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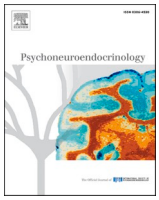

Adult age differences in the psychophysiological response to acute stress

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ABSTRACT

Age-related differences in the psychophysiology of the acute stress response are poorly understood given the limited number of studies and the high heterogeneity of findings. The present study contributes by investigating age differences in both the psychological and physiological responses to acute stress in a sample of healthy younger ($N = 50$; 18–30; $M_{age} = 23.06$; $SD = 2.90$) and older adults ($N = 50$; 65–84; $M_{age} = 71.12$; $SD = 5.02$). Specifically, the effects of psychosocial stress (i.e., age-adapted Trier Social Stress Test) were investigated at numerous timepoints throughout the stress response phases (i.e., baseline, anticipation, reactivity, recovery) on cortisol, heart rate, subjective stress, and anticipatory appraisal of the stressful situation. The study was conducted in a between-subject (younger vs. older) cross-over (stress vs. control) design. Results revealed age-related differences in both physiological and psychological variables: older adults had overall lower salivary cortisol levels in the stress and control conditions and lower stress-induced cortisol increase (i.e., AUCi). In addition, older adults' cortisol reactivity was delayed compared to younger adults. Older adults showed a lower heart rate response in the stress condition while no age differences were observed in the control condition. Finally, older adults reported less subjective stress and a less negative stress appraisal during the anticipation phase than younger adults, which could potentially explain lower physiological reactivity in this age group. Results are discussed in relation to the existing literature, potential underlying mechanisms, and future directions for the field.

1. Introduction

Adult age differences in response to acute psychosocial stress are currently poorly understood and establishing aging-related patterns in the stress response remains a major interdisciplinary challenge at the intersection of psychology, biology, and gerontology. Moreover, complex psychological, physiological, and neuroendocrine changes occur when the stress system is activated, composed of the sympathetic-adreno-medullar (SAM) axis and the hypothalamus-pituitary-adrenal (HPA) axis (Godoy et al., 2018). A systematic review showed that both exaggerated and blunted stress reactivity (of both the SAM and the HPA axes) were related to negative health outcomes such as risk factors for cardiovascular disease, shortening of telomeres, depression, anxiety, post-traumatic stress disorder symptoms, and reduced cognitive ability over time (Turner et al., 2020). Hence, examining stress reactivity in older age might help better understand health-related risk factors that are commonly associated with aging (e.g., cardiovascular disease, cognitive decline; Chida and Steptoe, 2010).

Past research suggested that the stress response in late adulthood may differ from young adulthood for several reasons. Firstly, normal changes in the brain and body including the SAM and HPA axes occur with aging, resulting in changes in both adrenocorticotropin and cortisol

Abbreviations: TSST, Trier Social Stress Test.

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secretion (Moffat et al., 2020; Yiallouris et al., 2019). Secondly, it is thought that a dysregulated diurnal cortisol secretion (e.g., high cortisol levels or flatter diurnal cortisol slope) in advanced age might also affect the normal endocrinological stress response (Aguilera, 2011; Gaffey et al., 2016; Pulopulos et al., 2018). Understanding aging-related differences in the stress response is important not only because it sheds light on the complex interaction between aging and stress but also because it carries significant clinical implications for stress-related disorders in older age. However, trajectories of health and function in late adulthood can vary significantly depending on the individual, and so far, empirical evidence regarding age-related differences in the stress response has been highly heterogeneous and inconclusive.

Regarding the cortisol response to acute psychosocial stress, older adults (compared to younger adults) have shown increased (Almela et al., 2011; Gotthardt et al., 1995; Kudielka et al., 2004a; Traustadóttir et al., 2005), similar (Crosswell et al., 2021; Kudielka et al., 2000; Schnitzspahn et al., 2022) or decreased (Hidalgo et al., 2015; Nicolson et al., 1997) cortisol reactivity. Participants' sex, stressor severity, or medication intake are known moderating factors (see Dickerson and Kemeny, 2004), but they do not fully explain these divergent results. In addition, the number of cortisol measurements pre-and post-stress induction widely varies between studies. More fine-grained cortisol measurements in younger and older adults could provide valuable insights into age differences in the temporal dynamics of cortisol reactivity, which has not yet been systematically investigated in the present literature.

There are many ways to assess the SAM response (Greene et al., 2016). For instance, when using indices of autonomic cardiovascular reactivity such as heart rate (HR) to inform about the SAM response, older adults (compared to younger) typically show decreased HR reactivity in response to psychosocial stress (Brindle et al., 2014; Strahler et al., 2010; Traustadóttir et al., 2005). This can be explained by the aging of the cardiovascular system which results in, among others, limited maximum HR and autonomic sensitivity due to decreases in sympathetic nervous system intracellular signaling and responsiveness (Lakatta, 1993). This is in line with a meta-analysis (Brindle et al., 2014) showing that advanced age was associated with decreased sympathetic activation under stress, mirrored by a decrease in HR reactivity with increasing age.

Despite an extensive literature on affective aging showing that younger and older adults differ in their expectations and interpretations of emotional situations (for reviews, see Carstensen et al., 2011; Young et al., 2021a), studies on acute stress do not typically find age-related differences in subjective stress measures nor cognitive appraisal (Crosswell et al., 2021; Hidalgo et al., 2015; Kudielka et al., 2000; Strahler et al., 2010). Thus, although frameworks on affective aging predict age-related differences in the evaluation of a stressor (see Lazarus and DeLongis, 1983;Young et al., 2021a), they are rarely investigated in the laboratory and supported by empirical data. Using an age-adapted version of the widely used Trier Social Stress Test (TSST, Kirschbaum et al., 1993), one study has shown that older adults appraised the TSST as less stressful than younger adults (Schnitzspahn et al., 2022).

