**Diurnal Dynamics of Stress and Mood during Covid-19 Lockdown -
An Ecological Momentary Assessment Study**

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Abstract

The COVID-19 pandemic resulted in severe disruption to people's lives as governments imposed national 'lockdowns'. Using ecological momentary assessment for seven days in 731 participants, we investigated how individual's stress and mood fluctuated diurnally during lockdown in spring 2020. We found that age, gender, financial security, depressive symptoms, and trait loneliness modulated the diurnal dynamics of participants' stress and mood. For example, younger and less financially secure individuals showed an attenuated reduction in stress as the day progressed and, similarly, more lonely individuals showed a diminished increase in calmness throughout the day. In addition, we collected hair samples from 140 participants and found a decrease in cortisol concentrations following lockdown, but these changes were not related to any of the assessed person-related characteristics. Our findings provide novel insights into the psychobiological impact of lockdown and have implications for how, when, and which individuals might benefit most from interventions during comparable psychologically demanding periods.

Keywords: ambulatory assessment, COVID-19, diurnal dynamics, diurnal fluctuations, ecological momentary assessment, hair cortisol, pandemic, lockdown, mood, stress

Introduction

Due to the COVID-19 pandemic, countries worldwide imposed multiple intermittent national lockdowns to slow the rate of infections. Many individuals experienced significant challenges in their everyday lives, including changes in their job status, social relationships, leisure activities, and family life due to the measures adopted by the government. Several large surveys have underlined the potential detrimental short- and long-term mental health consequences resulting from this social and economic disruption (Austria: Nitschke et al. 2020; Pieh, Budimir, and Probst 2020; Pieh et al. 2021; Simon et al. 2021; Traunmüller et al. 2020; Bangladesh: Mamun et al. 2020; Greece: Kalaitzaki 2020; Italy: Marchetti et al. 2020; Pancani et al. 2021; Rossi et al. 2020; Slovenia: Kavčič, Avsec, and Zager Kocjan 2020; the Netherlands: Taquet et al. 2020; UK: Banks and Xu 2020; USA: Browning et al. 2021; USA and Canada: Turna et al. 2021), and identified socio-demographic and psychological characteristics that might increase the risk of negative mental health outcomes in the context of the intense and prolonged stressors related to the pandemic (Brooks et al. 2020; Talevi et al. 2020 for review).

For example, *younger age* (Banks and Xu 2020; Birditt et al. 2020; Kalaitzaki 2020; Kavčič et al. 2020; O'Connor et al. 2020; Rossi et al. 2020; Taquet et al. 2020), *female gender* (Banks and Xu 2020; Kalaitzaki 2020; Kavčič et al. 2020; O'Connor et al. 2020; Rossi et al. 2020; Traunmüller et al. 2020), *caring responsibilities* (Freisthler et al. 2021), a *disadvantaged educational status* (Kalaitzaki 2020; Kavčič et al. 2020), *and/or a disadvantaged social background* (O'Connor et al. 2020), *loneliness* (Bzdok and Dunbar 2020; Kalaitzaki 2020; Tang et al. 2021), and *pre-existing psychiatric conditions* (Bendau et al. 2021; Holingue et al. 2020; O'Connor et al. 2020; Simon et al. 2021; Taquet et al. 2020; but see Pan et al. 2020 for mixed findings) have been highlighted as important risk factors with regard to short- and long-term mental health problems in response to the COVID-19 pandemic.

