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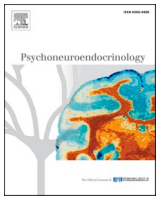

Biological stress responses to multitasking and work interruptions: A randomized controlled trial

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ABSTRACT

In the course of digitalization, new stressors are emerging. In modern working and living environments, two ubiquitous, technology-mediated stressors are multitasking demands and work interruptions. However, biological stress response patterns to multitasking and work interruptions have been sparsely investigated so far. We thus aimed to comprehensively assess biological stress response patterns to both stressors and, additionally, test whether responses differ between digital and partially non-digital settings. A controlled experimental set-up was established and humans' biological markers of the Sympathetic Nervous System (SNS), the hypothalamic-pituitary adrenal (HPA) axis, and the immune system were assessed. $N = 186$ healthy participants (mean age: 23.2 ± 4.3 years, 74.7% female, body mass-index: 22.3 ± 3.1 kg/m^2) took part in this pre-registered study. Each participant was randomly assigned to one of 6 experimental conditions (1 digital single-task, 3 dual-tasks [2 parallel tasks and 1 interruption], 1 multitasking, and 1 passive, control condition). Each one of the dual-tasking as well as the multitasking conditions included a non-digital sub-task, i.e., performing a task in presence of an examiner. All other conditions involved digital tasks only. Salivary alpha-amylase (sAA) levels as a marker for SNS reactivity significantly changed in work interruptions, parallel dual-tasking, and multitasking conditions. No changes were found for control conditions. Furthermore, no significant changes over time and no differences between the conditions were identified for three biological markers: cortisol as marker for HPA axis activity as well as for two immune system markers (secretory Immunoglobulin-A, C-reactive protein). A time course similar to sAA was found for perceived stress: with increases during task execution and decreases afterwards in multitasking and parallel dual-tasking. Yet, it did not change for the work interruption, passive control, and single-tasking condition. Overall, our findings show that dual- and multitasking are perceived as stressful and are associated with an activation of the SNS, but not with responses of HPA axis or immune system. This was consistent for digital as well as partially digital task demands. Our findings will also inform future research into the differential stress effects of digital and non-digital tasks to advance our understanding of biological stress response-patterns to multitasking and work interruptions. Therefore, our findings are highly relevant for understanding the long-term biological health effects of stress in modern (digitalized) environments.

1. Introduction

1.1. Background

In modern digitalized working and living environments, new and technology-mediated stressors are emerging. Digital stress refers to stress that is related to the usage of digital technology and media, which is similar to the concepts of techno strain and technostress (Brod, 1982; Salanova et al., 2013). Two highly relevant digital stressors are multitasking and work interruptions, e.g., due to flooding text messages or emails (Barley et al., 2011; Gupta et al., 2013; Hefner and Vorderer, 2016; Lindström, 2020; Reinecke et al., 2017). Both, multitasking and work interruptions, can be perceived as stressful and overwhelming (Kim et al., 2013; Mark et al., 2014; Weigl et al., 2017). However, only few attempts have been made so far to understand the effects of these stressors on biological stress system activity.

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Humans' stress responses are complex and involve the activation of several biological systems: the Autonomic Nervous System with its two branches, the Sympathetic Nervous System (SNS) and the Parasympathetic Nervous System (PNS), as well as the hypothalamic-pituitary adrenal (HPA) axis, and the immune system (Fulford and Harbuz, 2005; Selye, 1946). The SNS activates systems throughout the body, associated with the release of epinephrine and norepinephrine from the adrenal medulla and also an increase in heart rate (Selye, 1950; Ulrich-Lai and Herman, 2009). The activation, i.e., up-regulation, of the SNS is accompanied by a down-regulation of the PNS (Chrousos and Gold, 1992; Ulrich-Lai and Herman, 2009). With a delay, the HPA axis is activated, which results in the release of the stress hormone cortisol from the adrenal cortex (Sapolsky et al., 2000; Ulrich-Lai and Herman, 2009). With a further delay, complex responses of the immune system occur with up-regulation of some components (most importantly inflammatory pathways) and down-regulation of others (e.g., cellular immunity; Chrousos, 2009; Morey et al., 2015).

Although biological stress responses can be in principle triggered by all kinds of different stressors, humans' actual stress responses are associated with the nature of the stressor (so-called specificity hypothesis; Kemeny, 2003; Lazarus, 1990), i.e., specifically situations that are perceived as threatening trigger HPA axis responses. Overall, multitasking and work interruptions differ from commonly investigated stressors in their nature as they are primarily based on cognitive demands (in contrast to typical threatening psychosocial stressors), especially when induced digitally, i.e., without the direct presence of further persons (i.e., during digital job interviews; Becker et al., 2023). Therefore, with regards to the specificity hypothesis, it remains an open question whether physiological stress responses to multitasking and work interruptions differ between digital and non-digital stressors. For cognitive stressors such as multitasking, both SNS and HPA axis responses have been reported, depending on task difficulty and on the presence of further (e.g., social) stressors (Becker et al., 2020; Skoluda et al., 2015; Wetherell et al., 2017). In a recent meta-analysis, we found that multitasking in comparison to single-tasking is associated with an activation of the SNS, but studies investigating other biologicals stress systems such as HPA axis or immune system are scarce and lack methodological rigor (Becker et al., 2022a). To this end, it remains an unresolved question whether differences in humans' biological stress responses occur between digitally- and non-digitally mediated task demands.

1.2. Objectives

Our aim was to investigate the effects of multitasking and work interruptions on biological stress systems in a controlled laboratory setting. We developed a comprehensive experiment, in which participants were randomly assigned to one out of six distinct task conditions (one passive control, one active control single-tasking, one work interruption, two dual-tasking, and one multitasking condition; see 2.3.1).