Taken together, past research investigating SAM reactivity showed decreased HR in older (vs. younger) adults, but studies investigating age-related differences in HPA and psychological reactivity in response to psychosocial stress produced mixed findings. However, the existing literature is limited by several methodological shortcomings. Firstly, there are different ways to measure psychophysiological reactivity (e.g., cortisol, HR, self-report assessments) and they greatly vary between studies in acute stress and aging. Moreover, many studies only focus on the physiological age differences (i.e., cortisol, HR), thereby lacking an integrative perspective on age-related differences in psychological stress reactivity. Furthermore, most studies do not sufficiently provide insight into age differences in the temporal dynamics of the stress response (i.e., baseline, anticipation, reactivity, recovery). For instance, Strahler and colleagues (2010) found that cortisol's maximum level peaked later in older (vs. young) adults, but Kudielka and colleagues (2004a) did not find this difference. Finally, previous studies often did not compare reactivity to a stress induction with a control condition (e.g., Kudielka et al., 2004a, 2004b; Strahler et al., 2010; Traustadóttir et al., 2005) and without a control condition, potential age differences cannot be attributed specifically to the stressor (see Discussion in Lai, 2014).

Thus, currently, comparison between studies and, ultimately, an integrated understanding of age-related differences in psychophysiological reactivity to psychosocial stress is limited. Therefore, the present study aims to address these limitations by employing an integrative approach assessing the temporal dynamics of cortisol, HR, and subjective stress, as well as the anticipatory stress appraisal, in a sample of younger and older adults in response to both the TSST and a control condition. Importantly, the mean age of the older group was higher than in previous studies (e.g., Crosswell et al., 2021; Kudielka et al., 2004a; Strahler et al., 2010), thereby providing new insights on stress reactivity in more advanced age. Additionally, given that sex is an established modulating factor (for review see Pulopulos et al., 2018), a similar number of men and women was included in the two age groups and sex-related differences were taken into account.

Based on previous research, older adults were expected to show either increased or unchanged cortisol and decreased HR in response to acute psychosocial stress compared to younger adults. Based on the affective aging literature (e.g., Carstensen et al., 2011), older adults were expected to report a lower stress appraisal of the TSST than younger adults.

2. Method

2.1. Design and participants

The study used a between-subject (younger vs. older) cross-over (stress vs. control) design. Participants either started with the TSST or control condition in a counterbalanced order (randomly assigned). At the second testing time (2–3 weeks later), they performed the respective other condition. Data collection took place from October 2020 to April 2022 (see Supplementary Materials S1). The study was approved by the Cantonal Ethics Committee of Geneva. Participants received 100 CHF for their participation.

106 participants were recruited through advertisements in the Geneva community. Younger adults were mostly students across multiple disciplines. Older adults were community-dwelling older adults. Five older adults dropped out of the study and an additional one was excluded a posteriori due to a health condition (see exclusion criteria below). The sample size was a priori determined for a mixed ANOVA (within-between interaction) with G-Power3.1 ($N = 90, f^2 = 0.25$, power ≥ 0.95 and $\alpha = 0.05$). The final sample was composed of 100 healthy participants, 50 younger ($M = 23.06$; 18–30; $SD = 2.90$) and 50 older adults ($M = 71.12$; 65–84; $SD = 5.02$). In total, 20 younger women were in the follicular phase during the control condition, and 18 were in the luteal phase in the stress condition (see Table 1 for further details). All older women were in advanced post-menopause (i.e., > 4 years without menstruation). Further sociodemographic information is presented in

Table 1
Descriptives of Menstrual Phase for Each Condition in Younger Women.

Start with	Menstrual phase (Control)	Menstrual phase (Stress)	*N*
Control	Follicular	Follicular	1
		Luteal	13
	Luteal	Follicular	2
		Luteal	0
Stress	Follicular	Follicular	2
		Luteal	4
	Luteal	Follicular	2
		Luteal	1

Table 2
Descriptive Statistics (mean ± SD) and Age Differences of Younger and Older Adults.

Variables	Younger adults (N = 50)	Older adults (N = 50)	t-value	p-value
Age (years)	23.06 (2.90)	71.12 (5.02)	58.56	< 0.001
Education (years)	17.52 (2.23)	16.43 (4.72)	-1.47	0.147
Medication (number)	0.06 (0.24)	1.06 (1.39)	5.01	< 0.001

Note. For all variables, Levene's test was significant ($p < .001$), suggesting a violation of the equal variance assumption. Application of Welch's t-test for all age comparisons.

Table 2 and S2. The two age groups differed in the number of medication intake but not in years of education.

Participants were included if they were 18–30 years or ≥ 65 years old and retired, healthy, and French-speaking. Exclusion criteria included prior experience with the TSST, general anesthesia in the past three months, body mass index > 35, pregnant or lactating women, use of hormonal contraceptives or hormone replacement therapy, complete hysterectomy, diabetes, non-corrected visual or hearing problems, psychiatric diagnosis, drug abuse, presence of a stressful life event during the past 3 months. Given the high prevalence of hypertension in older adults (Bowling et al., 2021), anti-hypertensive or preventive medication in this age group was allowed (see inclusion criteria in Pulopulos et al., 2015), while any psychiatric medication and beta-blockers were not. In addition, for older adults, the French version of the Telephone Interview of Cognitive Status Status (F-TICS-m; Vercambre et al., 2010) was used as a screening instrument for cognitive impairments. The F-TICS includes questions regarding temporal and spatial orientation, recall of word lists to evaluate memory, questions evaluating semantic memory, and language. The maximum total score is 43; in line with the cut-off provided by the test authors, only participants who scored > 27 on the F-TICS-m were included in the study.

Before each testing session, participants had to refrain from intense physical activity (48 h before) and physical activity during the day of the session, and alcohol consumption (24 h before). In addition, one hour before the laboratory session, participants had to refrain from brushing their teeth and/or using dental floss, eating, or drinking (except water), smoking, or consuming stimulants (e.g., caffeine) as part of the upcoming saliva sampling procedure (see Narvaez Linares et al., 2020).