However, despite the abundance of new studies related to the psychosocial impact of COVID-19, relatively little is known about how individual well-being fluctuates throughout the day under prolonged lockdown restrictions, and how this may be influenced by pre-existing mental health risk factors, such as loneliness and depression. Most of the studies linking certain mental health risk and resilience factors during the COVID-19 pandemic have been cross-sectional in nature and employed retrospective measures. For example, by asking participants how they felt *generally* during the previous weeks or months. Notwithstanding their relevance for increasing our knowledge of the psychosocial sequelae related to the pandemic, these approaches are limited in several ways: they are prone to reporting biases (e.g., recall bias, hindsight bias), cannot accurately capture time-dependent processes, and thus do not provide insight into individuals' real-time experiences in their everyday lives (Shiffman, Stone, and Hufford 2008). To overcome these limitations, we employed an ecological momentary assessment (EMA) approach to examine *diurnal changes* in perceived stress and mood in 731 individuals – to the best of our knowledge, the largest EMA study conducted during COVID-19 lockdown.

A substantial number of EMA studies were conducted in the context of the current pandemic (Achterhof et al. 2021; Arend et al. 2021; Cobo et al. 2021; Freisthler et al. 2021; Fried, Papanikolaou, and Epskamp 2020; Haucke, Liu, and Heinzl 2021; Huckins et al. 2020; Khan 2021; Kleiman et al. 2020; Stieger, Lewetz, and Swami 2021; Taquet et al. 2020; Wolf, Freisthler, and Chadwick 2021). The available research to date has focused on mood regulation and anxiety in the daily life of students (Fried et al. 2020; Huckins et al. 2020; Kleiman et al. 2020; Taquet et al. 2020), parental stress and punitive parenting (Freisthler et al. 2021; Wolf et al. 2021), media use (Arend et al. 2021), and suicide risk in outpatients (Cobo et al. 2021) during and in response to the COVID-19 pandemic. However, these studies often examined a limited number of participants and did not systematically examine diurnal fluctuations of stress and mood during lockdown.

The diurnal dynamics of stress-associated biomarkers such as salivary cortisol and salivary alpha-amylase (Rohleder and Nater 2009; Strahler et al. 2017) and how these are

influenced by person-related characteristics like gender, age, body mass index, and psychological traits like depression and loneliness, are reasonably well-researched (Dedovic and Ngiam 2015; Doane and Adam 2010; Peeters, Nicolson, and Berkhof 2004; Strahler et al. 2017 for review). Much less is known with respect to the diurnal dynamics and fluctuations of *perceived* stress and mood. Previous research has provided evidence that age (Scott et al. 2014; Scott, Sliwinski, and Blanchard-Fields 2013; Wood and Magnello 1992), *depressive symptoms* (Cowdry 1991; Peeters et al. 2006; Zerssen et al. 1987), *being in nature* (Beute and de Kort 2018), *loneliness* (Doane et al. 2013; Doane and Adam 2010), and other *contextual factors* such as physical activity (Bourke, Hilland, and Craike 2021a, 2021b) induce variations in perceived stress and mood. In addition, some studies suggest that perceived stress and mood show a typical diurnal pattern, with perceived stress decreasing from morning to evening (Zawadzki et al. 2019) and positive affect (e.g., happiness) increasing towards the evening (see de Vries, Baselmans, and Bartels 2020). However, precise investigations into the diurnal fluctuations of stress and mood and how they may be modulated by person-related characteristics during the unique period of the COVID-19 pandemic are lacking (see de Vries et al. 2020 for an overview of EMA studies on mood fluctuations in the pre-pandemic period).

Under adverse conditions, the hypothalamic-pituitary-adrenal (HPA) axis upregulates the release of cortisol, which further impacts numerous bodily functions involving the metabolic, immune, cardiovascular, and gastrointestinal systems (Chrousos 2009). This response is highly adaptive in the short-term, but long-term HPA axis activation and excessive cortisol due to prolonged stressful conditions can increase the risk for the development and exacerbation of mental and physical disorders (McEwen 1998, 2008). As cortisol accumulates in hair (Stalder and Kirschbaum 2012), hair cortisol concentration (HCC) may provide a valuable insight into the psychobiological consequences of the COVID-19 pandemic. Most recently, two independent studies examining healthcare workers found elevated HCC during the COVID-19 pandemic compared to a pre-pandemic period (Ibar et al. 2021; Rajcani et al. 2021). Another study found that higher scores on the personality traits neuroticism and

extraversion predicted higher HCC during the COVID-19 crisis (Engert et al. 2021). While these findings suggest that individuals in certain occupations and with certain personality traits may be more vulnerable for increased psychobiological stress experiences during the turmoil brought about by the COVID-19 pandemic, the role of additional potential risk factors (e.g., loneliness, financial insecurity) remains to be elucidated.