As outlined in our previously published study protocol, our main research questions were (Becker et al., 2022b; pp. 3–4):

1) *Do dual- and multitasking conditions lead to physiological stress responses in comparison to a single-task control condition or a passive control condition?*
2) *Do work interruptions lead to physiological stress responses in comparison to a single-task control condition or a passive control condition?*
3) *Do the stress response patterns differ between digital and non-digital stressors?*

   Additionally, the following secondary research question was investigated to confirm the overall finding that multitasking and work interruptions trigger perceived stress responses.
4) *Do dual- and multitasking lead to perceived stress responses in comparison to a single-task control condition or a passive control condition?*

2. Material and methods

2.1. Participants

Initially, $N = 192$ (mean age 23.2 ± 4.4 years, 75.5% female, body mass-index (BMI): 22.3 ± 3.3 kg/m^2) healthy (i.e., no psychiatric or physical diseases according to self-reports) humans were recruited and joined the experiment. Data of $n = 6$ participants had to be excluded completely from statistical analysis, (i.e., due to the following reasons: acute psychiatric disorder with current medication intake, $n = 3$, technical problems with data capturing, $n = 1$, non-binary sex, $n = 1$, self-reported menopause, $n = 1$). The final sample included $N = 186$ participants (mean age: 23.2 ± 4.3 years, 74.7% female, mean BMI: 22.3 ± 3.1 kg/m^2). The study has been conducted according to the principles expressed in the Declaration of Helsinki and has been approved by the local ethics committee of the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU; protocol number: 397_19 B).

2.2. Power calculation and pre-registration

The study protocol has been previously peer-reviewed and published (Becker et al., 2022b). An a-priori and published power analysis has been conducted revealing an optimal sample size of $N = 174$ ($n = 29$ per condition). Due to an expected drop-out rate of about 10%, we collected data from $N = 192$ participants, from which $N = 186$ were eligible for statistical analysis, with between $n = 29$ and $n = 31$ participants per condition. Hence, the optimal sample size was fulfilled.

2.3. Materials

2.3.1. Tasks

Participants were randomly assigned to one out of six conditions (Table 1). Neither participants nor the experimenter knew in advance (i.e., during recruitment, before arriving at the laboratory) to which condition the participants were assigned to.

Condition 1 was a passive control condition which has been previously validated and in which participants watched a non-stressful and non-arousing documentary video (Langer et al., 2021).

Condition 2 was an active control condition, in which participants conducted a digital task, which was also the primary task throughout the following dual- and multitasking conditions 3 – 6. This primary task was an 'AX' – continuous-performance task (AX-CPT; Klee and Garfinkel, 1983; van den Bosch et al., 1996). In this task, the letters 'A′, 'B′, 'X′, and 'Y′ were presented. The target letter was an 'A′ occurring after an 'X′, i.e., that the response button should be pressed after each A-X pair. All other cases were non-targets (i.e., A-Y, B-X, and B-Y pairs), and the other response button should be pressed. The stimulus presentation time was 2000 ms and the inter-stimulus interval was 3500 ms. The probability of an A-X pair was 0.50 and 0.17 for the other pairs.

In condition 3 (dual-tasking with digital interruptions), the primary task was interrupted by a secondary task on the same screen. In this task, questions and five answer possibilities were presented, and the correct

Table 1
Overview of task conditions.

No.	Condition	Tasks
1	Passive control	Watching a video
2	Active control, digital single-tasking	CPT
3	Dual-tasking with digital interruptions	CPT + answering questions
4	Parallel dual-tasking (digital secondary task)	CPT + answering questions (digitally mediated)
5	Parallel dual-tasking (non-digital secondary task)	CPT + VFT
6	Parallel multitasking	CPT + answering questions + VFT

Note. CPT = continuous performance task; VFT = verbal-fluency task.

answer should be chosen as fast as possible. Items from the intelligence structure test (*Intelligenz-Struktur-Test 2000R*, IST-2000R; Amthauer et al., 2001; Petermann, 2014) were used as questions.

In condition 4 (parallel dual-tasking with digital secondary task), the primary and secondary task (identical to condition 3) were presented in parallel on two screens. Participants were instructed that both tasks were equally relevant, i.e., that none of the tasks should be prioritized, and that both tasks should be performed as accurately as possible.

In condition 5 (parallel dual-tasking with non-digital secondary task), a non-digital secondary task was conducted in parallel to the primary task. This non-digital secondary task was a verbal-fluency task (VFT; e.g., Becker et al., 2020; Tombaugh et al., 1999). The VFT-task instruction was to name as many words as possible that belong to a given category or which begin with a given letter. The time per category/letter was 2 min, and time between two sets was 1 min. Importantly, during this task the experimenter was present in the same room as the participant to induce a social-evaluative stress component. The VFT was introduced verbally by the experimenter, and categories were also named verbally, and the participant was "quizzed" by him/her.

In condition 6, which was the multitasking condition, conditions 4 and 5 were combined, i.e., participants conducted all three tasks (the AX-CPT, answering the questions, and the VFT) in parallel. The instruction was to perform all tasks as accurately as possible and not to prioritize any.

2.3.2. Assessment of biological and self-reported stress responses

Three outcomes of participant's biological stress response were captured with standardized and validated measures: (1) For assessment of SNS activity, salivary alpha-amylase (sAA; Nater and Rohleder, 2009) was used. It was measured from saliva samples that were collected by means of *Salivettes* (Sarstedt, Nümbrecht, Germany) at six time points (before [s_1], immediately after [s_2], 10 [s_3], 20 [s_4], 45 [s_5], and 90 min [s_6] after the task; Fig. 1). Samples s_1 – s_5 were used for statistical analysis, because fast SNS responses were expected immediately during and after task performance. (2) HPA axis activity was assessed from salivary cortisol, which was measured from the same samples as sAA. (3) For immune system activity-assessment, two markers were used. The first was secretory Immunoglobulin-A (s-IgA) which was measured at two time points (before and 90 min after the task) from unstimulated saliva samples using *Salicaps* (IBL international, Hamburg, Germany). The second one was C-reactive protein (CRP) which was measured from Dried Blood Spots (DBS; McDade et al., 2004) at three time points (before, 90 min after and 24 h after the task). The third time point was used for CRP only and not for s-IgA, because a slower reactivity for CRP than for s-IgA was expected.