2.2. Procedure

Potential participants completed an online screening with questions relating to the inclusion and exclusion criteria to verify their eligibility, and, at a second stage, eligible older adults were administered the F-TICS-m over the phone.[1]

Fig. 1 shows a timeline of the two laboratory sessions that took place either 14–16 h or 16–18 h depending on participants' availability. A repeated measures ANOVA showed that the average starting time of the testing session did not differ between age groups ($F(1, 98) = 0.00$, $p = .980$), conditions ($F(1, 98) = 3.05$, $p = .084$), nor for the interaction between the two ($F(1, 98) = 0.00$, $p = .960$). Upon arrival, inclusion criteria specific to each testing session (see above) were verified by the experimenter and the HR bracelet was put on the upper left arm of the participants. HR was measured continuously throughout the testing session and then chunked into 5-min epochs (see 2.3.1.2. below). Next, participants filled out the demographic questionnaire (see S2 for complete information) and (when applicable) the menstrual/menopausal questionnaires. Younger women were asked to report the first day of their last period and older women were asked to report the number of years since the end of their menopause (see recommendations by Narvaez Linares et al., 2020). Then, participants provided the baseline samples for salivary cortisol, HR, and subjective stress measures. They were then introduced to the TSST/control instructions, received 5 min to prepare their speech, and completed the appraisal questionnaire (PASA, see below) just before giving the oral presentation in front of the TSST jury/alone. At + 30 min and + 40 min, the participants performed two different cognitive tasks (results will be reported elsewhere).

2.2.1. Experimental induction of acute stress

Acute social stress was induced using the TSST (Kirschbaum et al., 1993). The TSST consists of three phases of five min each: preparation, oral presentation, and mental arithmetic task (i.e., 2043–17 - 17 -.). Importantly, the script of the oral presentation was adapted for older adults. Instead of imagining applying for their dream job (i.e., instructions for younger adults), older adults had to provide argumentation for being the best candidate for a volunteering job at a club or charity group implicated in a subject that was dear to their hearts. Since the TSST was initially developed for use with younger adults, adapting the content of the oral presentation to a context that is relevant, hence valid, to older adults has been shown to successfully induce stress in older adults and is in line with previous studies using the TSST with this population (e.g., Crosswell et al., 2021; Oei et al., 2018; Schnitzspahn et al., 2022). The speech and arithmetic tasks took place in front of a camera and a jury of two experimenters (one woman, one man) wearing lab coats and keeping a strictly neutral demeanor toward the participant.

The so-called 'Placebo' version of the TSST was used as a validated control condition (Het et al., 2009). It is similar to the TSST but lacks the stressful features of the protocol (i.e., no camera, no jury). Additionally, instead of the mock job interview, the participant presents a book, trip, or movie of their choice alone in the room. The arithmetic task is replaced by simple additions (i.e., 15 +15 +15).

2.3. Measures

2.3.1. Physiological stress measures

2.3.1.1. Salivary cortisol. Saliva samples were collected using Salivettes (Sarstedt, Switzerland). Participants had to keep a cotton swab in their mouths for two minutes. Saliva samples were taken before presenting the TSST/control instructions (0 min); at the end of the anticipation phase (+10 min); at the end of the TSST / control (+20 min); before, after, and between the two cognitive tasks (+30 to +50 min); twice during recovery period (+60, +75 min, see Fig. 1). Thus, each participant contributed 16 samples in total (eight per condition). Details regarding biochemical assay are provided in S3.

2.3.1.2. Heart rate. HR was continuously monitored throughout the laboratory session starting at − 10 min using Scosche Rhythm24™, a wearable HR bracelet, and recorded using an iOS app (Heart Rate Variability Logger, Marco Altini). Average HR was calculated in epochs of 5 min for each stress-relevant phase[2] (i.e., baseline, anticipation, middle of the stress/control induction, immediately post-stress induction, and 10 min after offset, see Fig. 1).

2.3.2. Psychological stress measures

2.3.2.1. Subjective stress. Using a one-item Visual Analogue Scale (VAS), participants were asked 'How stressed are you feeling right now

[1] As part of a different research question not investigated here, before each visit, participants received a telephone call to encode a narrative memory task.

[2] Baseline = −5 to 0 min; Anticipation = 5–10 min; Stress/Control induction = 10–15 min; Post-TSST = 21–26 min; Post-TSST + 10 min = 26–31 min

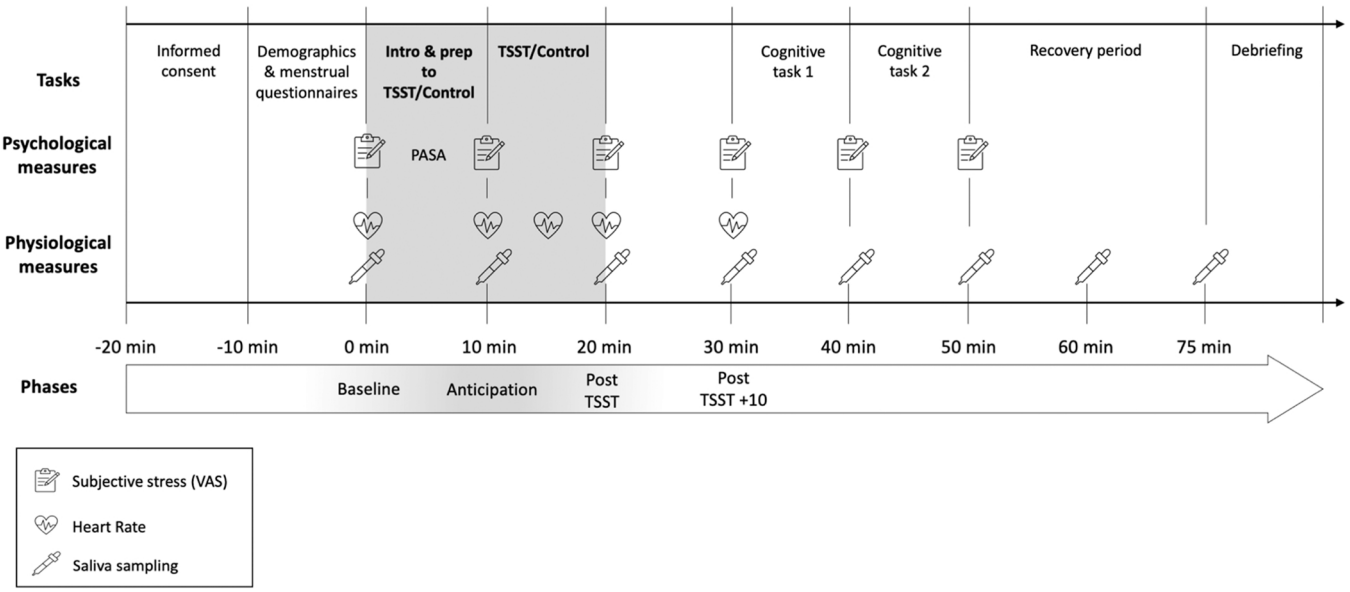

Fig. 1. Exemplary Timeline of the Laboratory Session. *Note.* TSST: Trier Social Stress Test; PASA: Primary Appraisal and Secondary Appraisal; VAS: Visual Analogue Scale.

on a continuum from 0 to 100?' at different timepoints throughout the session (see Fig. 2C); with high scores representing higher levels of subjective stress. Except for the last two timepoints, subjective stress assessments coincided with salivary cortisol sampling (i.e., six assessments).

