applicable)	Main findings regarding SSS
Rahal et al., 2020	Late adolescents (USA) ≥ 18 years, N = 87 (in high-school: N = 50, one year after high school: N = 37), mean age = 18.4, female (%) = 57.5	their friends (no socioeconomic anchors) SSS (i.e., family's standing) relative to others in society, in terms of income, education, and occupational standing	Cardiac reactivity and recovery: changes in HR and respiratory HRV from baseline to a preparation period (Trier Social Stress Test), to a recovery period.	Multilevel model, IV: SSS; DV: individual analysis for response in HR and respiratory sinus arrhythmia; adjusted for gender, ethnicity, and high school status (enrolled/graduated) with additional models adjusted for family income and parental education	diurnal activity of salivary alpha-amylase In late adolescents in high school (but not in those after high school), lower family SSS in the society was sign. associated with increased respiratory HRV from baseline to task preparation (i.e., reactivity) and smaller increases in respiratory HRV during recovery across all models; no sign. association between SSS and HR response
Ryan et al., 2022	Adults (USA) participating in the National Survey of Midlife Development in the US 2 (MIDUS 2, 2004–2006) and a lab based stress task (2004), N = 1155, mean age = 57.3 (SD = 11.6), female (%) = 56.8	SSS relative to others in the community (no socioeconomic anchors)	Cardiac reactivity: changes in HR, SBP, and DBP from baseline to stressor (Stroop and graded mental arithmetic task)	Correlations/linear regression models, IV: income inequality, SSS, income inequality \times SSS interaction; additional analyses testing three-way interactions considering the ethnic group; DV: individual analyses for changes in each cardiac outcome; adjusted for smoking, age, and gender	Adults with lower SSS in the community showed sign. higher SBP and DBP reactivity, as well as lower HR reactivity overall; among the white majority ethnic group and among the black and minority ethnic group with high state level income inequality, lower SSS was sign. related with higher SBP reactivity; among the black and minority ethnic group with low and medium state level income inequality, lower SSS was sign. related with reduced SBP reactivity
Tan et al., 2024	Young adults (USA), N = 164, mean age = 20.7 (SD = 3.7), female (%) = 65.1	SSS relative to others in the society, in terms of income, education, and occupational standing	Resting HRV: average 5-min RMSSD	Correlations	No sign. association between SSS in the society and HRV

Notes. ANS = autonomic nervous system, BMI = body mass index, DBP = diastolic blood pressure, DV = dependent variable, HF = high-frequency, HR = heart rate, HRV = heart rate variability, IV = independent variable, LF = low-frequency, PEP = pre-ejection period, RMSSD = root-mean-square of successive differences, SES = socioeconomic status, SSS = subjective social status, SBP = systolic blood pressure.

adults from the USA found that lower societal SSS was associated with reduced cortisol response to social stress in unadjusted analyses. However, the association with cortisol did not remain significant after adjusting for age (Prall et al., 2017). Finally, a study of females from the USA that explicitly focused on adaptation patterns across repeated cognitive stress sessions reported that lower SSS in the USA was associated with being a nonhabituator, with cortisol levels in the second or third sessions remaining equal to or higher than those in the first session (Adler et al., 2000).

3.2.1.4. Urinary & hair cortisol. While salivary cortisol corresponds to circulating cortisol levels with a short time-lag of several minutes, urinary and hair cortisol can inform about pooled cortisol reflecting longer lasting effects of stressful events with putative relevance for health outcomes (Flynn et al., 2023; Inoue et al., 2021; Iob and Steptoe, 2019; Martins-Silva et al., 2025; Vogelzangs et al., 2010). One study examined associations of both societal and community SSS with 12-h overnight urinary cortisol concentrations in middle-aged and older adults in Taiwan, but reported overall null findings (Gersten et al., 2015). Two studies analyzed hair cortisol concentrations over a 3-month period, in relation to community SSS in young adults from the USA (O'Brien et al., 2017) and to societal SSS in middle-aged and older adults from Spain (Zapater-Fajari et al., 2024), but found no significant associations.

3.2.2. DHEA

DHEA is a steroid hormone co-released with cortisol from the adrenal

cortex in response to ACTH and serves both as a precursor for sex hormones and as a potential counter-regulator of cortisol. In contrast to DHEA, its sulfated form DHEA-S is more stable due to its longer half-life and is therefore regarded as a marker of longer-term adrenal activity, whereas DHEA may better reflect rapid fluctuations in response to acute stress (Dutheil et al., 2021; Ring, 2025). DHEA and DHEA-S have mostly been examined in blood and saliva, though the measurement in hair as an indicator for prolonged stress is increasing (Zapater-Fajari et al., 2024). In addition to cortisol, three of the studies described in Section 3.2.1 also analyzed DHEA or, respectively DHEA-S (Gersten et al., 2015; Prall et al., 2017; Zapater-Fajari et al., 2024). With respect to SSS, one study found that younger male adults from the USA with lower societal SSS exhibited reduced salivary DHEA responsiveness to social stress, both in unadjusted analyses and after adjustment for age (Prall et al., 2017). Similar to urinary cortisol, neither societal nor community SSS were associated with blood DHEA-S concentrations in middle-aged and older adults in Taiwan (Gersten et al., 2015). Finally, societal SSS was not associated with 3-month hair concentrations of DHEA in middle-aged and older adults from Spain (Zapater-Fajari et al., 2024).

3.3. ANS

In addition to the HPA axis, the ANS is a core efferent component of the body's primary stress system. In response to psychological or physiological challenges, central autonomic networks coordinate sympathetic and parasympathetic outputs to adjust cardiovascular, metabolic, immunological, and visceral functions. The sympathetic nervous system

(SNS) mobilizes the body for action. Biomarkers that primarily reflect SNS contributions include cardiovascular measures (i.e., PEP, BP and HR reactivity to stressors, β -adrenergic receptor function), salivary α -amylase, indices of electrodermal activity, as well as catecholamines such as norepinephrine and epinephrine. The parasympathetic nervous system (PNS) supports recovery and homeostatic control via vagal activation, which is most commonly indexed by specific measures of HRV. Most common HRV indices that primarily reflect parasympathetic activity include high-frequency (HF)-HRV as a frequency-domain measure and the root mean square of successive differences between normal heartbeats (RMSSD) as a time-domain measure. A third category of HRV is respiratory HRV, which has traditionally been linked to vagally mediated heart rate variation, although its role as a measure of parasympathetic tone remains controversial (Menuet et al., 2025; Shaffer and Ginsberg, 2017). ANS biomarkers are assessed under different conditions that capture distinct physiological components and time-scales, including resting-state measures, acute reactivity, diurnal patterns, and long-term cumulative effects (Mills and Dimsdale, 1993; Nater et al., 2013; Nater and Rohleder, 2009; O'Connor et al., 2021; Olivieri et al., 2024).

3.3.1. Cardiovascular ANS measures

Among cardiovascular ANS measures, indices of HRV have predictive value for cardiovascular disease and are commonly used to index stress-related changes in the ANS, particularly vagal withdrawal and autonomic imbalance (Fang et al., 2020; Hillebrand et al., 2013; Kemp et al., 2017; Koch et al., 2019; Shaffer and Ginsberg, 2017). PEP in contrast, referring to the period between electrical stimulation of the heart and actual blood ejection, serves as a noninvasive index of sympathetic β -adrenergic cardiac control (Berntson et al., 1993; Pilz et al., 2023). In addition, BP and HR reactivity to a stressor, as well as cardiac output, have been primarily associated with sympathetic activation (Joyner et al., 2008; O'Connor et al., 2021; Seery, 2011).

3.3.1.1. Cardiovascular ANS measures at rest. Cardiovascular resting-state ANS activity, such as short-term resting HRV, is a valid trait marker of vagal tone and predicts poor health outcomes, such as CVD and mortality (Dekker et al., 2000; Hillebrand et al., 2013; Jarczok et al., 2022; Laborde et al., 2017; Orini et al., 2023; Tsuji et al., 1996). Only one study of young adults from the USA reported the association between societal SSS and short-term resting vagally mediated HRV, indexed by the RMSSD, and stated no significant findings (Tan et al., 2024).

3.3.1.2. Reactivity of cardiovascular ANS measures under laboratory conditions. Among the studies on SSS and cardiovascular ANS measures included in this review, three studies focused on cardiac changes during social stress (Akinola and Mendes, 2014; Eisen et al., 2024; Rahal et al., 2020). The first study found that among police officers in the USA, those with lower SSS within the police department (but not in society) exhibited decreased cardiac output and HR reactivity, though the findings for HR reactivity became non-significant in the adjusted analysis (Akinola and Mendes, 2014). The second study included late adolescents from the USA who were in high school or one year after high school (Rahal et al., 2020). This study found that lower family SSS in society was associated with increased respiratory HRV reactivity (i.e., from baseline to task preparation) but smaller increases during recovery, whereas no effects were observed for HR reactivity. The authors interpret their HRV findings as suggesting that individuals with lower SSS exhibit greater vagal withdrawal following social stress, although respiratory HRV as an index of vagal activity is debated (Menuet et al., 2025). Importantly, this pattern was only observed in the subgroup of adolescents who were in high school but not in the subsample of individuals who had already completed high school (Rahal et al., 2020). The third study, which included male students from the USA, did not

directly analyze associations between societal SSS and HRV changes in response to social stress but instead examined whether SSS was related to differences in several HRV indices (and HR) during recovery in a virtual nature environment versus an office environment, yielding no significant results (Eisen et al., 2024).