Additionally, during each of the saliva samplings, participants provided ratings on perceived stress, tiredness, and exertion on 10-point Likert scales (Becker et al., 2022b). Furthermore, positive and negative affect was assessed at four time points (before the task, immediately after it, 20 and 90 min after the task) using a German version of the Positive and Negative Affect Schedule (PANAS; Krohne et al., 1996). Note that only the first 3 time points were used for statistical analysis because of missing data due to technical issues at the latest time point. Moreover, state anxiety and state depression were assessed twice (before and immediately after the task) using the state items from the State-Trait Anxiety-Depression Inventory (STADI-S; Laux et al., 2013).

2.3.3. Further variables

Additionally, demographic, anthropometric, as well as health-related variables were queried via questionnaires (e.g., age, sex, BMI, diseases, medication intake [e.g., intake of contraceptives]). Moreover, the time of day was assessed.

2.4. Procedure

On day 1, on that participants came to our laboratory, they first provided informed and written consent. No person dropped out or refused to participate after arriving at the laboratory. Participants were then familiarized with the saliva collection procedure (i.e., the collection of the stimulated saliva samples. After this, all participants –

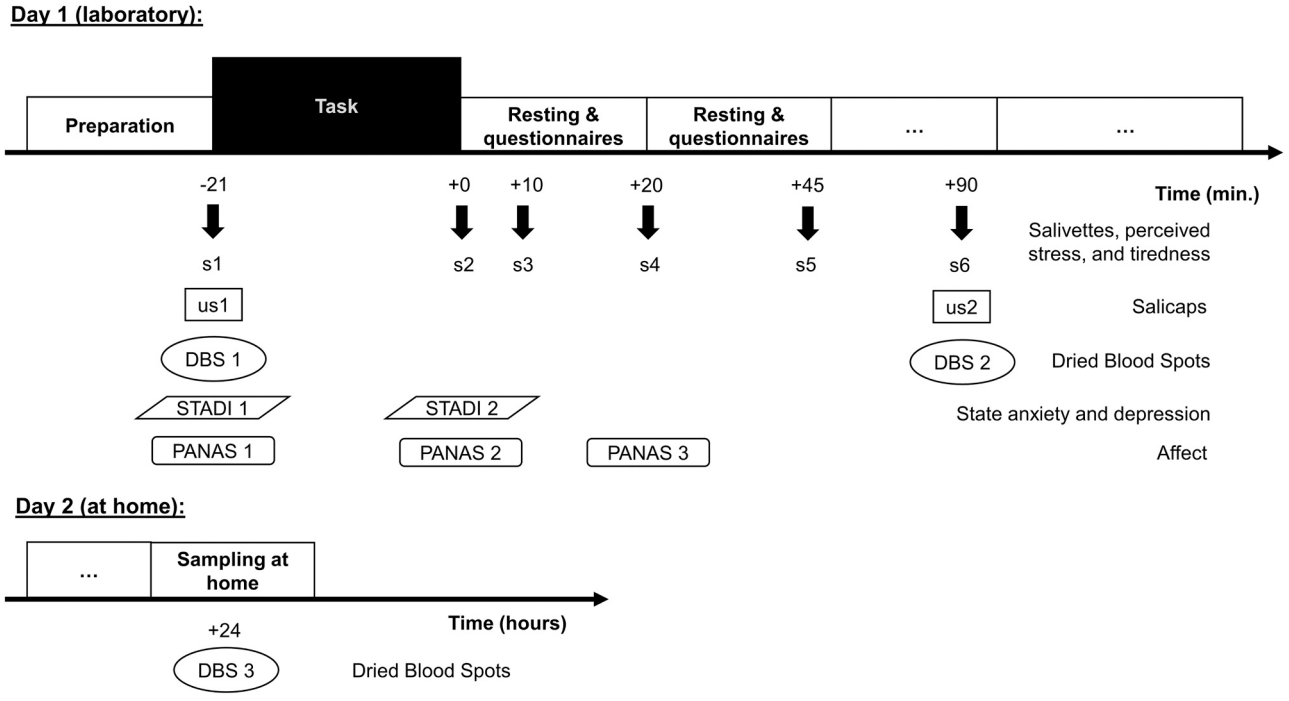

Fig. 1. Time course of the experiment. During the task, participants were randomly assigned to one out of six conditions. Salivettes were used for collection of stimulated saliva, from which salivary alpha-amylase and cortisol were assessed. Salicaps were used for collection of unstimulated saliva samples, from which secretory Immunoglobulin-A concentrations were assessed. *Note.* s = stimulated, us = unstimulated, DBS = Dried Blood Spots, STADI = State-Trait Anxiety-Depression Inventory, PANAS = Positive and Negative Affect Schedule.

irrespective of the actual group assignment – conducted practice trials of the VFT and the CPT and were informed that they will possibly have to repeat these tasks throughout the session. This was followed by a resting period of about 20 min. At the end of the resting period, the first samples (DBS_1, s_1, and us_1) were collected. After this, the main task was introduced and then started immediately. The task lasted about 21 min. Immediately after the end of the task, participants provided the second saliva sample (s_2). The subsequent saliva and DBS samples were collected as described in 2.3.2 and visualized in Fig. 1. During the time window between the task and the last saliva and blood sample, participants rested and filled out questionnaires (see 2.3.2 and 2.3.3) until the end of the session and were allowed to take as many breaks as they preferred. The entire session lasted about 3 h. On day 2, participants provided another blood sample (DBS_3) 24 h after the first one at their homes. These samples were sent back via mail.

2.5. Sample handling and laboratory analysis of saliva samples

Saliva samples were analyzed in our in-house laboratory (FAU, Chair of Health Psychology, Biopsychological Laboratory, Nürnberg, Germany) by trained staff. Sample handling and analysis is described in the study protocol in detail (Becker et al., 2022b). In short, all saliva samples were frozen immediately after collection at − 30 °C. The first and second DBS samples (DBS_1 and DBS_2) were dried over night for at least 8 h at room temperature before they were also stored at − 30 °C. The third DBS sample (DBS_3), which was collected at the participant's home, was also dried overnight, and sent to our laboratory the next day, where it was also immediately frozen. For analysis, saliva samples were thawed and centrifuged at 2000 *g* at 4 °C before further processing. On the evening before analysis, a circle with a diameter of 3.5 mm was punched out from the DBS samples and was eluted overnight in phosphate-buffered saline which contained 0.1% Tween 20 solution. The next morning, DBS samples were shaken at 300 rpm for one hour before further processing. sAA was measured with an enzyme kinetic assay as described elsewhere (e.g., Rohleder and Nater, 2009). For salivary cortisol, s-IgA, and CRP measurement, high-sensitive Enzyme-linked Immunosorbant Assays (ELISA) were used. Mean intra-assay coefficients of variation were 4.37 for sAA, 4.18 for cortisol, 2.19 for s-IgA, and 4.88 for CRP.