2.3.2.2. Primary and secondary appraisal. The primary and secondary appraisal (PASA) questionnaire was used to measure anticipatory appraisal of the stress and control situations (Gaab et al., 2005). The questionnaire consisted of 16 items rated on a 6-point Likert scale (from 1 = 'Strongly disagree' to 6 = 'Strongly agree'). In total, four subscales were assessed: 'Threat', 'Challenge', 'Self-concept of own abilities', and 'Control expectancy'.[3] Their scores were composed of the average score of the respective four items, with higher scores representing higher appraisal on that subscale. Moreover, the PASA allows computing of a difference score called 'Stress index' by subtracting primary appraisal ('Threat' and 'Challenge' subscales) from secondary appraisal ('Self--concept of own abilities', and 'Control expectancy' subscales) indicating how the two anticipatory appraisals relate to each other. The stress index was used as the primary outcome of the PASA, and higher scores represent a higher negative appraisal of stress.

2.4. Statistical analyses

Linear mixed models (LMMs) were used to analyze the effects of acute stress on cortisol concentrations, cortisol's AUCi,[4] HR, subjective stress scores, and appraisal scores (see Supplementary Materials S4-S8 for further details). Condition (TSST, control), age group (younger, older adults), sex (male, female), and time[5] were used as fixed effects and the subject as random intercept. Data were visually inspected to check LMMs assumptions using histograms, and cortisol was transformed using log10[6] (see Miller and Plessow, 2013). Raw data were used for AUCi and the remaining variables. Outliers that were ± 3 *SD* from the mean of each stress phase per age group and condition were removed from AUCi and HR data.

LMMs were performed in Jamovi (Version 2.3.3.0, jamovi, 2022) using the GAMLj module (Version 2.6.5, Gallucci, 2019) in conjunction with RStudio (Version 2022.7.1.554, RStudio, 2022). A step-down model-building approach was used to select the final model for each variable via the 'step' function[7] from the 'lmerTest' package in RStudio (Kuznetsova et al., 2017). Next, the final model of each variable was entered in Jamovi to perform simple effects analyzes (i.e., follow-up analyses). When the effect of the significant interactions was not apparent from simple effects analyses, difference-in-differences analysis was applied. Additionally, secondary analyses tested correlations between cortisol (AUCi and AUCg[8]) and psychological indices (subjective stress, PASA) in young and older adults (see S10) as well as correlations between age (continuous) and psychophysiological reactivity (cortisol, HR, subjective stress) in older adults (see S11). Retrospective power analyzes were later obtained for each LMM (see S12) using the SIMR R package (Green and MacLeod, 2016). The statistical significance level was set to $p < .05$.

3. Results

3.1. Cortisol

The LMM predicting cortisol levels revealed significant main effects of all factors: *condition* ($F(1, 1493.06) = 285.31$, $p < .001$), *age* ($F(1,$

[3] For the control condition of the TSST, the four items of the scale 'Control Expectancy' were altered or removed because of inappropriate wording. The word "interview'' was replaced by the word "situation'' and the mention "experts" was left out. In addition, two items (i.e., 4, 16) were excluded because of inappropriate content regarding the Placebo TSST ("It mainly depends on me whether I manage this situation successfully'' and "My success in this situation is a consequence of my effort and personal commitment'') as suggested by Gaab et al. (2005).

[4] Corresponds to cortisol's area under the curve with respect to increase. Calculated following Pruessner et al. (2003) formula.

[5] Not present in the analysis of the appraisal scores and AUCi.

[6] Performing the analyzes with raw instead of log cortisol data did not change the selection of the final model nor the LMM results.

[7] The 'step' function performs an automated backward elimination of the fixed effects (Kuznetsova et al., 2017). Supplementary materials (S4-S8) provide details regarding the models retained for each variable.

[8] Corresponds to cortisol's area under the curve with respect to the ground. Calculated following Pruessner et al. (2003) formula.