The present study

In the present paper, we investigated whether certain person-related characteristics put individuals at risk for altered diurnal fluctuations in stress and mood during COVID-19 lockdown in spring 2020. We collected real-time data multiple times per day across seven consecutive days whilst lockdown measures were in place (April - May 2020, see *Supplementary Material SOM-U* for further details on government restrictions and incidence of infections during the study period). Multiple demographics and mental-health-related factors were included to examine their potential impact on diurnal dynamics of perceived stress and mood. In addition to self-reported data, a subsample of participants provided hair samples for the determination of HCC. We predicted that age, female gender, financial security, depressive symptoms, chronic stress, trait loneliness, and concerns in relation to the COVID-19 crisis would impact perceived stress and mood, and their fluctuations in the daily life of individuals. Furthermore, we predicted changes in HCC because of this global stressor. The current study is a part of an ongoing larger preregistered project (<https://osf.io/gsvdf>).

Method

Participants

To participate in the EMA study, individuals had to be 18 years or older, be fluent in German or Italian, and own an Android device (as required by the EMA app software). Participants were recruited as a convenience sample via emails, postings on social media (e.g., Twitter,

Facebook), advertisements in online media outlets, and using the recruitment software hroot (Bock, Baetge, and Nicklisch 2014). Those participants who finished the study received 20€ monetary compensation and had the chance to win one of ten 100€ vouchers.

There are no clear-cut guidelines concerning an “optimal” threshold of compliance in EMA studies. However, with more missing data, the chance of systematic missingness might increase (Trull and Ebner-Priemer 2020). Therefore, we decided a priori to exclude participants from the statistical analyses who provided data in less than 50% entries during the EMA-period (see Doerr et al. 2015 for a similar approach and rationale). The final sample consisted of 731 participants (70.5% females, $M_{\text{age}} = 31.7$, $SD_{\text{age}} = 11.7$), out of which 480 were residing in Austria, 225 in Italy, and 26 in Germany. Although the focus of the study was on individuals residing in Austria or Italy during the first lockdown, we decided to retain those participants that reported residing in Germany since lockdown restrictions were largely comparable between Austria, Italy, and Germany. Further sociodemographic details are reported in Table 1. Details concerning participant attrition are reported in the *Supplementary Material SOM-R, S1*.

Procedure

Data collection took place between 1st April and 24th April 2020 for the German-speaking sample and between 13th April and 8th May 2020 for the Italian-speaking sample. Eligible participants received an email with a personalized link to the App “movisensXS” (movisens GmbH, Karlsruhe, Germany) and an electronic manual for further study instructions. Directly after downloading the app, participants filled in a brief introductory questionnaire. The EMA period started on the following day and lasted seven consecutive days. On the following day, participants received a link to a final online survey administered through SosciSurvey (SoSci Survey GmbH, Munich, Germany) which took around 30 minutes to complete.

For logistical reasons, only participants residing in Austria provided hair samples. Inclusion criteria were not being pregnant, not currently breast-feeding (which can confound hair cortisol measurements), and having another person that would be willing to collect hair

from them (without risk of infection from COVID-19; e.g., living in the same household). Eligible participants were contacted at the start of May 2020. Previous research has shown that participants are able to successfully collect hair samples for the reliable assessment of hair cortisol when given adequate instructions (Skoluda et al. 2021). Following this approach, eligible participants were sent detailed instructions on how to accurately collect the hair samples. After hair collection, participants were asked to send the hair samples back to our laboratory as soon as possible in a provided envelope.