2.6. Hypotheses

Our hypotheses were (Becker et al., 2022b; p. 11):

1) *Conditions 3 and 4 (digital work interruptions and digital parallel dual-tasking) will trigger responses of the SNS […] and the immune system that are stronger than in the passive control condition 1 and the single-task control condition 2. No HPA axis response are expected for conditions 3 and 4.*
2) *Conditions 5 and 6 (non-digital parallel dual-tasking and multitasking, [in which a person was present]) will trigger responses of the SNS, […] HPA axis, and the immune system that are stronger than in the passive control condition 1 and the single-task control condition 2.*

Regarding our secondary research question, we expected the following (Becker et al., 2022; p. 11).

3) *We hypothesize that conditions 3, 4, 5, and 6 will induce the perception [s] of being stressed and that perceived stress will be stronger in these conditions than in the passive control condition 1 and the single-task control condition 2 immediately after the stressor.*

Additionally, we 4) hypothesized that positive affect will decrease and that negative affect, state anxiety and state depression will increase during the task in conditions 3, 4, 5, and 6, but not in the control conditions 1 and 2. Note that hypothesis 4 was not included in our study protocol.

2.7. Statistical data analysis

Descriptive statistics, including frequencies, means (*M*), and standard deviations (*SD*) were computed to describe the sample characteristics. Because of skewness and violation of normality, which was tested using the Kolmogorov-Smirnov test, all sAA, cortisol, s-IgA, and CRP levels were transformed using the natural logarithm (ln). For age and BMI, box-cox transformations were applied (box(age) = $age^{-2.55}$, box (BMI) = $BMI^{-2.727}$; Hemmerich, 2016). For all variables of interest, no outliers were identified that differed more than 3 standard deviations from the group's mean. Potential baseline differences between the six groups were tested using Chi^2 tests for nominal variables and one-factorial analyses of variance (ANOVAs) for metric variables.

For main hypotheses testing, ANOVAs for repeated measurements (rmANOVAs) with the within-subjects factors 'time point' ('s_1' to 's_5') and the between-subjects factor 'condition' were calculated. If necessary, sphericity violations (determined by Mauchly's test of sphericity) were corrected by adjusting the degrees of freedom with the procedure by Greenhouse and Geisser. For s-IgA, the factor time point comprised 2 levels (before and 90 min after the task), and 3 levels (before, 90 min and 24 h after the task) were available for CRP. For post-hoc comparisons, *t*-tests for paired samples were used.

Research question 4 (i.e., perceived stress, state anxiety, and affect) was investigated analogously to research questions 1–3 by means of rmANOVAs with the within-subjects factors dimension (perceived stress vs. tiredness) for the rating scales, valence (positive vs. negative) for affect and dimension (anxiety vs. depression) for state anxiety and depression, as well as the between-subjects factor condition for all analyses. The factor time point included five levels (s_1-s_5) for the rating scales (perceived stress and tiredness), three levels for positive and negative affect (before, immediately after, and 20 min after the task), and two levels (before and immediately after the task) for state anxiety and state depression.

The potential confounders age, sex, BMI, intake of oral contraceptives, and time of day were included as covariates in the statistical analyses. A Bonferroni-adjusted α-level of $\alpha_{adjusted} = 0.017$ was used for all statistical analyses as specified in the study protocol (Becker et al., 2022b). For statistical analyses, IBM SPSS statistics (version 29 for Windows) was used. The data set that was used for statistical analysis is freely available on the Open Science Framework (https://osf.io/6nyah/).

3. Results

3.1. Descriptive statistics

The final sample included $N = 186$ participants. The sample characteristics are summarized in Table 2, separately for the six conditions. Randomized allocation was established since there were no differences in age, sex, BMI, time of day, and use of contraceptives between the conditions (box(age): $F(5) = 0.16$, $p = .98$, $\eta^2 = 0.004$; sex: $Chi^2(5) = 1.58$, $p = .90$; box(BMI): $F(5) = 0.64$, $p = .67$, $\eta^2 = 0.02$, time of day: $F(5) = 0.06$, $p = .99$, $\eta^2 = 0.002$; contraceptives: $Chi^2(5) = 6.79$, $p = .24$). Furthermore, no baseline differences between the groups could be identified for sAA, cortisol, s-IgA, and CRP ($ln(sAA_1)$: $F(5) = 1.28$, $p = .27$, $\eta^2 = 0.04$; $ln(cortisol_1)$: $F(5) = 0.76$, $p = .58$, $\eta^2 = 0.02$; $ln(s\text{-}IgA_1)$: $F(5) = 1.29$, $p = .27$, $\eta^2 = 0.04$; $ln(CRP_1)$: $F(5) = 0.30$, $p = .91$, $\eta^2 = 0.01$).

3.2. Biological stress responses (hypotheses 1 and 2)

3.2.1. Salivary alpha-amylase

A rmANOVA with the factors 'time point' ('s_1'–'s_5') and 'condition' ('1′–'6′) revealed a significant interaction of time point * condition (*F*

Table 2
Sample characteristics.