In addition to the previously described studies on social stress, one study examined the relationship between community SSS and cardiac reactivity measured through BP and HR during a cognitive stressor in U. S. adults (Ryan et al., 2022). This study reported that adults with lower community SSS showed greater overall blood pressure reactivity and lower heart rate reactivity. In the white majority and in Black and minority groups living in states with high income inequality, lower SSS was linked to higher systolic BP reactivity. In contrast, among Black and minority groups in states with low or medium income inequality, lower SSS was associated with reduced systolic BP reactivity (Ryan et al., 2022). Ryan et al. (2022) interpret these subgroup effects as context-dependent, suggesting that higher community SSS tends to be protective for White participants, whereas for Black and minority participants this protective pattern emerges primarily in high-inequality states.

A further study examined associations between financial SSS, assessed relative to the undergraduate population of the Chicago area (USA), and ANS responses to the perception of social targets in male undergraduate students (Cloutier et al., 2013). Regarding HF-HRV, which reflects vagal modulation of heart rate, findings indicated that, compared with undergraduates with lower SSS, those with higher SSS showed a decrease in HF-HRV when viewing high- and medium-status faces, but not when viewing low-status targets. This finding was interpreted as suggesting that individuals with higher SSS may exhibit more pronounced parasympathetic withdrawal, indicating social stress when confronted with social targets that could potentially challenge their social standing. Furthermore, individuals with high SSS showed a decrease in PEP, indicating reduced sympathetic activity when viewing low- and medium-status targets, but not when viewing high-status targets, as compared to those with low subjective status (Cloutier et al., 2013).

Alongside the studies on SSS and cardiac ANS reactivity in the context of stress or perception of social targets reviewed previously, societal SSS and community SSS have also been examined in relation to HF-HRV, HR, and BP reactivity during anger recall in a male community sample from the USA, yielding no significant findings (Cundiff et al., 2019).

Finally, one study directly examined the responsiveness of β -adrenergic receptors in vivo using an isoproterenol stimulation test (i.e., the dose of isoproterenol which is necessary to increase the HR by 25 beats/min) (Euteneuer et al., 2012). Since prolonged sympathetic over-activation downregulates β -adrenergic receptor function, diminished receptor responsiveness is regarded as a marker of sympathetic over-activity and a cardiovascular risk factor (Mills and Dimsdale, 1993). This study found that β -adrenergic receptor responsiveness was reduced in U. S. adults with lower SSS in society and in those with lower SSS in the community, although the findings for SSS in society became non-significant in a fully adjusted model (Euteneuer et al., 2012). Euteneuer et al. (2012) interpreted these findings as consistent with the notion that lower SSS may be associated with chronic sympathetic activation, a mechanism that has been linked to increased cardiovascular risk.

3.3.2. Salivary α -amylase

In stress research, salivary α -amylase has been proposed as a proxy measure of sympathetic activation, though its validity as a biomarker of SNS activity remains debated (Ali and Nater, 2020; Bosch et al., 2011). A study of Swiss police officers found that those with lower SSS in the police exhibited higher basal salivary α -amylase activity throughout the day, potentially indicating chronic stress-related SNS activation (Habersaat et al., 2018). This effect was particularly driven by elevated wake-up levels and higher concentrations during the latter part of the

day. Importantly, the study did not report significant associations between societal or community SSS and salivary α -amylase activity.

3.3.3. Urinary epinephrine and norepinephrine

In addition to urinary cortisol and DHEA-S, Gersten et al. (2015) examined associations between societal and community SSS and 12-h overnight concentrations of urinary epinephrine and norepinephrine, which serve as proxies of sympathetic nervous system (SNS) activation, in middle-aged and older adults in Taiwan. Contrary to expectations, individuals with lower societal SSS had lower urinary norepinephrine levels, although this association became non-significant after adjusting for education and occupation. Community SSS was not significantly associated with either catecholamine.

4. Discussion

Stress-related psychobiological mechanisms have been hypothesized as key pathways linking SSS to adverse health outcomes. This scoping review sought to identify, characterize, and synthesize the available literature on associations between SSS and biomarkers of the two primary stress systems: the HPA axis and the ANS. Across 25 empirical studies, 17 involved biomarkers of the HPA axis and 10 involved biomarkers related to the ANS, with some studies examining both systems. Overall, we identified both promising directions and substantial gaps in the evidence base and research. While some studies suggest that lower SSS is associated with alterations in biological stress regulation, findings were highly inconsistent across biomarkers, contexts, and populations.

4.1. Synthesizing findings on SSS and HPA axis biomarkers

Among the 17 studies investigating SSS in relation to HPA axis functioning, salivary cortisol was the most frequently analyzed biomarker, assessed as awakening response and part of diurnal rhythms, or acute reactivity to laboratory stress. Importantly, these different cortisol measurement approaches capture, to a substantial extent, distinct aspects of HPA axis functioning rather than a single, unitary stress response (O'Connor et al., 2021; Ring, 2025). Findings for diurnal rhythms were inconsistent. Two studies reported blunted diurnal cortisol slopes in association with lower societal SSS (Agbedia et al., 2011; Hooker et al., 2020), with one suggesting that this link emerged particularly under conditions of low social support (Hooker et al., 2020), whereas four other studies yielded null results (García et al., 2017; Hidalgo et al., 2021; Zapater-Fajará et al., 2022). The majority of studies on the CAR and SSS reported null findings (Agbedia et al., 2011; Geiger et al., 2019; Hidalgo et al., 2021; Pulopulos et al., 2016), with the exception of Wright and Steptoe (2005), who observed a larger CAR among lower-SSS older adults. Acute stress paradigms yielded mixed results. Some studies suggest heightened cortisol reactivity and patterns of nonhabituation in relation to lower SSS (Adler et al., 2000; Rahal et al., 2020), partly when considering the moderating role of psychosocial vulnerabilities such as low social support or stronger essentialist beliefs (Hooker et al., 2018; Weiss and Weiss, 2016). Other findings suggested blunted cortisol reactivity to acute stress (Prall et al., 2017). Longer-term indices such as hair cortisol (O'Brien et al., 2017; Zapater-Fajará et al., 2024) or urinary cortisol (Gersten et al., 2015) showed null findings. Similarly, the three studies of DHEA or DHEA-S provided little evidence for robust associations (Gersten et al., 2015; Prall et al., 2017; Zapater-Fajará et al., 2024), although one investigation links lower SSS with reduced DHEA in response to social stress (Prall et al., 2017). In sum, research on SSS and HPA axis biomarkers reveals a heterogeneous pattern. Lower SSS has occasionally been linked to blunted diurnal slopes and altered cortisol reactivity, particularly in vulnerable contexts, yet the majority of studies reported null findings. These inconsistencies suggest that any association between SSS and HPA axis regulation is likely contingent on contextual or moderating factors rather than uniform across populations.

4.2. Synthesizing findings on SSS and ANS biomarkers

Across 10 studies investigating ANS biomarkers, results were heterogeneous across cardiovascular and neuroendocrine indices. Two studies support the notion that lower SSS, although assessed with different SSS measures, relates to higher chronic sympathetic activation, as indexed by reduced β -adrenergic receptor responsiveness (Euteneuer et al., 2012) and higher basal salivary α -amylase activity throughout the day (Habersaat et al., 2018). Results from studies that assessed cardiac reactivity indices are mixed and difficult to synthesize, with findings linking lower SSS to overall increased BP reactivity during cognitive stress in the presence of complex moderating effects (Ryan et al., 2022), smaller increases in respiratory HRV during recovery following social stress (Rahal et al., 2020), or blunted reactivity with respect to HR and cardiac output to social stress (Akinola and Mendes, 2014). Null findings or unexpected results were reported for associations of SSS with HF-HRV, HR, and BP changes during anger recall (Cundiff et al., 2019), resting HRV (Tan et al., 2024) and urinary norepinephrine (Gersten et al., 2015). Other studies did not directly focus on general associations between SSS and ANS measures, although both variables were assessed (Cloutier et al., 2013; Eisen et al., 2024). In summary, as with HPA axis biomarkers, findings on ANS biomarkers are inconclusive. While several studies link lower SSS to alterations in ANS-related biomarkers, no consistent pattern emerges, suggesting that potential associations between SSS and ANS activity may depend on context, study population and the choice of biomarkers.

4.3. Overall considerations on potential sources of heterogeneous findings

With regard to the relative strength of the available evidence, clear repeated support across studies is largely absent. Even within biomarker domains in which more than one study reported associations with SSS, findings often differed in direction, analytic approach, or reliance on moderating conditions rather than reflecting convergent effects. Accordingly, many reported associations may represent single-study findings or conditional effects that emerge only under specific contextual or psychosocial moderators. Across several biomarker domains, including CAR, longer-term cortisol indices, and resting ANS measures, findings are predominantly null. This pattern underscores the exploratory and fragmentary nature of the current evidence base.

The overall inconclusive findings on SSS and biomarkers of primary stress systems raise several questions. The available studies are, in large part, heterogeneous and therefore difficult to compare. In addition, partly differing analytic approaches across studies, including differences in statistical models and covariate adjustment, may have contributed to inconsistent or null findings. From a scoping review perspective, this variability complicates the identification of systematic patterns across studies.