All participants provided electronic informed consent prior to the first data entry upon the download of the app. The study was approved by the Ethics Board of the University of Vienna (reference number 00553, addendum 0041 for the hair cortisol) and all procedures were undertaken in accordance with the latest revision of the Declaration of Helsinki (2013).

Measures

Sociodemographic and psychometric questionnaires

During the initial introductory questionnaire participants entered their age, gender, country of residence as well as a range of other sociodemographic variables into the app (for a full list please see <https://osf.io/rzqn6/>). Participants were also asked the extent to which they agreed with the following statements: (1) “I am concerned about the effects of the virus on my health”; (2) “I am concerned about the impact of the virus on the health of the most important people in my life”; (3) “I am concerned about the personal financial implications of the crisis”; (4) “I am concerned about the impact of the crisis on my relationships with the most important people in my life.” on visual analogue scales (VAS) ranging from 0 (*do not agree at all*) to 100 (*strongly agree*). We calculated the mean of these four items to create an aggregate measure of COVID-related concerns. Given the novelty of the pandemic, our COVID-related items were based on similar COVID-19 studies which preregistered their methodology (e.g., <https://osf.io/xpey8/>). As a perceived financial security measure, participants answered to the item “How financially secure do you feel at the time being?” on a VAS ranging from 0 (*not at all*) to 100 (*very good*). Both subjective and objective

measures of socioeconomic status are related to psychological well-being (Hoebel et al. 2017; Tan et al. 2020). Nevertheless, we choose a subjective measure, giving its general stronger relationship with well-being (Adler et al. 2000).

In the final online survey, the Perceived Stress Scale was administered to measure self-reported chronic stress during the preceding four weeks (PSS-10; Klein et al. 2016; Mondo, Sechi, and Cabras 2021). Depressive symptoms in the prior two weeks were measured using the depressive symptom subscale of the Patient Health Questionnaire (PHQ-9; Löwe et al. 2002), and the UCLA Loneliness Scale was used to assess trait loneliness (Elbing 1991; Russell, Peplau, and Ferguson 1978). Since there is no Italian version for the UCLA Loneliness scale available, team members who are native Italian speakers translated the German version.

Ecological Momentary Assessment (EMA)

The EMA protocol included five data entries per day for a duration of seven consecutive days. Data entries were scheduled semi-randomly throughout the day (between 10 am - 11 am, 11 am - 2 pm, 2 pm - 5 pm, 5 pm - 8 pm, with minimum time in between prompts of 1 hour 29 minutes) and signalled via an alarm. The fifth and final daily entry was self-initiated before going to bed, with a reminder alarm at 9 pm. Participants were able to postpone data entries for up to 30 minutes. Overall compliance with the EMA protocol was good with data being provided in 78.6% of entries. Participants took on average 2:41 minutes ($SD = 1:38$ minutes) to complete a data entry. Further details concerning compliance are reported in the *Supplementary Material SOM-R, S2*.

Perceived stress. We used a single item to measure perceived stress, as this has been shown to be a both valid and efficient instrument for stress measurement (Lesage, Berjot, and Deschamps 2012). Participants answered the item “At the moment, I feel stressed” on a VAS ranging from 0 (*‘not at all’*) to 100 (*‘very much’*).

Mood dimensions. We used an adapted version of the Multidimensional Mood Questionnaire (Steyer et al. 1997) that has been validated for use in daily diary studies and

is characterized by satisfactory within- and between-person reliabilities (Wilhelm and Schoebi 2007). We changed the original instrument slightly by reverse-scoring inverted items and applying a VAS for each item ranging from 0 to 100 instead of 7-point Likert scales (higher values correspond to higher levels of the respective mood dimension). Participants answered six bipolar items each pair of items constituted one of the three mood dimensions: mood valence (unwell-well; dissatisfied-satisfied), energetic arousal (weak-energetic; tired-awake), and calmness (tense-relaxed; restless-calm).