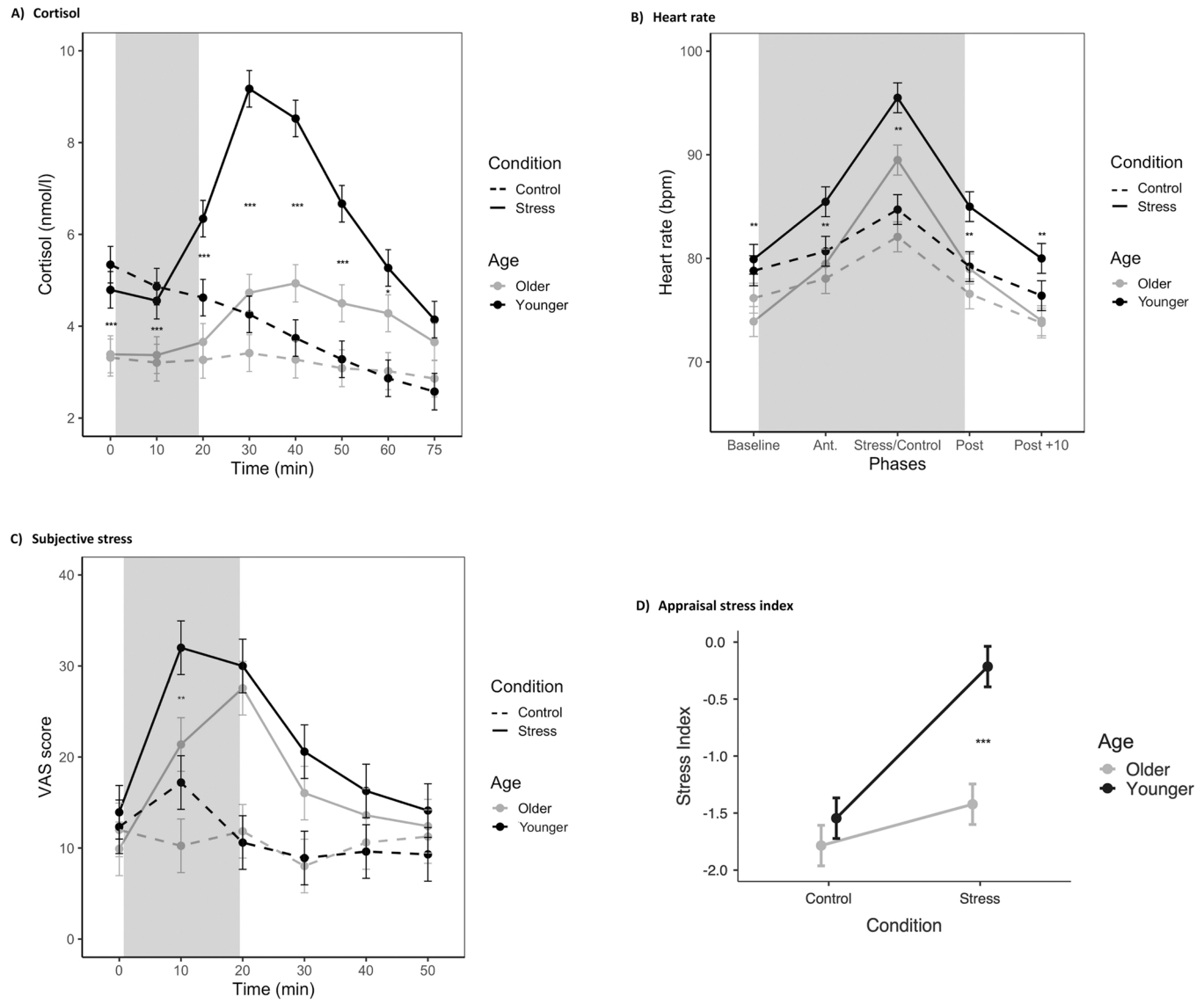

Fig. 2. Age Differences in Control vs. Stress Conditions for A) Cortisol Response, B) HR Response, C) Subjective Stress Response, and D) Appraisal Stress Index. *Note.* Error bars represent standard error. The shaded area represents the stress or control inductions. Significance is only reported for age differences in the stress condition: * $p < .05$, * * $p < .01$, * ** $p < .001$. Appraisal stress index = [(Threat + Challenge)/2 – (Self-concept + Control expectancies)/2].

100) = 15.86, $p < .001$), *sex* ($F(1, 100) = 26.87$, $p < .001$), and *time* ($F(7, 1493.06) = 26.58$, $p < .001$). Crucially, older and younger adults differed in their cortisol response over time in the stress vs. control condition (*condition x age x time*, $F(7, 1493.03) = 2.35$, $p = .022$), and all lower-order interactions were significant (*condition x age, condition x time, age x time*, all $ps < 0.005$).

Follow-up analyses probing the *condition x age x time* interaction (Fig. 2A) revealed that older adults showed lower baseline cortisol levels than younger adults in both the stress ($b = 0.17$, $SE = 0.05$, $t(287.81) = 3.62$, $p < .001$) and control condition ($b = 0.19$, $SE = 0.05$, $t(287.81) = 4.21$, $p < .001$). In the stress condition, age differences were present for all remaining timepoints (all $ps < 0.025$), except the last one (+75 min, $p = .099$). In the control condition, age differences were present until + 40 min (all $ps < 0.050$) but starting at + 50 min both age groups had similar cortisol levels (all $ps > 0.100$). Importantly, however, no baseline differences between the stress and control conditions were observed within each age group (younger: $b = -0.03$, $SE = 0.03$, $t(1493) = -1.13$, $p = .260$; older: $b = -0.01$, $SE = 0.03$, $t(1493) = -0.24$, $p = .814$). For both age groups, cortisol levels were higher for the stress (vs. control) condition starting from + 20 min until + 75 min (all $ps \leq 0.015$). Compared to their baseline levels in the stress condition, older adults' cortisol increased from + 30 to + 60 min (all $ps \leq 0.010$) and returned to baseline by + 75 min ($p = .560$), whereas younger adults' cortisol increased from + 20 to + 50 min (all $ps < 0.001$), returned to baseline by + 60 min ($p = .558$) and further decreased below baseline at + 75 min ($p = .019$). Conversely, compared to their baseline levels in the control condition, older adults' cortisol decreased significantly only starting from + 60 min onwards (both $ps < 0.050$), whereas younger adults' cortisol started decreasing from + 30 min onwards (all $ps < 0.015$ for subsequent timepoints).

In addition, *sex x condition* ($F(1, 1493.06) = 8.88$, $p = .003$), *sex x age* ($F(1, 100) = 10.95$, $p = .001$), and *sex x time* ($F(7, 1493.06) = 2.73$, $p = .008$) interaction effects were observed. Follow-up analyses probing the *sex x condition* interaction indicated that the effect of sex was significant in both conditions, with men showing higher cortisol levels than women, during both stress ($b = 0.20$, $SE = 0.04$, $t(110) = 5.70$, $p < .001$) and control ($b = 0.16$, $SE = 0.04$, $t(109.90) = 4.42$, $p < .001$). Moreover, men showed a larger cortisol response in stress vs. control compared to women in stress vs. control ($b = 0.05$, $SE = 0.02$, $t(1532) = 2.94$, $p = .003$). The *sex x age* interaction revealed that younger women

showed higher cortisol levels than older women ($b = 0.26$, $SE = 0.05$, $t(99.98) = 5.38$, $p < .001$), whereas no age differences were present in men ($b = 0.02$, $SE = 0.05$, $t(100.02) = 0.46$, $p = .648$). Furthermore, older men had higher cortisol levels than older women ($b = 0.30$, $SE = 0.05$, $t(110.06) = 5.97$, $p < .001$), whereas no sex differences were present in younger adults ($b = 0.07$, $SE = 0.05$, $t(99.95) = 1.33$, $p = .185$). Finally, the *sex x time* interaction showed that men (compared to women) showed higher cortisol across all timepoints (all $ps < 0.005$). Additionally, the increase in cortisol from baseline to + 30, + 40, and + 50, respectively, was stronger in men than women (all $ps < 0.05$).