As already outlined above, one potential contributor to heterogeneous findings concerns differences in the temporal characteristics of stress biomarkers. Across the included studies, SSS has been examined in response to acute stress, diurnal regulation, and longer-term indices such as hair or urinary measures. These indicators capture partly distinct aspects of HPA axis and ANS functioning, which may limit convergence across findings.

In addition, study populations varied considerably. As summarized in Tables 2 and 3, samples ranged from undergraduate and late-adolescent groups to occupational and community samples as well as middle-aged or older adults. Moreover, several studies involved small sample sizes, which likely limit their representativeness. Differences in life stage, stability of perceived social position, cumulative stress exposure, and baseline regulation of stress systems may partly contribute to heterogeneous findings across studies.

Heterogeneity may also relate to how SSS was assessed. Studies differed in part with respect to the reference group used to define SSS (e.g., society, community, workplace, family, or financial comparisons).

Such differences may influence the salience of social comparisons and could contribute to variability in whether associations with stress-related biomarkers are observed.

In addition, methodological diversity across studies, including assessment protocols, sampling density, outcome operationalization, and analytic strategies, further limits comparability. Moreover, stress-related biological responses are known to vary depending on stressor characteristics, such as social-evaluative threat or controllability, which differed in part across studies using stress induction paradigms.

Finally, it also warrants critical consideration to what extent lower SSS can be assumed to be consistently associated with alterations in the biological stress systems examined here. Experimental research indicates that not all stressors have the same impact on biological stress systems and also for social stressors, biological responses may vary depending on stressor characteristics (Allen et al., 2016; Dickerson and Kemeny, 2004; Shahrestani et al., 2015). For example, while experimentally induced reductions in perceived social rank are associated with heightened cardiovascular reactivity when manipulations are based on socioeconomic factors (Williams et al., 2025), experiences of social exclusion, which might be core experiences of individuals with lower social status (Albath et al., 2023; Büttner et al., 2024; Janke et al., 2024), have yielded divergent results for cortisol and ANS biomarker changes in experimental studies (Bass et al., 2014; Carlyle et al., 2020; Kothgassner et al., 2021, 2014; Kroll et al., 2019; Peterson et al., 2020; Pieritz et al., 2017; Radke et al., 2018; Seidel et al., 2013; Weik et al., 2017; Zwolinski, 2012). Of note, experimental studies which manipulate SSS to examine acute biological stress responses were not within the scope of the present review, since we focus on biological correlates of real-life SSS.

4.4. Research gaps and future directions

Assuming that the experience of stress and negative emotions due to a lower perceived social position accumulates over time (Hallqvist et al., 2004), an important gap in the literature is the lack of longitudinal studies assessing reciprocal associations between SSS and biomarkers of the HPA axis or the ANS over several months or years. For other outcomes, such as self-rated health, sleep, or inflammatory immune markers, such longitudinal links have already been examined in some studies (Euteneuer et al., 2021; Euteneuer and Süssenbach, 2021; Jones et al., 2023; Nobles et al., 2013). When potential effects accumulate over time and ultimate consequences may be of relevance, an observation at a single time point or in young populations may underestimate existing links (Funder and Ozer, 2019). Future research should therefore prioritize prospective longitudinal designs with repeated measurements of both SSS and stress-related biomarkers to capture temporal dynamics, potential accumulation effects, and bidirectional associations, and where feasible, complement these with intensive ambulatory assessment (i.e., diurnal assessment of cortisol and α -amylase). In addition, future research should prioritize larger and more representative samples, particularly samples with broader age ranges and sufficient representation of midlife and older adults. Beyond longitudinal age-related dynamics, considering age as a moderating variable may help to clarify previously inconclusive findings.

A further gap concerns the selection and coverage of biomarkers. Certain indicators regarded as meaningful markers of the respective biological stress pathways have rarely been assessed in relation to SSS. For example, we identified only one study that reported resting HRV (Tan et al., 2024), with limited interpretability due to a sample restricted to young adults. This is noteworthy because short-term resting HRV is a valid trait marker of vagal tone (Laborde et al., 2017) and a well-established predictor of CVD and mortality (Dekker et al., 2000; Hillebrand et al., 2013; Jarczok et al., 2022; Orini et al., 2023; Tsuji et al., 1996). Similarly, salivary α -amylase, widely used as a proxy for SNS activity (Ali and Nater, 2020; Bosch et al., 2011), was examined in only one study (Habersaat et al., 2018), while electrodermal indicators

of SNS activity (Freeman and Chapleau, 2013) have not yet been assessed in relation to SSS. Relatedly, some theoretically expected positive results remain isolated. These include, for example, evidence suggesting higher prolonged sympathetic activation among individuals with lower SSS, as indicated by reduced in-vivo β -adrenergic receptor responsiveness (Euteneuer et al., 2012) and higher basal salivary α -amylase activity throughout the day (Habersaat et al., 2018). Accordingly, replication across independent samples using comparable designs and measurement protocols is essential to distinguish robust associations from isolated or context-specific findings.

Overall, future studies would benefit from systematically assessing multiple SSS referents (e.g., societal, community, and workplace) to enable direct comparisons across dimensions of perceived social position. Where feasible, SSS measures should be complemented by objective indicators of relative socioeconomic rank, such as relative income rank (Boyce et al., 2010; Brown et al., 2008; Daly et al., 2015; Euteneuer et al., 2024; Garratt et al., 2017; Hounkpatin et al., 2015, 2016; Macchia, 2023; Stewart et al., 2006), to examine convergence and divergence between subjective and objective relative status. Although objective indicators of relative socioeconomic rank were not the primary focus of the present scoping review, none of the included studies incorporated such objective rank indicators alongside SSS. Finally, future studies should specify and test theoretically motivated moderators a priori, such as social support and inequality-related contextual factors (Hooker et al., 2018; Schneider, 2019).

4.5. Limitations

The findings of this scoping review should be interpreted considering its limitations. Although common for scoping reviews (Pham et al., 2014), non-English-language papers and grey literature were not included. Moreover, only the PubMed and PsycINFO databases were searched, and although reference lists of identified articles were examined, it is possible that some relevant studies were not retrieved and therefore were not reviewed. The lack of longitudinal research is also an important limitation of the present review, alongside the limited representativeness of many included studies.

5. Concluding remarks

To our knowledge, this is the first scoping review to systematically map the literature on SSS and biomarkers of primary biological stress systems. To conclude, although some findings suggest that lower SSS relates to alterations in primary stress systems, the literature is inconclusive. Future research may address existing research gaps by conducting longitudinal studies on SSS and stress biomarkers, replicating previous positive findings, focusing on more representative and larger samples, as well as examining understudied biomarkers.

CRedit authorship contribution statement

Frank Euteneuer: Writing – original draft, Resources, Project administration, Methodology, Investigation, Conceptualization. **Stefan Salzmann:** Writing – review & editing, Validation, Conceptualization. **Philipp Süssenbach:** Writing – review & editing, Methodology, Conceptualization. **Linn K. Kuehl:** Writing – review & editing, Validation, Conceptualization. **Marcel Wilhelm:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization.

Data availability

No data was used for the research described in the article.