Additional variables. At the end of each assessment, participants indicated what activity they were currently engaged in at the time of the data entry (either working, studying, or engaging in free time). Furthermore, the start of each assessment was time-stamped, so that a variable indicating time point of the assessment was created. An overview of all items and questionnaires employed in the context of the larger project are available through <https://osf.io/rzqn6/>.

Hair cortisol

Hair growth rate is around 1 cm per month (Wennig 2000). During hair growth, free (i.e., biologically active) cortisol is incorporated into the hair shaft, indicating cumulative HPA axis activity depending on the length of the analyzed hair segment (Stalder and Kirschbaum 2012). In an Austrian subsample, hair collection took place between 8th and 18th of May 2020. We analysed two subsequent segments of hair per participant with a length of 1.5 cm each, reflecting approximately six weeks, respectively. The hair segment most proximal to the scalp reflected the time period from around mid-March 2020 to the end of April 2020, i.e., the time period of the lockdown; while the subsequent hair segment reflected the 6-week pre-lockdown period, ranging from around the beginning of February to mid-March 2020.

HCC for all hair segments was analysed in the Biochemical laboratory of the Faculty of Psychology, University of Vienna, Austria. Each hair segment was washed twice with 3 mL isopropanol to remove external contaminants. After drying, the segments were cut into 1-2 mm pieces and 10.0 ± 0.5 mg of finely cut hair was then transferred to a 20 mL glass tube.

To extract hair cortisol, 1.8 mL methanol was added. After 18 hours, 1.6 mL of the extract methanol supernatant was transferred to 3 mL glass tubes and subsequently evaporated at 50°C under a stream of nitrogen until complete dryness. For the determination of cortisol, samples were resuspended with 225 µL ultra-pure water and then analyzed using commercially available luminescence immunoassay (IBL-Tecan, Hamburg, Germany). Intra-assay variance was below 3% and inter-assay variance was below 8%. HCC is reported in pg/mg.

Statistical analyses

Perceived stress and mood. We conducted linear mixed effects models with random intercepts and slopes using the R package lme4 (Bates et al. 2014; R Core Team 2020), with two levels (observations on level 1 nested within individuals on level 2) and perceived stress and the three mood measures (mood valence, calmness, energetic arousal) as outcome variables, respectively.

Following the recommendations by Aguinis, Gottfredson, and Culpepper (2013), we investigated the main effects of time of day and potential risk factors on the respective outcome in a first model and included cross-level interactions (time x risk factor) in a subsequent model. To examine diurnal fluctuations, we included a time variable centered on 10 am of the respective day, indicating hours passed since 10 am until the respective data entry (EMA time). In addition, the person-related factors of interest (age, gender, COVID-related worries, chronic stress, depressive symptoms, loneliness, and financial security) were added simultaneously as predictors on level 2. Next, for each potential risk factor in each model, we included a cross-level interaction term with EMA time to investigate whether these moderated the relationship between EMA time and perceived stress and the three mood dimensions. We used Satterthwaite's method to test the significance of the predictors with the *lmerTest* package in R (Kuznetsova, Brockhoff, and Christensen 2017). Interactions were explored with simple slope analysis using *sim_slopes* and *interact_plot* from the *jtools* package in R (Long and Long 2019).

All models controlled for whether participants were engaged in free time at the moment of the assessment (free time; 1 = free time, 0 = not free time). This level-1 covariate was participant-mean centered, whereas all continuous person-related factors were grand-mean centered and dummy-coded level-2 variables remained uncentered (Enders and Tofighi 2007). We kept the random effects structure ‘maximal’ (Barr et al. 2013) in all models. Listwise deletion was performed on the level of observations, therefore, the final number of observations included in the models may vary.