Given that the age-related differences in cortisol at each timepoint may be explained by baseline differences, age-related stress-induced cortisol responses using the AUCi index were also investigated. The model showed a main effect for *condition* ($F(1, 95.56) = 46.65$, $p < .001$), *sex*[9] ($F(1, 96.39) = 4.64$, $p = .034$), and a *condition* x *age* interaction ($F(1, 95.56) = 14.81$, $p < .001$). Follow-up analyses revealed that older (vs. younger) adults had lower AUCi in the stress condition ($b = 55.76$, $SE = 27.53$, $t(188.76) = 2.03$, $p = .044$). In the control condition, older adults had higher AUCi than younger adults ($b = -80.89$, $SE = 27.53$, $t(188.75) = -2.94$, $p = .004$) reflecting a slower decrease in cortisol levels. Importantly, both age groups had higher AUCi in the stress (vs. control) condition (younger: $b = 189.58$, $SE = 25.13$, $t(96.56) = 7.54$, $p < .001$; older: $b = 52.93$, $SE = 25.08$, $t(94.57) = 2.11$, $p = .037$). The main effect of *age* did not reach significance ($F(1, 96.25) = 0.36$, $p = .552$).

3.2. Heart rate

There was a significant main effect of *condition* ($F(1, 876.97) = 58.47$, $p < .001$), *age* ($F(1, 100.28) = 6.28$, $p = .014$), and *time* ($F(4, 872.38) = 82.90$, $p < .001$), but not *sex* ($F(1, 100.28) = 1.43$, $p = .235$). Moreover, *condition* x *age* ($F(1, 876.97) = 13.38$, $p < .001$), and *condition* x *time* ($F(4, 872.38) = 12.19$, $p < .001$) interactions were significant. Follow-up analysis revealed that younger adults showed higher HR than older adults in the stress condition ($b = 6.01$, $SE = 1.79$, $t(115.17) = 3.36$, $p = .001$), while no age differences were present in the control condition ($b = 2.64$, $SE = 1.78$, $t(114.80) = 1.48$, $p = .142$). Both age groups showed higher HR in the stress (vs. control) condition (younger: $b = 5.21$, $SE = 0.66$, $t(879.42) = 7.90$, $p < .001$; older: $b = 1.84$, $SE = 0.64$, $t(874.37) = 2.85$, $p = .004$). While HR did not differ in stress vs. control conditions at baseline ($b = -0.58$, $SE = 1.02$, $t(873.32) = -0.56$, $p = .574$), HR was higher in the stress (vs. control) condition in the anticipation, TSST, and immediate post-TSST phase (all $ps < 0.005$), but was again comparable between conditions 10 min after TSST/control offset ($b = 1.91$, $SE = 1.02$, $t(873.30) = 1.87$, $p = .062$, Fig. 2B). Finally, there was an *age* x *sex* interaction ($F(1, 100.28) = 6.21$, $p = .014$). Follow-up analysis revealed that younger women had overall higher HR than older women ($b = 8.62$, $SE = 2.36$, $t(100.19) = 3.65$, $p < .001$), whereas no age differences in HR were detected in men ($b = 0.02$, $SE = 2.51$, $t(100.36) = 0.01$, $p = .992$). Moreover, younger women had also higher HR than younger men ($b = -6.36$, $SE = 2.43$, $t(100.52) = -2.61$, $p = .010$), whereas no sex differences in HR were detected in older adults ($b = 2.24$, $SE = 2.45$, $t(100.04) = 0.91$, $p = .363$).

3.3. Subjective stress (VAS)

The model[10] showed main effects of *condition* ($F(1, 1100) = 98.92$, $p < .001$), and *time* ($F(5, 1100) = 16.54$, $p < .001$), but not *age* ($F(1, 100) = 0.54$, $p = .463$). Furthermore, *condition* interacted with *age* ($F(1, 1100) = 5.23$, $p = .022$), and *time* ($F(5, 1100) = 11.50$, $p < .001$). Follow-up analysis of *condition x age* showed that both age groups reported more stress in the stress (vs. control) condition (younger: $b = 9.83$, $SE = 1.14$, $t(1100) = 8.65$, $p < .001$; older: $b = 6.15$, $SE = 1.14$, $t(1100) = 5.42$, $p < .001$). Importantly, this difference between conditions was larger in younger than older adults ($b = 3.67$, $SE = 1.62$, $t(1117) = 2.27$, $p = .023$). No age differences were found in subjective stress in the control condition ($b = 0.66$, $SE = 3.49$, $t(111.49) = 0.19$, $p = .850$) nor in the stress condition ($b = 4.34$, $SE = 3.49$, $t(111.49) = 1.24$, $p = .216$).

Condition x time interaction showed that while subjective stress did not differ between the stress and control conditions at baseline ($b = -0.24$, $SE = 1.97$, $t(1100) = -0.12$, $p = .903$), more stress was present in the stress (vs. control) condition from + 10 to + 40 min (all $ps < 0.015$), but was again comparable between conditions by + 50 min ($b = 2.98$, $SE = 1.97$, $t(1100) = 1.51$, $p = .130$, Fig. 2C).

Finally, there was an *age* x *time* interaction ($F(5, 1100) = 2.73$, $p = .018$) showing that, across conditions, younger adults reported feeling more stressed than older adults during the anticipation phase (i.e., +10 min, $b = 8.79$, $SE = 3.84$, $t(162.71) = 2.29$, $p = .023$), while no other age differences were found at other timepoints (all $ps > 0.400$).