		Age (years)		Sex		BMI (kg/m^2)		Time of day (hours)		Use of contraceptives	
Condition	***N***	***M***	***SD***	***N* female**	**% female**	***M***	***SD***	***M***	***SD***	***N* yes**	**% yes**
1	31	23.6	4.44	24	77.4	22.6	2.92	15.5	1.84	4	12.9
2	31	22.8	4.04	21	67.7	23.0	3.72	15.5	1.91	1	3.2
3	33	23.4	5.25	26	78.8	22.1	3.52	15.5	1.81	5	15.2
4	31	23.2	3.57	22	71.0	22.1	2.77	15.5	2.16	8	25.8
5	29	23.1	4.54	22	75.9	21.9	2.45	15.7	1.91	4	13.8
6	31	23.3	4.24	24	77.4	21.9	3.26	15.5	1.99	6	19.4
Overall	186	23.2	4.33	139	74.7	22.3	3.13	15.5	1.91	28	15.1

Note. $N = 186$; BMI = body mass-index; *M* = mean; *SD* = standard deviation; condition 1 = passive control (digital), condition 2 = active control (digital single-tasking), condition 3 = dual-tasking with digital interruptions, condition 4 = parallel dual-tasking (digital secondary task), condition 5 = Parallel dual-tasking (non-digital secondary task), condition 6 = parallel multitasking.

(17.9, 616.4) = 2.11, $p = .01$, $\eta_p^2 = 0.06$), and an interaction between time point and the covariate contraceptives ($F(3.58, 616.43) = 3.30$, $p = .01$, $\eta_p^2 = 0.02$). Post-hoc *t*-tests showed that sAA levels increased significantly between s_1 and s_2 in condition 5 ($t(28) = 3.66$, $p = .001$, $d = 0.68$) and decreased between s_2 and s_3 in conditions 3, 4 and 6 (condition 3: $t(32) = 2.59$; $p = .01$, $d = 0.45$; condition 4: $t(30) = 3.13$, $p = .004$, $d = 0.56$; condition 6: $t(28) = 5.08$, $p < .001$, $d = 0.94$). No significant changes in sAA levels were found for the conditions 1, 2, and 3 (Fig. 2A).

3.2.2. Cortisol

For cortisol, no significant effects for the variables of interest were found, reflecting that cortisol levels did not significantly change over time and did not differ between the conditions (Fig. 2B). Merely, the interaction between the factor time point and the covariate time of day was significant ($F(2.6, 441.42) = 5.61$, $p = .002$, $\eta_p^2 = 0.03$) as well as the main effect of time of day ($F(1, 170) = 19.50$, $p < .001$. $\eta_p^2 = 0.10$), reflecting lower cortisol levels for later times of the day.

3.2.3. Secretory Immunoglobulin-A

No significant effects were found for s-IgA (all $p > .15$), suggesting that s-IgA levels did not change over time and did not differ between conditions (Fig. 2C).

3.2.4. C-reactive protein

No significant associations of the variables of interest were identified for CRP either (all $p > .38$), indicating that CRP levels did not change over time and did not differ between the conditions (Fig. 2D). However, a significant interaction between time point and BMI ($F(1.57, 226.48) = 19.50$, $p = .003$. $\eta_p^2 = 0.05$) as well as a main effect of the covariate contraceptives ($F(1, 144) = 10.02$, $p = .002$. $\eta_p^2 = 0.01$) were found.

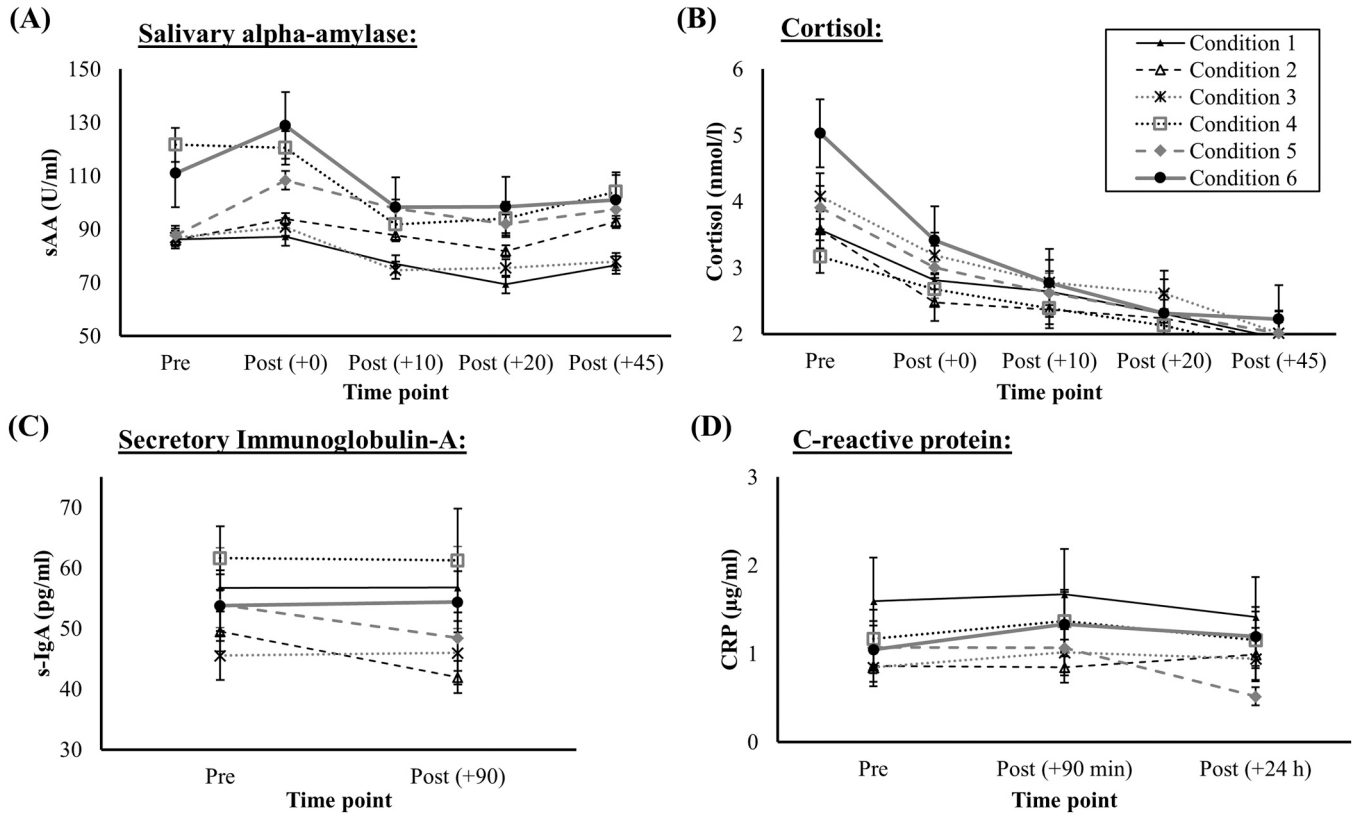

Fig. 2. Time course of salivary alpha-amylase (sAA), cortisol, secretory Immunoglobulin-A (s-IgA), and C-reactive protein (CRP) levels. *Note*. Standard errors are shown as error bars. Condition 1 = passive control (digital), condition 2 = active control (digital single-tasking), condition 3 = dual-tasking with digital interruptions, condition 4 = parallel dual-tasking (digital secondary task), condition 5 = Parallel dual-tasking (non-digital secondary task), condition 6 = parallel multitasking.