To estimate effect sizes, we calculated semi-partial correlation coefficients (r) between each individual predictor and each outcome measure, following the approach of Edwards et al. (2008) and Jaeger et al. (2017). Following directions from Cohen (1992), r values between 0.1 and 0.3 can be interpreted as small, between 0.3 and 0.5 as medium, and greater than 0.5 as large. The associated data and code for all models is available online (<https://osf.io/fdnm7/>).

Hair cortisol. 145 participants residing in Austria provided hair samples. Five participants had to be excluded as the hair samples were too short to capture both time periods of interest. First, we compared the change in HCC of these 140 subjects using a Wilcoxon paired samples t-test to see if there were differences pre-lockdown compared to post the implementation of the lockdown restrictions.

Next, we matched the participants who provided hair cortisol data with the final EMA sample, which resulted in 127 participants (98 female; M_{age} (SD_{age}) = 34.48 (12.55)), i.e., provided complete data from the EMA part of the study and hair cortisol data (see *Supplementary Material SOM-R, S3* for further information concerning the sample). This sample allowed us to test whether any of the potential risk factors were associated with hair cortisol levels during lockdown, we included age, gender, depression, perceived stress, virus concerns, financial security, and loneliness as predictors. As the data were strongly skewed and not normally distributed, we log transformed the raw cortisol values and all linear regression analyses reported below were conducted using the log-transformed values. We

also included pre-lockdown cortisol levels and body mass index (BMI) as control variables in the model.

Results

We report findings for each dependent variable separately (stress, mood valence etc.). First, we report main effects (e.g., diurnal fluctuation, main effect of person-related factors). Next, we report interactions between risk factors and EMA time to investigate how diurnal fluctuations of stress and mood varied by person-related characteristics.

Descriptive Results

The sample consisted of 731 participants (515 female; $M_{age} (SD_{age}) = 31.67 (11.74)$) and most of these participants were in Austria ($n = 480$) and Italy ($n = 225$) during the study period with some also residing in Germany ($n = 26$). Further details of the sample can be found in Table 1.

Compared to values gathered pre-pandemic from a German representative sample (there are no representative values for Austria or Italy available), the present sample reported higher levels of chronic stress (mean PSS = 18.87 in the present study, mean PSS ranging from 11.94 - 12.74 depending on age and sex in Klein et al. 2016) However, this finding is comparable to the one obtained on an Austrian representative sample during the same time period - in April 2020 (PSS-10 mean = 15.97, SD = 7.47; PHQ-9 mean = 6.19, SD = 5.40 in Pieh et al. 2020). Loneliness levels of the present sample did not differ markedly from the average loneliness in a normative sample (mean loneliness score 38.3 in the present study; mean in the normative sample ranges from 31.51 in elderly and 40.8 in students, Russell 1996). Comparing individual PHQ-9 scores to the existing cut-offs scores for severity of depressive symptoms (mild: 5-9, moderate: 10-14, severe: 15-27, Kroenke, Spitzer, & Williams, 2001), 19.29% of the sample reported moderate and 10.12% severe depressive symptoms. This number is notably higher from 5.6% of participants with

moderate and severe symptoms in a German normative sample collected before the pandemic (no representative values available for Austria and Italy) (Kocalevent, Hinze, and Brähler 2013). Nevertheless, it is comparable to the finding on the Austrian representative sample in April 2020, where 21% of participants scoring above the cut-off for moderate depressive symptoms (Pieh et al. 2020).

Figure 1 displays diurnal fluctuations of perceived stress and mood dimensions. Averaged across the whole sample, a mean perceived stress was 29.97 ($SD = 25.89$), mood valence was 63.47 ($SD = 21.33$), calmness was 61.92 ($SD = 22.35$), and energetic arousal was 50.97 ($SD = 23.12$). The intraclass correlation coefficients (ICC) indicated that 46% of the variance in perceived momentary stress, mood valence, and calmness was attributable to person-related differences (level 2), while 54% of the variance could be explained by observational variables (level 1), respectively. For energetic arousal, 18% of the variance could be explained by person-related differences, while 82% of the variance was attributable to differences at the observational level. Details regarding descriptive statistics and correlations within- and between-persons for the outcome variables are reported in the *Supplementary Material SOM-R, S4*.