3.4. Anticipatory stress appraisal (PASA stress index)[11]

For the stress index, the model showed main effects of *condition* ($F(1, 100) = 45.79$, $p < .001$), *age* ($F(1, 100) = 11.01$, $p = .001$). Crucially, *condition* interacted with *age* ($F(1, 100) = 14.96$, $p < .001$, Fig. 2D): younger adults reported higher stress appraisal than older adults in the stress condition ($b = 1.21$, $SE = 0.25$, $t(159.32) = 4.80$, $p < .001$), but the two groups did not differ in their stress appraisal in the control condition ($b = 0.24$, $SE = 0.25$, $t(159.32) = 0.95$, $p = .341$). Importantly, both age groups had higher stress appraisals in the stress (vs. control) condition (younger: $b = 1.33$, $SE = 0.18$, $t(100) = 7.52$, $p < .001$; older: $b = 0.36$, $SE = 0.18$, $t(100) = 2.05$, $p = .043$). Additionally, the four individual PASA subscales were analyzed separately and are presented in Supplementary Materials (S9).

3.5. Secondary results

While no significant correlations between cortisol and psychological indices emerged across age groups (all $ps > 0.100$, see S10a), younger adults' AUCg was positively correlated with "Control expectancy" appraisal ($r(48) = 0.29$, $p = .040$, see S10b), whereas older adults' AUCi was positively correlated with "Challenge" appraisal ($r(46) = 0.44$, $p = .002$, see Supplementary Materials S10c).

Moreover, age correlated positively with AUCg ($r(47) = 0.31$, $p = .027$), reflecting that with increasing age older adults tend to produce more total cortisol output under stress. However, age did not correlate with AUCi, HR, nor subjective stress measurements (all $ps \geq 0.075$, see S11) among older adults under stress. Additionally, there was a positive correlation between age and cortisol levels at + 30 min ($r(48) = 0.28$, $p \leq .050$), + 60 min ($r(48) = 0.32$, $p = .023$), and + 75 min ($r(47) = 0.39$, $p = .005$) among older adults (see S11), suggesting higher levels of cortisol during the peak and the recovery phase of the stress response with increasing age. Given the sex differences shown by the main results on cortisol and HR (see above), separate analyses were run for older men and women. The correlations with age were significant in older men for AUCg ($r(19) = 0.54$, $p = .012$), cortisol levels at baseline (0 min; $r(20) = 0.43$, $p = .044$), at + 50 min ($r(19) = 0.46$, $p = .035$), + 60 min ($r(20) = 0.47$, $p = .027$), and + 75 min ($r(20) = 0.57$, $p = .006$), while no significant association between age and

[9] Overall, men had higher AUCi than women ($b = 45.40$, $SE = 21.08$, $t(96.39) = 2.15$, $p = .034$).

[10] Sex did not contribute significantly to the model predicting subjective stress; thus, it was automatically dropped from further analyses involving subjective stress.

[11] Sex did not contribute significantly to the model predicting stress index; thus, it was automatically dropped from further analyses involving the stress index.

any psychophysiological variable was detected in older women ($N = 28$, all $ps > 0.290$).

4. Discussion

The present study set out to investigate adult age differences across different phases of the psychophysiological response to psychosocial stress vs. control in a sample of younger and older adults using a within-subjects design.

Results revealed that, compared to younger adults, older adults not only showed overall lower *cortisol* levels but also a lower stress-induced cortisol increase (i.e., AUCi). These findings are consistent with one previous study reporting lower cortisol response to a TSST in older vs. younger adults (Hidalgo et al., 2015). Importantly, like Hidalgo et al. (2015), the present study used a within-subjects design with a similar sample size. However, a lower cortisol response in older adults in both TSST/control stands in contrast to previous findings showing either increased cortisol in older age or no age differences during TSST/control (Almela et al., 2011; Crosswell et al., 2021; Kudielka et al., 2004a; Schnitzspahn et al., 2022). Nevertheless, earlier work from Nicolson et al. (1997) demonstrated that middle-aged adults (50 years) showed higher cortisol responses than older adults (> 70 years). These results are in line with the present study where the older group was on average 71 years old and hence older than older age groups in past studies comparing younger and older adults (e.g., Crosswell et al., 2021; Strahler et al., 2010). In addition, and perhaps even more pertinent for experimental purposes, compared to younger adults, older adults displayed a different *temporal dynamic* of cortisol reactivity. Compared to their control conditions, younger adults' cortisol increased from + 20 to + 50 min, whereas older adults' cortisol increased from + 30 to + 60 min. In other words, older adults' cortisol reactivity appeared slightly delayed compared to younger adults (one measurement later). Importantly, an ineffective stress induction in older adults cannot explain these age differences given that both age groups showed a significant increase in cortisol in the stress condition compared to their respective control conditions. Moreover, this result extends previous research by Strahler and colleagues (2010) who showed that cortisol in older adults peaked at + 20 min post-stress whereas in younger adults and children it peaked at + 10 min post-stress. Nevertheless, the amount of cortisol secreted during the stress response was lower in older (vs. younger) adults, which is in contrast with Strahler et al. (2010) findings indicating that older adults showed the highest mean cortisol increase from baseline. In this regard, our results revealed that sex contributed to age differences in the cortisol response across conditions. Older women had a lower cortisol response than older men and younger women across conditions, whereas younger and older men did not differ. This result is again in line with Nicolson et al. (1997) who showed that women > 70 years were least likely to show any cortisol response to stress. Thus, taken together, the results of the present study suggest that cortisol reactivity tends to decrease, rather than increase, with advanced age.

Concerning *HR*, the results indicated that older (vs. younger) adults showed lower HR in the stress condition, whereas no age differences in HR were observed in the control condition. This pattern of results is in line with previous literature investigating HR responses to stress in younger and older adults with mixed-sex samples (see Brindle et al., 2014; Kudielka et al., 2004b; Strahler et al., 2010). Moreover, in line with cortisol results, older women had again lower HR than younger women across conditions, while no age differences were detected in men. This is in line with previous studies reporting lower HR to acute stress specifically in older compared to younger women (Kudielka et al., 2004b; Traustadóttir et al., 2005). However, while these previous studies did not have a control condition, older women in the present study showed lower HR than younger women independent of the experimental condition, suggesting a broader effect of age on HR in women. This is in line with the idea that differences in HR responses in premenopausal versus postmenopausal women are modulated by a difference in reproductive hormones (Kudielka et al., 2004b).