References

- Adam, E.K., Kumari, M., 2009. Assessing salivary cortisol in large-scale, epidemiological research. *Psychoneuroendocrinology* 34, 1423–1436. <https://doi.org/10.1016/J.PSYNEUEN.2009.06.011>.
- Adam, E.K., Quinn, M.E., Tavernier, R., McQuillan, M.T., Dahlke, K.A., Gilbert, K.E., 2017. Diurnal cortisol slopes and mental and physical health outcomes: a systematic review and meta-analysis. *Psychoneuroendocrinology* 83, 25–41. <https://doi.org/10.1016/J.PSYNEUEN.2017.05.018>.
- Adler, N.E., Ostrove, J.M., 1999. Socioeconomic status and health: what we know and what we don't. *Ann. N. Y. Acad. Sci.* 896, 3–15.
- Adler, N.E., Epel, E.S., Castellazzo, G., Ickovics, J.R., 2000. Relationship of subjective and objective social status with psychological and physiological functioning: preliminary data in healthy white women. *Health Psychol.* 19, 586–592. <https://doi.org/10.1037/0278-6133.19.6.586>.
- Agbedia, O.O., Varma, V.R., Seplaki, C.L., Seeman, T.E., Fried, L.P., Li, L., Harris, G.C., Rebok, G.W., Xue, Q.L., Tan, E.J., Tanner, E., Parisi, J.M., McGill, S., Carlson, M.C., 2011. Blunted diurnal decline of cortisol among older adults with low socioeconomic status. *Ann. N. Y. Acad. Sci.* 1231, 56–64. <https://doi.org/10.1111/J.1749-6632.2011.06151.X>.
- Ahmed, T., Qassem, M., Kyriacou, P.A., 2023. Measuring stress: a review of the current cortisol and dehydroepiandrosterone (DHEA) measurement techniques and considerations for the future of mental health monitoring. *Stress* 26, 29–42. <https://doi.org/10.1080/10253890.2022.2164187>.
- Akinola, M., Mendes, W.B., 2014. It's good to be the king: neurobiological benefits of higher social standing. *Soc. Psychol. Personal. Sci.* 5, 43–51. <https://doi.org/10.1177/1948550613485604>.
- Albath, E.A., Büttner, C.M., Rudert, S.C., Sibley, C.G., Greifeneder, R., 2023. Young, unemployed, excluded: unemployed young adults report more ostracism. *Eur. J. Soc. Psychol.* 53, 1078–1097. <https://doi.org/10.1002/EJSP.2953>.
- Albinet, C.T., De Faria, C., Causse, M., 2024. Cardiac pre-ejection period to index motivation and effort mobilization in cognitive studies: a critical narrative review. *J. Psychophysiol.* 38, 81–101. <https://doi.org/10.1027/0269-8803/A000332>.
- Ali, N., Nater, U.M., 2020. Salivary alpha-amylase as a biomarker of stress in behavioral medicine. *Int. J. Behav. Med.* 27, 337–342. <https://doi.org/10.1007/S12529-019-09843-X>.
- Allen, A.P., Kennedy, P.J., Dockray, S., Cryan, J.F., Dinan, T.G., Clarke, G., 2016. The Trier Social Stress Test: principles and practice. *Neurobiol. Stress* 6, 113. <https://doi.org/10.1016/J.YNSTR.2016.11.001>.
- Arnsten, A.F.T., 2009. Stress signalling pathways that impair prefrontal cortex structure and function. *Nat. Rev. Neurosci.* 10, 410–422. <https://doi.org/10.1038/NRN2648>.
- Barthel, M.C., Fricke, K., Muehlhan, M., Vogel, S., Alexander, N., 2025. Habituation of the biological response to repeated psychosocial stress: a systematic review and meta-analysis. In: *Neurosci. Biobehav. Rev.*, 169. <https://doi.org/10.1016/J.NEUBIOREV.2024.105996>.
- Bass, E.C., Stednitz, S.J., Simonson, K., Shen, T., Gahtan, E., 2014. Physiological stress reactivity and empathy following social exclusion: a test of the defensive emotional analgesia hypothesis. *Soc. Neurosci.* 9, 504–513. <https://doi.org/10.1080/17470919.2014.929533>.
- Beekman, J.B., Stock, M.L., Marcus, T., 2016. Need to belong, not rejection sensitivity, moderates cortisol response, self-reported stress, and negative affect following social exclusion. *J. Soc. Psychol.* 156, 131–138. <https://doi.org/10.1080/00224545.2015.1071767>.
- Berntson, G.G., Cacioppo, J.T., Quigley, K.S., 1993. Cardiac psychophysiology and autonomic space in humans: empirical perspectives and conceptual implications. *Psychol. Bull.* 114, 296–322. <https://doi.org/10.1037/0033-2909.114.2.296>.
- Bosch, J.A., Veerman, E.C.I., de Geus, E.J., Proctor, G.B., 2011. α -Amylase as a reliable and convenient measure of sympathetic activity: don't start salivating just yet! *Psychoneuroendocrinology* 36, 449–453. <https://doi.org/10.1016/J.PSYNEUEN.2010.12.019>.
- Boyce, C.J., Brown, G.D.A., Moore, S.C., 2010. Money and happiness: rank of income, not income, affects life satisfaction. *Psychol. Sci.* 21, 471–475. <https://doi.org/10.1177/0956797610362671>.
- Brown, G.D.A., Gardner, J., Oswald, A.J., Qian, J., 2008. Does wage rank affect employees' well-being? *Ind. Relat.* 47, 355–389. <https://doi.org/10.1111/J.1468-232X.2008.00525.X>.
- Bunea, I.M., Szentágotai-Tátar, A., Miu, A.C., 2017. Early-life adversity and cortisol response to social stress: a meta-analysis. *Transl. Psychiatry* 7. <https://doi.org/10.1038/S41398-017-0032-3>.
- Büttner, C.M., Ren, D., Stavrova, O., Rudert, S.C., Williams, K.D., Greifeneder, R., 2024. Ostracism in everyday life: a framework of threat and behavioral responses in real life. *J. Pers. Soc. Psychol.* <https://doi.org/10.1037/PSPI0000471>.
- Camelo, L.V., Giatti, L., Barreto, S.M., 2013. Subjective social status, self-rated health and tobacco smoking. *Brazilian Longitudinal Study of Adult Health (ELSA-Brasil)*. *J. Health Psychol.* <https://doi.org/10.1177/1359105313490772>.
- Carlyle, M., Rowley, M., Stevens, T., Karl, A., Morgan, C.J.A., 2020. Impaired empathy and increased anger following social exclusion in non-intoxicated opioid users. *Psychopharmacology* 237, 419–430. <https://doi.org/10.1007/S00213-019-05378-X>.
- Cheon, B.K., Bittner, J.M.P., Pink, A.E., 2025. Contributions of subjective status to eating behaviors, obesity, and metabolic health across development. *Appetite* 204. <https://doi.org/10.1016/J.APPET.2024.107735>.
- Cloutier, J., Norman, G.J., Li, T., Bernston, G.G., 2013. Person perception and autonomic nervous system response: the costs and benefits of possessing a high social status. *Biol. Psychol.* 92, 301–305. <https://doi.org/10.1016/J.biopsycho.2012.09.006>.
- Cohen, S., 1999. Social status and susceptibility to respiratory infections. *Ann. N. Y. Acad. Sci.* 896, 246–253. <https://doi.org/10.1111/j.1749-6632.1999.tb08119.x>.
- Coughlin, S.S., Vernon, M., Hatzigeorgiou, C., George, V., 2020. Health literacy, social determinants of health, and disease prevention and control. *J. Environ. Heal. Sci.* 6, 3061.
- Creswell, D., Brown, K.W., Cohen, S., Creswell, K., Zoccola, P., Dickerson, S., Dutcher, J., Wu, S., Chin, B., 2025. Does high perceived stress over the past month alter cortisol reactivity to the Trier Social Stress Test? *Psychoneuroendocrinology* 172. <https://doi.org/10.1016/J.PSYNEUEN.2024.107256>.
- Cundiff, J.M., Matthews, K.A., 2017. Is subjective social status a unique correlate of physical health? A meta-analysis. *Health Psychol.* 36, 1109–1125. <https://doi.org/10.1037/hea0000534>.
- Cundiff, J.M., Jennings, J.R., Matthews, K.A., 2019. Social stratification and risk for cardiovascular disease: examination of emotional suppression as a pathway to risk. *Personal. Soc. Psychol. Bull.* 45, 1202–1215. <https://doi.org/10.1177/0146167218808504>.
- Cundiff, J.M., Boylan, J.M., Muscatell, K.A., 2020. The pathway from social status to physical health: taking a closer look at stress as a mediator. *Curr. Dir. Psychol. Sci.* <https://doi.org/10.1177/0963721420901596>, 096372142090159.
- Daly, M., Boyce, C., Wood, A., 2015. A social rank explanation of how money influences health. *Health Psychol.* 34, 222–230. <https://doi.org/10.1037/hea0000098>.
- Dauphinaut, V., Gosse, P., Kossovsky, M.P., Schott, A.M., Rouch, I., Pichot, V., Gaspoz, J. M., Roche, F., Barthelemy, J.C., 2010. Autonomic nervous system activity is independently associated with the risk of shift in the non-dipper blood pressure pattern. *Hypertens. Res.* 33, 1032–1037. <https://doi.org/10.1038/HR.2010.130>.
- Dekker, J.M., Crow, R.S., Folsom, A.R., Hannan, P.J., Liao, D., Swenne, C.A., Schouten, E. G., 2000. Low heart rate variability in a 2-minute rhythm strip predicts risk of coronary heart disease and mortality from several causes: the ARIC Study. *Atherosclerosis Risk In Communities*. *Circulation* 102, 1239–1244. <https://doi.org/10.1161/01.CIR.102.11.1239>.
- Demakakos, P., Biddulph, J.P., de Oliveira, C., Tsakos, G., Marmot, M.G., 2018. Subjective social status and mortality: the English Longitudinal Study of Ageing. *Eur. J. Epidemiol.* 33, 729–739. <https://doi.org/10.1007/s10654-018-0410-z>.
- D'Hooge, L., Achterberg, P., Reeskens, T., 2018. Mind over matter. The impact of subjective social status on health outcomes and health behaviors. *PLoS One* 13. <https://doi.org/10.1371/JOURNAL.PONE.0202489>.
- Di Raimondo, D., Miceli, G., Casuccio, A., Tuttolomondo, A., Buttà, C., Zappulla, V., Schimmenti, C., Musiari, G., Pinto, A., 2016. Does sympathetic overactivation feature all hypertensives? Differences of sympathovagal balance according to night/day blood pressure ratio in patients with essential hypertension. *Hypertens. Res.* 39, 440–448. <https://doi.org/10.1038/HR.2016.6>.
- Dickerson, S.S., Kemeny, M.E., 2004. Acute stressors and cortisol responses: a theoretical integration and synthesis of laboratory research. *Psychol. Bull.* 130, 355–391. <https://doi.org/10.1037/0033-2909.130.3.355>.
- Dougall, I., Vasiljevic, M., Wright, J.D., Weick, M., 2023. How, when, and why is social class linked to mental health and wellbeing? A systematic meta-review. *Soc. Sci. Med.* 343, 116542. <https://doi.org/10.1016/j.socscimed.2023.116542>.
- Dowd, J.B., Simanek, A.M., Aiello, A.E., 2009. Socio-economic status, cortisol and allostatic load: a review of the literature. *Int. J. Epidemiol.* 38, 1297–1309. <https://doi.org/10.1093/IJE/DYP277>.
- Dutheil, F., de Saint Vincent, S., Pereira, B., Schmidt, J., Moustafa, F., Charkhabi, M., Bouillon-Minois, J.B., Clinchamps, M., 2021. DHEA as a biomarker of stress: a systematic review and meta-analysis. *Front. Psychol.* 12, 688367. <https://doi.org/10.3389/FPSYT.2021.688367/FULL>.
- Eisen, A.M., Bratman, G.N., Olvera-Alvarez, H.A., 2024. Susceptibility to stress and nature exposure: unveiling differential susceptibility to physical environments; a randomized controlled trial. *PLoS One* 19, 1–26. <https://doi.org/10.1371/journal.pone.0301473>.
- Euteneuer, F., 2014. Subjective social status and health. *Curr. Opin. Psychiatry* 27, 337–343. <https://doi.org/10.1097/YCO.000000000000083>.
- Euteneuer, F., Süßenbach, P., 2021. Longitudinal reciprocal relationships between subjective social status and short sleep duration in a German population-based sample. *Nat. Sci. Sleep* 13, 803–810. <https://doi.org/10.2147/NSS.S301293>.
- Euteneuer, F., Mills, P.J., Rief, W., Ziegler, M.G., Dimsdale, J.E., 2012. Subjective social status predicts in vivo responsiveness of β -adrenergic receptors. *Health Psychol.* 31. <https://doi.org/10.1037/a0025990>.
- Euteneuer, F., Schäfer, S.J., Neubert, M., Rief, W., Süßenbach, P., 2021. Subjective social status and health-related quality of life—a cross-lagged panel analysis. *Health Psychol.* 40, 71–76. <https://doi.org/10.1037/HEA0001051>.
- Euteneuer, F., Salzmann, S., Süßenbach, P., 2024. Income rank and depressive symptoms among employees in Germany — a 5-year cross-lagged panel analysis. *Int. J. Clin. Health Psychol.* 24, 100485. <https://doi.org/10.1016/J.IJCHP.2024.100485>.
- Fang, S.-C., Wu, Y.-L., Tsai, P.-S., 2020. Heart rate variability and risk of all-cause death and cardiovascular events in patients with cardiovascular disease: a meta-analysis of cohort studies. *Biol. Res. Nurs.* 22, 45–56. <https://doi.org/10.1177/1099800419877442>.
- Festinger, L., 1954. A theory of social comparison processes. *Hum. Relat.* 7, 117–140. <https://doi.org/10.1177/001872675400700202>.
- Flynn, S., Srikanthan, P., Ravellette, K., Inoue, K., Watson, K., Horwich, T., 2023. Urinary cortisol and cardiovascular events in women vs. men: the multi-ethnic study of atherosclerosis. *Am. Heart J. Plus Cardiol. Res. Pract.* 36. <https://doi.org/10.1016/J.AHJO.2023.100344>.
- Freeman, R., Chapleau, M.W., 2013. Testing the autonomic nervous system. *Handb. Clin. Neurol.* 115, 115–136. <https://doi.org/10.1016/B978-0-444-52902-2.00007-2>.
- Frerichs, L., Huang, T.T.K., Chen, D.R., 2014. Associations of subjective social status with physical activity and body mass index across four Asian countries. *J. Obes.* 2014. <https://doi.org/10.1155/2014/710602>.