3.3. Subjective stress perception

3.3.1. Rating scales (hypothesis 3)

Since perceived stress and exertion were highly correlated (all $r > 0.65$, all $p < .001$), only perceived stress and tiredness were included in hypothesis testing. An rmANOVA with the factors 'time point' ('s_1'–'s_5'), 'dimension' ('stress' vs. 'tiredness'), and 'condition' ('1′–'6′) were calculated. This revealed a significant interaction of time point * condition ($F(15.99, 5556.79) = 6.13$, $p < .001$, $\eta_p^2 = 0.15$), a significant interaction of dimension * condition ($F(6.70, 172) = 3.74$, $p < .001$, $\eta_p^2 = 0.10$), and a significant three-way interaction of time * dimension * condition ($F(23.7, 528.30) = 10.69$, $p < .001$, $\eta_p^2 = 0.24$).

The post-hoc rmANOVA for perceived stress revealed a significant interaction of time point * condition ($F(15.69, 539.59) = 14.17$, $p < .001$, $\eta_p^2 = 0.29$). Perceived stress significantly decreased between s_1 and s_2 for conditions 1 and 2 (condition 1: $t(30) = 4.52$, $p < .001$, $d = 0.81$; condition 2: $t(30) = 3.41$, $p = .002$, $d = 0.61$). For conditions 4, 5, and 6, perceived stress significantly increased between s_1 and s_2 (condition 4: $t(28) = 3.83$, $p < .001$, $d = 0.71$; condition 5: $t(27) = 6.62$, $p < .001$, $d = 1.25$; condition 6: $t(30) = 6.73$, $p < .001$, $d = 1.21$) and decreased between s_2 and s_3 (condition 4: $t(28) = 6.73$, $p < .001$, $d = 1.25$; condition 5: $t(27) = 7.30$, $p < .001$, $d = 1.38$; condition 6: $t(30) = 9.10$, $p < .001$, $d = 1.63$) and between s_3 and s_4 (condition 4: $t(28) = 6.33$, $p < .001$, $d = 1.18$; condition 5: $t(27) = 4.97$, $p < .001$, $d = 0.94$; condition 6: $t(30) = 6.86$, $p < .001$, $d = 1.23$). Perceived stress did not significantly change in condition 3 (all $p > .07$; Fig. 3A).

For tiredness, a significant interaction time point * condition was identified as well ($F(16.08, 552.97) = 5.36$, $p < .001$, $\eta_p^2 = 0.10$). Tiredness significantly increased between s_1 and s_2 for conditions 1 and 2 (condition 1: $t(30) = 3.82$, $p < .001$, $d = 0.69$; condition 2: $t(30) = 6.48$, $p < .001$, $d = 1.16$). Furthermore, tiredness significantly decreased between s_2 and s_3 for conditions 2 and 3 (condition 2: $t(30) = 2.89$, $p = .007$, $d = 0.52$; condition 3: $t(32) = 3.57$, $p < .001$, $d = 0.62$) and between s_4 and s_5 ($t(30) = 2.80$, $p = .009$, $d = 0.501$) for condition