Concerning psychological stress reactivity, *subjective stress* measures showed that both age groups reported feeling more stressed in the stress condition (vs. control) indicating that the stressor effectively induced psychological stress. (Kudielka et al., 2000; Strahler et al., 2010) Importantly, extending previous results, the present data also revealed specific age-related differences in the anticipation phase. Younger adults reported feeling more stressed than older adults exclusively in the phase preceding the active part of the TSST/control (i.e., oral presentation and math task). To the best of our knowledge, this is the first time that an age-related difference in anticipation of subjective stress has been reported. Nonetheless, this result is in line with previous affective aging literature, suggesting that higher age is associated with a higher positive expectancy bias – especially when processing socially relevant or negative scenarios – indicating less sensitivity to, or influence from, negative information in older adults (Steinman et al., 2013). Finally, consistent with lower subjective stress reported by older adults during the anticipation phase, the scores on the *appraisal stress index* indicated that older adults had a lower anticipatory stress appraisal than younger adults, meaning that older adults anticipated the upcoming TSST to be less stressful than younger adults. Importantly, no age differences were found in the control condition, confirming that stress appraisal differences were specific to the stressful situation and cannot be explained by appraisal differences in the control condition.

4.1. Integrative discussion

Taken together, the results of the present study revealed age differences on several levels of the stress response. On the *physiological level* (i.e., cortisol and HR), older adults presented not only reduced HPA and autonomic stress responses but also delayed HPA reactivity, compared to younger adults. Furthermore, taking a closer look, the results revealed that age-related differences in both cortisol and HR vary between men and women across conditions: while no age differences were detected between younger and older men, older women had a consistently lower response than younger women.

On the *psychological level* (i.e., subjective stress and appraisal), consistent with the physiological results, older adults appraised the upcoming stressful situation less negatively. This is of interest given the importance of expectation and anticipation of a stressor for acute stress regulation and cortisol output (Pulopulos et al., 2020). In Pulopulos et al. (2020), younger participants that appraised the TSST less negatively (as seen with the appraisal stress index) also showed a lower cortisol reactivity to stress. Similarly, older adults in the present study reported a less negative anticipatory stress appraisal and lower cortisol reactivity compared to younger adults.

However, secondary analyses revealed that appraising the situation as more challenging was associated with *greater* stress-induced cortisol increase (AUCi) in older adults, while higher expectancy of controlling the situation was associated with overall more cortisol being released (AUCg) in younger adults. This hints at the idea that different mechanisms might underlie the association between psychological and physiological reactivity in younger vs. older adults and that a high challenge appraisal might be particularly relevant for HPA reactivity in older age. Moreover, the correlation between age and cortisol was positive in older men, suggesting higher cortisol levels with advancing age in men, particularly regarding the recovery phase of the stress response (i.e., +50, +60, +75 min). This in contrast with the direction of our main physiological results and Nicolson's et al. (1997) conclusions, but it is in line with the idea of HPA axis hyperreactivity in older age (see Sapolsky et al., 1986). However, as mentioned, these results cannot be generalized to older women, highlighting again the important role of sex differences in understanding the cortisol stress response in older age. Thus, more research investigating age and sex differences considering a large older age range (or preferably continuously throughout the entire adult lifespan) not only during the psychological anticipation of a stressor, but

also during stress recovery is warranted.

Moreover, while past and current research show that the TSST is an effective protocol for inducing psychophysiological stress reactivity in both younger and older adults, there is no standardized age-adapted version of the TSST for older adults. Thus, it cannot be ruled out that the TSST might not be as effective in older (vs. young) adults and that lower physiological reactivity might be explained, at least in part, by lower stress appraisal in older adults. This could also explain partly differing results between the present and past studies, as different age-adapted versions of the speech task might vary in their relevance for older adults (see Discussion in Mikneviciute et al., 2022). Thus, it seems important to validate an age-adapted version of the speech task of the TSST, especially for adults aged 65 + to better compare between studies inducing psychosocial stress in older age.

To summarize, the present results highlight the need to better integrate psychological and physiological indicators to understand age differences in the stress response. Age differences on the psychological level might explain differences observed on the physiological level. Future research needs to properly explore this research question by using a validated age-adapted version of the TSST.

4.2. Limitations

A limitation of the present study is the timeline of data collection which overlapped with the COVID-19 pandemic. Given that greater chronic stress has been shown to potentially blunt the HPA response to acute stress (Chida and Hamer, 2008; Lam et al., 2019), baseline differences in chronic stress (i.e., Perceived Stress Scale and Coronavirus Impact Scale, see S2) were assessed in both age groups. However, in line with previous reports (Young et al., 2021b), older adults in this study reported lower chronic stress than younger adults, therefore excluding the possibility that higher chronic stress in older adults could explain a blunted cortisol response in this age group. However, we cannot rule out the possibility that the extraordinary pandemic situation might have had different confounding effects on the data collected during this study. Thus, it is important to replicate the present results in both younger and older adults in a non-pandemic context. Moreover, selection bias of older participants due to the online screening cannot be ruled out. However, measures were put in place to avoid selection bias in this age group. Firstly, thorough instructions for the completion of the online screening were provided by telephone to older participants, with remote assistance in case of technical difficulties. Moreover, if participants did not have access to the internet or a computer, they were invited to complete the online screening in the laboratory during an additional visit. Finally, any ambiguous information reported in the screening was further clarified with older participants over the phone. Additionally, the two age groups differed in medication intake which cannot be statistically controlled for as these covariate analyses can be misleading (see Miller and Chapman, 2001), thus possibly confounding the results. Similarly, due to the time window separating the two laboratory visits (i.e., 2–3 weeks), most younger women were in a different menstrual phase during the two experimental conditions, which confounded cortisol results in these participants specifically. Thus, results regarding sex differences in cortisol response should be interpreted with caution and further research is necessary to investigate the interplay between sex and age in the stress response.

5. Conclusions

Establishing age-related patterns in the psychophysiological stress response has been a long-standing interdisciplinary open question given the scarcity of studies and contrasting results. In addition, studies rarely integrated different psychophysiological stress indicators in one study design and compared the effects of stress to a control condition in different age groups. The current study provides a more comprehensive overview of the psychophysiological age differences in the stress response while comparing them to a control condition. Compared to younger adults, older adults showed lower cortisol and HR responses, as well as lower subjective stress and less negative stress appraisal during the anticipation of the stressor/control. Thus, overall, older adults seemed less affected by acute stress than younger adults when using an age-adapted version of the TSST.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psyneuen.2023.106111.

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