- Fries, E., Hesse, J., Hellhammer, J., Hellhammer, D.H., 2005. A new view on hypocortisolism. *Psychoneuroendocrinology* 30, 1010–1016. <https://doi.org/10.1016/j.psyneuen.2005.04.006>.
- Funder, D.C., Ozer, D.J., 2019. Evaluating effect size in psychological research: sense and nonsense. *Adv. Methods Pract. Psychol. Sci.* 2, 156–168. <https://doi.org/10.1177/2515245919847202>.
- García, A.R., Gurven, M., Blackwell, A.D., 2017. A matter of perception: perceived socioeconomic status and cortisol on the island of Utila, Honduras. *Am. J. Hum. Biol.* 29. <https://doi.org/10.1002/ajhb.23031>.
- Garratt, E.A., Chandola, T., Purdam, K., Wood, A.M., 2017. Income and social rank influence UK children's behavioral problems: a longitudinal analysis. *Child Dev.* <https://doi.org/10.1111/cdev.12649>.
- Geiger, A.M., Kirschbaum, C., Wolf, J.M., 2019. Comparison group matters for chronic stress effects of subjective social status. *J. Health Psychol.* 24, 1923–1928. <https://doi.org/10.1177/1359105317709511>.
- Gersten, O., Timiras, P.S., Boyce, W.T., 2015. Does lower subjective social status yield riskier biomarker profiles? *J. Biosoc. Sci.* 47, 746–761. <https://doi.org/10.1017/S002193201400042X>.
- Gilbert, P., 2006. Evolution and depression: issues and implications. *Psychol. Med.* 36, 287–297. <https://doi.org/10.1017/S0033291705006112>.
- Godwin, A., MacNevin, G., Zadro, L., Iannuzzelli, R., Weston, S., Gonsalkorale, K., Devine, P., 2014. Are all ostracism experiences equal? A comparison of the autobiographical recall, cyberball, and O-Cam paradigms. *Behav. Res. Methods* 46, 660–667. <https://doi.org/10.3758/s13428-013-0408-0>.
- Goodman, E., Adler, N.E., Kawachi, I., Frazier, A.L., Huang, B., Colditz, G.A., 2001. Adolescents' perceptions of social status: development and evaluation of a new indicator. *Pediatrics* 108, e31. <https://doi.org/10.1542/peds.108.2.e31>.
- Goon, S., Slotnick, M., Leung, C.W., 2024. Associations between subjective social status and health behaviors among college students. *J. Nutr. Educ. Behav.* 56, 184–192. <https://doi.org/10.1016/j.jneb.2023.12.005>.
- Guerra, O., Eboeime, E., 2021. The impact of economic recessions on depression, anxiety, and trauma-related disorders and illness outcomes—a scoping review. *Behav. Sci.* 11. <https://doi.org/10.3390/BS11090119>.
- Habersaat, S., Abdellaoui, S., Geiger, A.M., Urben, S., Wolf, J.M., 2018. Low subjective social status in the police is linked to health-relevant changes in diurnal salivary alpha-amylase activity in Swiss police officers. *Stress* 21, 11–18. <https://doi.org/10.1080/10253890.2017.1389882>.
- Hallqvist, J., Lynch, J., Bartley, M., Lang, T., Blane, D., 2004. Can we disentangle life course processes of accumulation, critical period and social mobility? An analysis of disadvantaged socio-economic positions and myocardial infarction in the Stockholm Heart Epidemiology Program. *Soc. Sci. Med.* 58, 1555–1562. [https://doi.org/10.1016/S0277-9536\(03\)00344-7](https://doi.org/10.1016/S0277-9536(03)00344-7).
- Hidalgo, V., Pulpulos, M.M., Puig-Perez, S., Montoliu, T., Salvador, A., 2021. Diurnal cortisol secretion and health-related quality of life in healthy older people. *Int. J. Psychophysiol.* 166, 127–133. <https://doi.org/10.1016/j.ijpsycho.2021.05.012>.
- Hillebrand, S., Gast, K.B., de Mutser, R., Swenne, C.A., Jukema, J.W., Middeldorp, S., Rosendaal, F.R., Dekkers, O.M., 2013. Heart rate variability and first cardiovascular event in populations without known cardiovascular disease: meta-analysis and dose-response meta-regression. *EP Eur.* 15, 742–749. <https://doi.org/10.1093/europace/eus341>.
- Hoebel, J., Lampert, T., 2018. Subjective social status and health: multidisciplinary explanations and methodological challenges. *J. Health Psychol.* <https://doi.org/10.1177/1359105318800804>, 1359105318800800.
- Hooker, E.D., Campos, B., Zoccola, P.M., Dickerson, S.S., 2018. Subjective socioeconomic status matters less when perceived social support is high: a study of cortisol responses to stress. *Soc. Psychol. Personal. Sci.* 9, 981–989. <https://doi.org/10.1177/1948550617732387>.
- Hooker, E.D., Campos, B., Hoffman, L., Zoccola, P., Dickerson, S.S., 2020. Is receiving social support costly for those higher in subjective socioeconomic status? *Int. J. Behav. Med.* 27, 325–336. <https://doi.org/10.1007/s12529-019-09836-w>.
- Houkpatin, H.O., Wood, A.M., Brown, G.D.A., Dunn, G., 2015. Why does income relate to depressive symptoms? Testing the income rank hypothesis longitudinally. *Soc. Indic. Res.* 124, 637–655. <https://doi.org/10.1007/s11205-014-0795-3>.
- Houkpatin, H.O., Wood, A.M., Dunn, G., 2016. Does income relate to health due to psychosocial or material factors? Consistent support for the psychosocial hypothesis requires operationalization with income rank not the Yitzhaki Index. *Soc. Sci. Med.* 150, 76–84. <https://doi.org/10.1016/j.socscimed.2015.12.008>.
- Immanuel, S., Teferia, M.N., Baumert, M., Bidargaddi, N., 2023. Heart rate variability for evaluating psychological stress changes in healthy adults: a scoping review. *Neuropsychobiology* 82, 187–202. <https://doi.org/10.1159/000530376>.
- Inoue, K., Horwich, T., Bhatnagar, R., Bhatt, K., Goldwater, D., Seeman, T., Watson, K.E., 2021. Urinary stress hormones, hypertension, and cardiovascular events: the multi-ethnic study of atherosclerosis. *Hypertension* 78, 1640–1647. <https://doi.org/10.1161/HYPERTENSIONAHA.121.17618>.
- Iob, E., Steptoe, A., 2019. Cardiovascular disease and hair cortisol: a novel biomarker of chronic stress. *Curr. Cardiol. Rep.* 21, 116. <https://doi.org/10.1007/s11886-019-1208-7>.
- Janke, S., Messerer, L.A.S., Merkle, B., Rudert, S.C., 2024. Why do minority students feel they don't fit in? Migration background and parental education differentially predict social ostracism and belongingness. *Group Process. Intergr. Relat.* 27, 278–299. <https://doi.org/10.1177/13684302221142781/ASSET/8946F174-345B-4948-870C-91CA3CB98CCC/ASSETS/IMAGES/LARGE/10.1177.13684302221142781-FIG.4.JPG>.
- Jarczok, M.N., Weimer, K., Braun, C., Williams, D.W.P., Thayer, J.F., Gundel, H.O., Balint, E.M., 2022. Heart rate variability in the prediction of mortality: a systematic review and meta-analysis of healthy and patient populations. *Neurosci. Biobehav. Rev.* 143. <https://doi.org/10.1016/j.neubiorev.2022.104907>.
- Jiang, T., Chen, Z., 2020. Relative deprivation: a mechanism for the ostracism-aggression link. *Eur. J. Soc. Psychol.* 50, 347–359. <https://doi.org/10.1002/ejsp.2621>.
- Jones, E.J., Marsland, A.L., Kraynak, T.E., Votruba-Drzal, E., Gianaros, P.J., 2023. Subjective social status and longitudinal changes in systemic inflammation. *Ann. Behav. Med.* 57, 951–964. <https://doi.org/10.1093/abm/kaad044>.
- Joyner, M.J., Charkoudian, N., Wallin, B.G., 2008. A sympathetic view of the sympathetic nervous system and human blood pressure regulation. *Exp. Physiol.* 93, 715–724. <https://doi.org/10.1113/expphysiol.2007.039545>.
- Kemp, A.H., Koenig, J., Thayer, J.F., 2017. From psychological moments to mortality: a multidisciplinary synthesis on heart rate variability spanning the continuum of time. *Neurosci. Biobehav. Rev.* 83, 547–567. <https://doi.org/10.1016/j.neubiorev.2017.09.006>.
- Kim, J.H., Sumerlin, T.S., Goggins, W.B., Kwong, E.M.S., Leung, J., Yu, B., Kwok, T.C.Y., 2021. Does low subjective social status predict cognitive decline in Chinese older adults? A 4-year longitudinal study from Hong Kong. *Am. J. Geriatr. Psychiatry* 29, 1140–1151. <https://doi.org/10.1016/j.jagp.2021.01.014>.
- Koch, C., Wilhelm, M., Salzmann, S., Rief, W., Euteneuer, F., 2019. A meta-analysis of heart rate variability in major depression. *Psychol. Med.* <https://doi.org/10.1017/S0033291719001351>.
- Korzan, W.J., Summers, C.H., 2021. Evolution of stress responses refine mechanisms of social rank. *Neurobiol. Stress* 14. <https://doi.org/10.1016/j.ynstr.2021.100328>.
- Kothgassner, O.D., Kafka, J.X., Rudyk, J., Beutl, L., Hlavacs, H., Felnhofner, A., 2014. Does social exclusion hurt virtually like it hurts in real-life? The role of agency and social presence in the perception and experience of social exclusion. *Proc. Int. Soc. Presence Res.* 45–56.
- Kothgassner, O.D., Goreis, A., Glenk, L.M., Kafka, J.X., Beutl, L., Kryspin-Exner, I., Hlavacs, H., Palme, R., Felnhofner, A., 2021. Virtual and real-life ostracism and its impact on a subsequent acute stressor. *Physiol. Behav.* 228. <https://doi.org/10.1016/j.physbeh.2020.113205>.
- Kraft, P., Kraft, B., 2021. Explaining socioeconomic disparities in health behaviours: a review of biopsychological pathways involving stress and inflammation. *Neurosci. Biobehav. Rev.* 127, 689–708. <https://doi.org/10.1016/j.neubiorev.2021.05.019>.
- Kraus, M.W., Piff, P.K., Keltner, D., 2009. Social class, sense of control, and social explanation. *J. Pers. Soc. Psychol.* 97, 992–1004. <https://doi.org/10.1037/a0016357>.
- Kroll, S.L., Williams, D.W.P., Thoma, M., Staib, M., Binz, T.M., Baumgartner, M.R., Kirschbaum, C., Thayer, J.F., Quednow, B.B., 2019. Non-medical prescription opioid users exhibit dysfunctional physiological stress responses to social rejection. *Psychoneuroendocrinology* 100, 264–275. <https://doi.org/10.1016/j.psyneuen.2018.09.023>.
- Laborde, S., Mosley, E., Thayer, J.F., 2017. Heart rate variability and cardiac vagal tone in psychophysiological research — recommendations for experiment planning, data analysis, and data reporting. *Front. Psychol.* 8, 1–18. <https://doi.org/10.3389/fpsyg.2017.00213>.
- Lê-Scherban, F., Brenner, A.B., Hicken, M.T., Needham, B.L., Seeman, T., Sloan, R.P., Wang, X., Diez Roux, A.V., 2018. Child and adult socioeconomic status and the cortisol response to acute stress: evidence from the Multi-Ethnic Study of Atherosclerosis. *Psychosom. Med.* 80, 184. <https://doi.org/10.1097/PSY.0000000000000543>.
- Lodhi, H.A., Peri-Okonny, P.A., Schesing, K., Phelps, K., Ngo, C., Evans, H., Arbieue, D., Price, A.L., Vernino, S., Phillips, L., Mitchell, J.H., Smith, S.A., Yano, Y., Das, S.R., Wang, T., Vongpatanasin, W., 2019. Usefulness of blood pressure variability indices derived from 24-hour ambulatory blood pressure monitoring in detecting autonomic failure. *J. Am. Heart Assoc.* 8. <https://doi.org/10.1161/JAHA.118.010161>.
- Lorant, V., Deliège, D., Eaton, W., Robert, A., Philippot, P., Anseau, M., 2003. Socioeconomic inequalities in depression: a meta-analysis. *Am. J. Epidemiol.* 157, 98–112.
- Macchia, L., 2023. Having less than others is physically painful: income rank and pain around the world. *Soc. Psychol. Personal. Sci.* <https://doi.org/10.1177/19485506231167928>.
- Madigan, A., Daly, M., 2023. Socioeconomic status and depressive symptoms and suicidality: the role of subjective social status. *J. Affect. Disord.* 326, 36–43. <https://doi.org/10.1016/j.jad.2023.01.078>.
- Maharani, A., Richards, L., Präg, P., 2024. Subjective social status and trajectories of frailty: findings from the English Longitudinal Study of Ageing. *BMJ Public Heal.* 2, e000629. <https://doi.org/10.1136/bmjph-2023-000629>.
- Mandelli, L., Milaneschi, Y., Hiles, S., Serretti, A., Penninx, B.W., 2022. Unhealthy lifestyle impacts on biological systems involved in stress response: hypothalamic-pituitary-adrenal axis, inflammation and autonomous nervous system. *Int. Clin. Psychopharmacol.* 38, 127. <https://doi.org/10.1097/YIC.0000000000000437>.
- Martins-Silva, T., Martins, R.C., Murray, J., Carvalho, A.M., Rickes, L.N., Corrêa, B. de F., Fraga, B.B., Brum, C.B., Freitas, D.F., Meyer, F.D.T., Carpena, M.X., Goularte, L.M., Gonzalez, de Oliveira, I.O., Tovo-Rodrigues, L., 2025. Hair cortisol measurement: a systematic review of current practices and a customized checklist for reporting standards. *Psychoneuroendocrinology* 171. <https://doi.org/10.1016/j.psyneuen.2024.107185>.
- Matthews, K.A., Gallo, L.C., Taylor, S.E., 2010. Are psychosocial factors mediators of socioeconomic status and health connections? A progress report and blueprint for the future. *Ann. N. Y. Acad. Sci.* 1186, 146–173. <https://doi.org/10.1111/j.1749-6632.2009.05332.x>.
- McEwen, B., 1998. Stress, adaptation, and disease. Allostasis and allostatic load. *Ann. N. Y. Acad. Sci.* 840, 33–44. <https://doi.org/10.1111/J.1749-6632.1998.TB09546.X>.