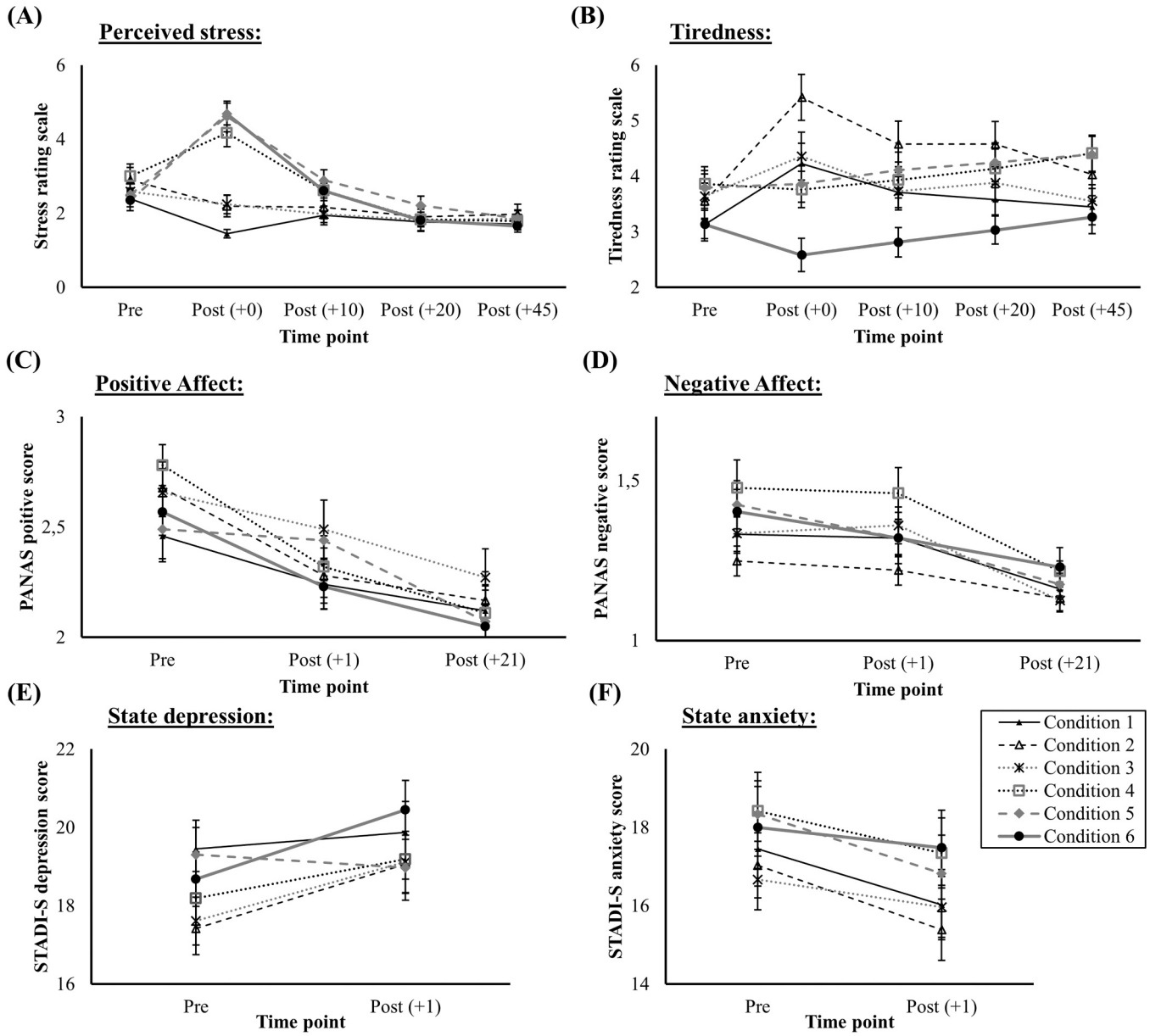

Fig. 3. Time course of perceived stress, tiredness, positive and negative affect, as well as state depression and anxiety. *Note*. Standard errors are shown as error bars. Condition 1 = passive control (digital), condition 2 = active control (digital single-tasking), condition 3 = dual-tasking with digital interruptions, condition 4 = parallel dual-tasking (digital secondary task), condition 5 = Parallel dual-tasking (non-digital secondary task), condition 6 = parallel multitasking.

2. Tiredness did not significantly change for conditions 4, 5, and 6 (all $p > .08$; Fig. 3B).

3.3.2. Positive and negative affect (hypothesis 4)

A rmANOVA with the factors 'time point', 'valence' ('positive' vs. 'negative'), and condition revealed no significant results for the variables of interest (all $p > .034$). Only a significant three-way interaction between the factors time point, valence, and the covariate contraceptives was found $F(2.56, 296.81) = 4.52$, $p = .006$, $\eta_p^2 = 0.03$; Figs. 3C and 3D).

3.3.3. State anxiety and state depression (hypothesis 4)

A rmANOVA with the factors 'time point', 'dimension' ('state anxiety' vs. 'state depression'), and condition revealed no significant findings (all $p > .10$; Figs. 3E and 3F).

4. Discussion

4.1. Summary of main findings

In this study, we systematically investigated biological stress responses to multitasking and work interruptions. Our main finding was that sAA levels as a marker for SNS reactivity consistently changed significantly (i.e., increased during and/or decreased after the task) for the conditions of work interruptions, parallel dual-tasking, and multitasking. This change in SNS activity was not found for the passive and active control conditions. No significant changes over time and no differences between the conditions were found for the further biological markers, i.e., cortisol, s-IgA, and CRP.

A similar time course as for sAA was found for participants' perceived stress. Stress ratings increased significantly during parallel dual-tasking and multitasking demands and decreased thereafter (i.e., conditions 4, 5, and 6). Yet, they were not associated with passive control, single-tasking, and work interruption demands (i.e., conditions 1, 2, and 3). Perceived tiredness showed the opposite pattern, with an increase for conditions 1, 2, and 3 and no change for the further conditions. No effects over time were found for positive and negative affect as well as for state anxiety and state depression.

4.2. Discussion of main hypotheses

Overall, our study shows that dual- and multitasking as well as work interruptions trigger specific biological stress responses, namely of the SNS. To the very best of our knowledge, for the first time, we have shown in a controlled manner that no HPA axis as well as no immune system responses are induced by these stressors. This complements previous research, which has mainly focused on subjective perceived stress measures and SNS markers (Becker et al., 2022a). Interestingly, no changes in perceived stress were found for the condition, in which the primary task was interrupted by the secondary task. This highlights the importance of not only assessing subjective perceived stress measures, but complementing it with objective biological stress assessments, e.g., by collecting SNS markers. Moreover, this study provides important contributions concerning humans' stress responses under single- and multiple task demands through applying a robust, experimental design that allows inferences concerning potential causality and sequence of effects. The importance of the SNS response for stressors under investigation, which mainly contained cognitive demands, is in line with previous research on biological stress responses to cognitive stressors (e.g., Skoluda et al., 2015; Wetherell and Carter, 2014) and with our recent meta-analysis investigating biological stress in response to multitasking (Becker et al., 2022a).

The absence of an increase in cortisol levels is in line with the specificity hypothesis (Kemeny, 2003; Lazarus, 1990), which states that specifically situations that are perceived as threatening in contrast to challenging trigger HPA axis responses. However, conditions 5 and 6 included a non-digital component, i.e., the presence of a further person, with the intention to induce a social-evaluative component. Although this task (i.e., a VFT) has led to HPA axis responses in previous studies (Becker et al., 2020) without being combined with further tasks, it did not trigger cortisol responses in the present study. Post-hoc, we assume, that cognitive demands of additional tasks were too high to fully notice the presence of the experimenter and thereby not perceiving the situation as threatening or socially-evaluative. Overall, in our study no differences between purely digitally-mediated and partly non digital stressors were found. However, future research is needed in which stronger social-evaluative sub-tasks with salient evaluative aspects are included which may induce HPA axis responses. Post-hoc, we assume that in our setup with additional digital sub-tasks the situational demands were not sufficiently perceived as social-evaluative. Moreover, further variables may have been associated with the non-reactivity of the HPA axis, such as the time of day (see below). Overall, our findings support the specificity hypothesis (Kemeny, 2003; Lazarus, 1990). We, therefore, conclude that our setup was perceived as rather challenging and cognitively demanding than being primarily evaluated as threatening or socially-evaluative.