- Menuet, C., Ben-Tal, A., Linossier, A., Allen, A.M., Machado, B.H., Moraes, D.J.A., Farmer, D.G.S., Paterson, D.J., Mendelowitz, D., Lakatta, E.G., Taylor, E.W., Ackland, G.L., Zuckerman, I.H., Fisher, J.P., Schwaber, J.S., Shanks, J., Paton, J.F.R., Buron, J., Spyer, K.M., Shivkumar, K., Dutschmann, M., Joyner, M.J., Herrington, N., Grossman, P., McAllen, R.M., Ramchandra, R., Yao, S.T., Ritz, T., Gourine, A.V., 2025. Redefining respiratory sinus arrhythmia as respiratory heart rate variability: an international expert recommendation for terminological clarity. *Nat. Rev. Cardiol.* <https://doi.org/10.1038/s41569-025-01160-z>.
- Miller, G.E., Chen, E., Zhou, E.S., 2007. If it goes up, must it come down? Chronic stress and the hypothalamic-pituitary-adrenocortical axis in humans. *Psychol. Bull.* 133, 25–45. <https://doi.org/10.1037/0033-2909.133.1.25>.
- Mills, P.J., Dimsdale, J.E., 1993. The promise of adrenergic receptor studies in psychophysiological research II: applications, limitations, and progress. *Psychosom. Med.* 55, 448–458.
- Nater, U.M., Rohleder, N., 2009. Salivary alpha-amylase as a non-invasive biomarker for the sympathetic nervous system: current state of research. *Psychoneuroendocrinology* 34, 486–496. <https://doi.org/10.1016/j.psyneuen.2009.01.014>.
- Nater, U.M., Skoluda, N., Strahler, J., 2013. Biomarkers of stress in behavioural medicine. *Curr. Opin. Psychiatry* 26, 440–445. <https://doi.org/10.1097/YCO.0B013E328363B4ED>.
- Nobles, J., Weintraub, M.R., Adler, N.E., 2013. Subjective socioeconomic status and health: relationships reconsidered. *Soc. Sci. Med.* 82, 58–66. <https://doi.org/10.1016/j.socscimed.2013.01.021>.
- O'Brien, K.M., Meyer, J., Tronick, E., Moore, C.L., 2017. Hair cortisol and lifetime discrimination: moderation by subjective social status. *Health Psychol. Open* 4. <https://doi.org/10.1177/2055102917695176>.
- Obrist, P.A., 1981. Cardiovascular psychophysiology: a perspective. In: *Cardiovascular Psychophysiology*. Plenum Press, New York. <https://doi.org/10.1007/978-1-4684-8491-5>.
- O'Connor, D.B., Thayer, J.F., Vedhara, K., 2021. Stress and health: a review of psychobiological processes. *Annu. Rev. Psychol.* 72, 663–688. <https://doi.org/10.1146/ANNUREV-PSYCH-062520-122331>.
- O'Leary, D., Uysal, A., Rehkopf, D.H., Gross, J.J., 2021. Subjective social status and physical health: the role of negative affect and reappraisal. *Soc. Sci. Med.* 291, 114272. <https://doi.org/10.1016/j.socscimed.2021.114272>.
- Olivieri, F., Biscetti, L., Pimpini, L., Pelliccioni, G., Sabbatinelli, J., Giunta, S., 2024. Heart rate variability and autonomic nervous system imbalance: potential biomarkers and detectable hallmarks of aging and inflammaging. *Ageing Res. Rev.* 101. <https://doi.org/10.1016/j.arr.2024.102521>.
- Oparil, S., Acelajado, M.C., Bakris, G.L., Berlowitz, D.R., Cifková, R., Dominiczak, A.F., Grassi, G., Jordan, J., Poulter, N.R., Rodgers, A., Whelton, P.K., 2018. Hypertension. *Nat. Rev. Dis. Prim.* 41 (4), 1–21. <https://doi.org/10.1038/nrdp.2018.14>.
- Orini, M., van Duijvenboden, S., Young, W.J., Ramirez, J., Jones, A.R., Hughes, A.D., Tinker, A., Munroe, P.B., Lambiase, P.D., 2023. Long-term association of ultra-short heart rate variability with cardiovascular events. *Sci. Rep.* 13. <https://doi.org/10.1038/s41598-023-45988-2>.
- Packard, A.E.B., Egan, A.E., Ulrich-Lai, Y.M., 2016. HPA axis interactions with behavioral systems. *Compr. Physiol.* 6, 1897–1934. <https://doi.org/10.1002/CPHY.C150042>.
- Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 372. <https://doi.org/10.1136/bmj.n71>.
- Pampel, F.C., Krueger, P.M., Denney, J.T., 2010. Socioeconomic disparities in health behaviors. *Annu. Rev. Sociol.* 36, 349–370. <https://doi.org/10.1146/annurev.soc.012809.102529>.
- Peterson, L.M., Stock, M.L., Monroe, J., Molloy-Paolillo, B.K., Lambert, S.F., 2020. Racial exclusion causes acute cortisol release among emerging-adult African Americans: the role of reduced perceived control. *J. Soc. Psychol.* 160, 658. <https://doi.org/10.1080/00224545.2020.1729685>.
- Pham, M.T., Rajić, A., Greig, J.D., Sargeant, J.M., Papadopoulos, A., Mcewen, S.A., 2014. A scoping review of scoping reviews: advancing the approach and enhancing the consistency. *Res. Synth. Methods* 5, 371–385. <https://doi.org/10.1002/JRSM.1123>.
- Pickett, K.E., Wilkinson, R.G., 2010. Inequality: an underacknowledged source of mental illness and distress. *Br. J. Psychiatry* 197, 426–428. <https://doi.org/10.1192/bjp.bp.109.072066>.
- Pickett, K.E., Wilkinson, R.G., 2015. Income inequality and health: a causal review. *Soc. Sci. Med.* 128, 316–326. <https://doi.org/10.1016/j.socscimed.2014.12.031>.
- Pieritz, K., Schäfer, S.J., Strahler, J., Rief, W., Euteneuer, F., 2017. Chronic stress moderates the impact of social exclusion on pain tolerance: an experimental investigation. *J. Pain Res.* 10. <https://doi.org/10.2147/JPR.S129872>.
- Pilz, N., Patzak, A., Bothe, T.L., 2023. The pre-ejection period is a highly stress dependent parameter of paramount importance for pulse-wave-velocity based applications. *Front. Cardiovasc. Med.* 10, 1138356. <https://doi.org/10.3389/fcvm.2023.1138356/FULL>.
- Prall, S.P., Larson, E.E., Muehlenbein, M.P., 2017. The role of dehydroepiandrosterone on functional innate immune responses to acute stress. *Stress. Health* 33, 656–664. <https://doi.org/10.1002/smi.2752>.
- Prendergast, C.N., Schubert, T., 2020. Investigating reflexive responses to explicit and implicit forms of social exclusion using immersive virtual environment technology. *Front. Psychol.* 11, 2693. <https://doi.org/10.3389/fpsyg.2020.575783/BIBTEX>.
- Pruessner, J.C., Wolf, O.T., Hellhammer, D.H., Buske-Kirschbaum, A., Von Auer, K., Jobst, S., Kaspers, F., Kirschbaum, C., 1997. Free cortisol levels after awakening: a reliable biological marker for the assessment of adrenocortical activity. *Life Sci.* 61, 2539–2549. [https://doi.org/10.1016/S0024-3205\(97\)01008-4](https://doi.org/10.1016/S0024-3205(97)01008-4).
- Pulopulos, M.M., Puig-Perez, S., Hidalgo, V., Villada, C., Salvador, A., 2016. Cortisol awakening response and walking speed in older people. *PLoS One* 11, 1–12. <https://doi.org/10.1371/journal.pone.0152071>.
- Radke, S., Seidel, E.M., Boubela, R.N., Thaler, H., Metzler, H., Kryspin-Exner, I., Moser, E., Habel, U., Dertl, B., 2018. Immediate and delayed neuroendocrine responses to social exclusion in males and females. *Psychoneuroendocrinology* 93, 56–64. <https://doi.org/10.1016/j.psyneuen.2018.04.005>.
- Rahal, D., Chiang, J.J., Bower, J.E., Irwin, M.R., Venkatraman, J., Fuligni, A.J., 2020. Subjective social status and stress responsibility in late adolescence. *Stress* 23, 50–59. <https://doi.org/10.1080/10253890.2019.1626369>.
- Reitzel, L.R., Nguyen, N., Strong, L.L., Wetter, D.W., McNeill, L.H., 2013. Subjective social status and health behaviors among African Americans. *Am. J. Health Behav.* 37, 104–111. <https://doi.org/10.5993/AJHB.37.1.12>.
- Ring, M., 2025. An integrative approach to HPA axis dysfunction: from recognition to recovery. *Am. J. Med.* <https://doi.org/10.1016/j.amjmed.2025.05.044>.
- Rinne, G.R., Hartstein, J., Guardino, C.M., Dunkel Schetter, C., 2023. Stress before conception and during pregnancy and maternal cortisol during pregnancy: a scoping review. *Psychoneuroendocrinology* 153. <https://doi.org/10.1016/j.psyneuen.2023.106115>.
- Ryan, M., Gallagher, S., Jetten, J., Muldoon, O.T., 2022. State level income inequality affects cardiovascular stress responses: evidence from the Midlife in the United States (MIDUS) study. *Soc. Sci. Med.* 311. <https://doi.org/10.1016/j.socscimed.2022.115359>.
- Sagioglou, C., Hommerich, C., 2024. Perceived social exclusion partially accounts for social status effects on subjective well-being: a comparative study of Japan, Germany, and the United States. *Appl. Res. Qual. Life* 19, 1337–1363. <https://doi.org/10.1007/s11482-024-10285-1/FIGURES/2>.
- Sanz, J., Maurizio, P.L., Snyder-Mackler, N., Simons, N.D., Voyles, T., Kohn, J., Michopoulos, V., Wilson, M., Tung, J., Barreiro, L.B., 2020. Social history and exposure to pathogen signals modulate social status effects on gene regulation in rhesus macaques. *Proc. Natl. Acad. Sci. USA* 117, 23317–23322. https://doi.org/10.1073/PNAS.1820846116/SUPPL_FILE/PNAS.1820846116.SD03.XLSX.
- Sapolsky, R.M., 2005. The influence of social hierarchy on primate health. *Science* 308, 648–652. <https://doi.org/10.1126/SCIENCE.1106477>.
- Schneider, S.M., 2019. Why income inequality is dissatisfying — perceptions of social status and the inequality-satisfaction link in Europe. *Eur. Sociol. Rev.* 35, 409–430. <https://doi.org/10.1093/esr/jcz003>.
- Scholasko, L., Wadhwa, P.D., Entringer, S., 2021. Acculturation and biological stress markers: a systematic review. *Psychoneuroendocrinology* 132. <https://doi.org/10.1016/j.psyneuen.2021.105349>.
- Scott, K.M., Al-Hamzawi, A.O., Andrade, L.H., Borges, G., Caldas-de-Almeida, J.M., Fiestas, F., Gureje, O., Hu, C., Karam, E.G., Kawakami, N., Lee, S., Levinson, D., Lim, C.C.W., Navarro-Mateu, F., Okoliyski, M., Posada-Villa, J., Torres, Y., Williams, D.R., Zakhohza, V., Kessler, R.C., 2014. Associations between subjective social status and DSM-IV mental disorders: results from the world mental health surveys. *JAMA Psychiatry* 71, 1400–1408. <https://doi.org/10.1001/jamapsychiatry.2014.1337>.
- Seery, M.D., 2011. Challenge or threat? Cardiovascular indexes of resilience and vulnerability to potential stress in humans. *Neurosci. Biobehav. Rev.* 35, 1603–1610. <https://doi.org/10.1016/j.neubiorev.2011.03.003>.
- Seidel, E.M., Silani, G., Metzler, H., Thaler, H., Lamm, C., Gur, R.C., Kryspin-Exner, I., Habel, U., Dertl, B., 2013. The impact of social exclusion vs. inclusion on subjective and hormonal reactions in females and males. *Psychoneuroendocrinology* 38, 2925–2932. <https://doi.org/10.1016/j.psyneuen.2013.07.021>.
- Shaffer, F., Ginsberg, J.P., 2017. An overview of heart rate variability metrics and norms. *Front. Public Health* 5, 258. <https://doi.org/10.3389/fpubh.2017.00258>.
- Shahrestani, S., Stewart, E.M., Quintana, D.S., Hickie, I.B., Guastella, A.J., 2015. Heart rate variability during adolescent and adult social interactions: a meta-analysis. *Biol. Psychol.* 105, 43–50. <https://doi.org/10.1016/j.biopsycho.2014.12.012>.
- Shively, C.A., 1998. Social subordination stress, behavior, and central monoaminergic function in female cynomolgus monkeys. *Biol. Psychiatry* 44, 882–891. [https://doi.org/10.1016/S0006-3223\(97\)00437-X](https://doi.org/10.1016/S0006-3223(97)00437-X).
- Singh-Manoux, A., Marmot, M.G., Adler, N.E., 2005. Does subjective social status predict health and change in health status better than objective status? *Psychosom. Med.* 67, 855–861. <https://doi.org/10.1097/01.psy.0000188434.52941.a0>.
- Slavich, G.M., O'Donovan, A., Epel, E.S., Kemeny, M.E., 2010. Black sheep get the blues: a psychobiological model of social rejection and depression. *Neurosci. Biobehav. Rev.* 35, 39. <https://doi.org/10.1016/j.neubiorev.2010.01.003>.
- Snyder-Mackler, N., Sanz, J., Kohn, J.N., Brinkworth, J.F., Morrow, S., Shaver, A.O., Grenier, J.C., Pique-Regi, R., Johnson, Z.P., Wilson, M.E., Barreiro, L.B., Tung, J., 2016. Social status alters immune regulation and response to infection in macaques. *Science* 354, 1041–1045. <https://doi.org/10.1126/SCIENCE.AAH35580>.
- Stepptoe, A., Serwinski, B., 2016. Cortisol awakening response. In: Fink, G. (Ed.), *Tress: Concepts, Cognition, Emotion, and Behavior*. Academic, London, pp. 277–283.
- Stewart, N., Chater, N., Brown, G.D.A., 2006. Decision by sampling. *Cogn. Psychol.* 53, 1–26. <https://doi.org/10.1016/j.cogpsy.2005.10.003>.
- Tan, J.J.X., Tan, C.H., Kraus, M.W., 2024. Subjective socioeconomic status moderates how resting heart rate variability predicts pain response. *Affect. Sci.* 5, 1–8. <https://doi.org/10.1007/s42761-023-00234-w>.
- Tang, K.L., Rashid, R., Godley, J., Ghali, W.A., 2016. Association between subjective social status and cardiovascular disease and cardiovascular risk factors: a systematic review and meta-analysis. *BMJ Open* 6, e010137. <https://doi.org/10.1136/bmjopen-2015-010137>.