A further interesting finding is that no differences between the passive and active single-task control conditions were found. Although we used a previously validated control condition, this may be due to the comparatively low demanding primary task, which – like the passive control task – led to an increase in participants' tiredness. Whether differences can be found for more demanding tasks, should be investigated in future research.

4.3. Limitations and future research

One potential limitation of our study is the operationalization of work interruptions, dual- and multitasking for inducing stress responses. Although we established a well-controlled, experimental set up of validated tasks with distinct requirements, nonetheless, a variety of further primary and distracting subtasks is potentially feasible. Therefore, our findings should be interpreted with caution concerning external validity and generalizability to other settings. However, our findings are in line with our systematic review and meta-analysis on biological stress responses in several dual- and multitasking scenarios, which also included pure cognitive as well as pure motoric, and combinations of cognitive and motor tasks (Becker et al., 2022a). Future studies should therefore examine further scenarios including other tasks with different levels of difficulty. Moreover, field studies are needed in which biological stress responses to work interruptions, dual- and multitasking are investigated in naturalistic settings (i.e., technology-intensive work environments with multiple sources of interruptions or multiple task demands). Beyond work interruptions and multitasking, a variety of further digital stressors is conceivable (e.g., techno insecurity, techno overload, or techno invasion; Ragu-Nathan et al., 2008). In a recent systematic review, we identified that prospective studies on associations between technostress at work and immune system activity are still missing (Kaltenegger et al., 2021).

Another potential limitation may be our time windows and lags of biomarker assessments. We carefully designed our study and chose assessment time points for saliva and blood samplings to the best of our knowledge and in line with previous studies of similar designs (e.g., Wetherell et al., 2004). Yet, our time windows that we chose for the s-IgA and CRP assessments may have contributed to the non-reactivity findings for the immune system-markers. As pointed out in a recent meta-analysis, consensus on appropriate windows for capturing immune system-reactivity has yet to be reached and may depend on the stressor, its lengths, and the specific marker that is used (Szabo et al., 2020). Moreover, it was not possible to restrict the assessments to a specific time of day, although all appointments were scheduled either noon, afternoon or early evening (between 12:30 p.m. and 8 p.m.) to account for diurnal variations in stress systems' activities. Participants were

instructed to be awake at least 4 h before the appointment. Despite these precautions, we found a significant association between time of day and cortisol levels, reflecting lower cortisol levels at later times of the day. Therefore, it cannot be completely ruled out that this masked potential HPA axis responses. However, no association between time of day and condition was found, which supports our conclusion that HPA axis activity did not differ between single- and multitasking conditions.

Another starting point for future research is to investigate associations between the stress systems of interest (i.e., SNS, HPA axis, and immune system) and their joint reactivity to multitasking and work interruptions, because these systems are not entirely independent (e.g., McEwen, 2007; Selye, 1950, 1946). Previous research on acute stress responses on social-evaluative stress has shown the importance of considering the joint activation of HPA axis and immune system responses in adolescents (Bendezú et al., 2022). Looking at joint activation of these systems rather than looking at isolated systems has the potential to examine the impact of complex dysregulations in their interplay on acute stress responses. However, our sample size did not allow us to investigate this in the context of this study.

Furthermore, here we only reported the findings for the salivary and blood spot-based biological markers (i.e., sAA, cortisol, s-IgA, and CRP). Besides, we collected participants' heart rate and heart rate variability. The findings regarding these electrophysiological recordings will be reported elsewhere, because these analyses would have gone beyond the scope of this article. For future research, the assessment of further biological stress measures in response to intense, technology-induced task demands should be considered, such as skin conductance level, blood pressure, or further immune system markers. Additionally, associations between biological stress responses and further variables we collected (e.g., personality, experience with multimedia usage; see Becker et al., 2022b) will be analyzed in the future to fully understand inter-individual differences in the stress responses between single- and multitasking (Shirtcliff et al., 2014). Moreover, individual differences between participants who showed a stress response vs. participants who did not respond should be investigated in future research (Becker and Rohleder, 2020, 2019; Bendezú et al., 2022). Not at least, it should be noted that we used self-report BMI measures, which may be biased by social desirability.

4.4. Implications

Our findings may have important implications for humans' health and well-being in modern living and working environments where multitasking and work interruptions are ubiquitous. Temporarily, the acute physiological stress responses are adaptive. However, potentially harmful consequences can arise when stress becomes chronic, i.e., when long-term stress exposure occurs (e.g., Hänsel et al., 2010; McEwen, 2008; Pretscher et al., 2021; Rohleder et al., 2009), or when so-called maladaptive stress-response patterns are used (e.g., Richardson et al., 2014; Russell and Lightman, 2019; Wadsworth, 2015). A long-term overactivation of the SNS can result in common diseases such as hypertension. Moreover, the SNS (as well as the PNS and the HPA axis) interacts with pathophysiologically relevant systems, e.g., the inflammatory system (Rohleder, 2014). Inflammatory processes are one of the central mechanisms in mediating the negative effects of stress on health (Rohleder, 2014). Ultimately, long term stress exposure leads to systemic low-grade inflammation, which is a key factor for the development of the most important diseases in industrialized nations such as cardiovascular diseases, type-2 diabetes, and cancer (Couzin-Frankel, 2010; Rohleder, 2014).

5. Conclusions

We presented here the first comprehensive investigation into humans' biological stress responses to multitasking and work interruptions in a controlled experimental setting. The observed activation of the SNS as well as the increase in perceived stress are of high relevance for the understanding of long-term health effects of these stressors in modern (digitalized) working and living environments.

CRediT authorship contribution statement

Conceptualization: LB, NR, HK, DN, MW; Methodology: LB, NR, HK, DN, MW; Formal analysis: LB; Investigation: LB; Resources: NR; Data curation: LB; Writing – original draft: LB: Writing – review & editing: NR, HK, DN, MW; Visualization: LB; Supervision: NR, DN, MW. All authors read and approved the final version of the manuscript.

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Declaration of Competing Interest

None.

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