- Tricco, A.C., Lillie, E., Zarin, W., O'Brien, K.K., Colquhoun, H., Levac, D., Moher, D., Peters, M.D.J., Horsley, T., Weeks, L., Hempel, S., Akl, E.A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M.G., Garritty, C., Lewin, S., Godfrey, C.M., MacDonald, M.T., Langlois, E.V., Soares-Weiser, K., Moriarty, J., Clifford, T., Tunçalp, Ö., Straus, S.E., 2018. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. *Ann. Intern. Med.* 169, 467–473. <https://doi.org/10.7326/M18-0850>.
- Tsuji, H., Larson, M.G., Venditti, F.J., Manders, E.S., Evans, J.C., Feldman, C.L., Levy, D., 1996. Impact of reduced heart rate variability on risk for cardiac events. The Framingham Heart Study. *Circulation* 94, 2850–2855. <https://doi.org/10.1161/01.CIR.94.11.2850>.
- Tung, J., Barreiro, L.B., Johnson, Z.P., Hansen, K.D., Michopoulos, V., Toufexis, D., Michelini, K., Wilson, M.E., Gilad, Y., 2012. Social environment is associated with gene regulatory variation in the rhesus macaque immune system. *Proc. Natl. Acad. Sci. USA* 109, 6490–6495. <https://doi.org/10.1073/PNAS.1202734109>.
- Vogelzangs, N., Beekman, A.T.F., Milaneschi, Y., Bandinelli, S., Ferrucci, L., Penninx, B. W.J.H., 2010. Urinary cortisol and six-year risk of all-cause and cardiovascular mortality. *J. Clin. Endocrinol. Metab.* 95, 4959–4964. <https://doi.org/10.1210/JC.2010-0192>.
- Weik, U., Ruhweza, J., Deinzer, R., 2017. Reduced cortisol output during public speaking stress in ostracized women. *Front. Psychol.* 8. <https://doi.org/10.3389/FPSYG.2017.00060>.
- Weiss, D., Weiss, M., 2016. The interplay of subjective social status and essentialist beliefs about cognitive aging on cortisol reactivity to challenge in older adults. *Psychophysiology* 53, 1256–1262. <https://doi.org/10.1111/PSYP.12667>.
- Wetherall, K., Robb, K.A., O'Connor, R.C., 2019. Social rank theory of depression: a systematic review of self-perceptions of social rank and their relationship with depressive symptoms and suicide risk. *J. Affect. Disord.* 246, 300–319. <https://doi.org/10.1016/j.jad.2018.12.045>.
- Williams, A.C., Cundiff, J.M., O'Neill, R.M., Garrison, K.E., Boylan, J.M., 2025. Perceived social rank and physiology: a meta-analysis of experimental manipulations. *Health Psychol.* 44. <https://doi.org/10.1037/HEA0001493>.
- Williams, K.D., 2007. Ostracism: the kiss of social death. *Soc. Personal. Psychol. Compass* 1, 236–247. <https://doi.org/10.1111/j.1751-9004.2007.00004.x>.
- Wright, C.E., Steptoe, A., 2005. Subjective socioeconomic position, gender and cortisol responses to waking in an elderly population. *Psychoneuroendocrinology* 30, 582–590.
- Zapater-Fajarf, M., Crespo-Sanmiguel, I., Pérez, V., Hidalgo, V., Salvador, A., 2022. Subjective Memory Complaints in young and older healthy people: importance of anxiety, positivity, and cortisol indexes. *Pers. Individ. Differ.* 197. <https://doi.org/10.1016/j.paid.2022.111768>.
- Zapater-Fajarf, M., Crespo-Sanmiguel, I., Montoliu, T., Hidalgo, V., Salvador, A., 2024. Hair cortisol and dehydroepiandrosterone and their associations with optimism and pessimism in older people. *Horm. Behav.* 159, 105474. <https://doi.org/10.1016/j.yhbeh.2023.105474>.
- Zell, E., Strickhouser, J.E., Krizan, Z., 2018. Subjective social status and health: a meta-analysis of community and society ladders. *Health Psychol.* 37, 979–987. <https://doi.org/10.1037/hea0000667>.
- Zhang, Y., Agnoletti, D., Blacher, J., Safar, M.E., 2012. Blood pressure variability in relation to autonomic nervous system dysregulation: the X-CELLENT study. *Hypertens. Res.* 35, 399–403. <https://doi.org/10.1038/HR.2011.203>.
- Zwolinski, J., 2012. Psychological and neuroendocrine reactivity to ostracism. *Aggress. Behav.* 38, 108–125. <https://doi.org/10.1002/AB.21411>.