Table 1**Sample Characteristics**

		Range (sample)	Range (scale)
N	731		
Gender	515 female (70.45%)		
Country of Residence	Austria: $n = 480$ (65.66%) Italy: $n = 225$ (30.78%) Germany: $n = 26$ (3.56%)		
Education	237 (32.42%) postgraduate degree 189 (25.85) undergraduate degree 270 (36.93%) high school 33 (4.51%) middle school 2 (0.27%) elementary school or none		
Age (in years)	$M = 31.67$ ($SD = 11.74$).	[18.00 - 80.00]	
Chronic stress ^a	$M = 18.87$ ($SD = 7.34$).	[1.00 - 40.00]	[0.00 - 40.00]
Depressive symptoms ^b	$M = 8.20$ ($SD = 5.19$).	[0.00 - 27.00]	[0.00 - 27.00]
Loneliness ^c	$M = 38.30$ ($SD = 9.71$)	[20.00 - 72.00]	[20.00- 80.00]
Financial security ^d	$M = 58.62$ ($SD = 31.46$)	[1.00- 100.00]	[0.00- 100.00]
Virus concerns ^e	$M = 49.91$ ($SD = 18.49$)	[2.75- 99.25]	[0.00- 100.00]

Note. The following variables were assessed only once at entry/ baseline (d, e) or on the final day (a-c) by using questionnaires: *a* = Perceived Stress Scale (PSS-10; Klein et al. 2016; Mondo et al. 2021); *b* = Patient Health Questionnaire (PHQ-9; Löwe et al. 2002); *c* = the UCLA Loneliness Scale (Elbing 1991; Russell et al. 1978); or single item measures: *d* = "How financially secure do you feel at the time being?"; *e* = the mean of four items measuring COVID-related concerns.

Figure 1. Diurnal fluctuations of perceived stress and mood. Notes: Displayed are the means (averaged over the whole sample) per measurement time point, respectively. Higher values correspond to a higher level of perceived stress, mood valence, calmness, and energetic arousal, respectively.

Perceived momentary stress

Perceived momentary stress declined throughout the day [estimate = -0.449, $SE = 0.037$, $p < .001$, $r = 0.416$] and engaging in free time was associated with lower stress [estimate = -7.603, $SE = 0.639$, $p < .001$, $r = .430$]. Men reported higher stress levels [estimate = 1.342, $SE = 0.615$, $p < .05$, $r = .081$]. Moreover younger participants reported higher stress levels [estimate = -0.147, $SE = 0.047$, $p < .01$, $r = .115$]. Furthermore, higher chronic stress [estimate = 0.977, $SE = 0.105$, $p < .001$, $r = .327$], more severe depressive symptoms [estimate = 0.443, $SE = 0.150$, $p < .01$, $r = .109$], loneliness [estimate = 0.140, $SE = 0.063$, $p < .05$, $r = .082$] and concerns about the virus [estimate = 0.073, $SE = 0.033$, $p < .05$, $r = .082$] were all significantly associated with higher perceived momentary stress. Financial security [$p = .236$] was not a significant predictor of perceived stress.

When taking cross-level interaction with EMA time into account (i.e., the effect of risk factors on diurnal fluctuations), we found a significant interaction between EMA time and age [estimate = -0.009, $SE = 0.003$, $p < .01$, $r = .110$]. Simple slope analysis revealed that older age (+1 SD) was associated with a steeper decline in stress throughout the day [estimate = -0.564, $SE = 0.052$, $p < .001$] compared to mean-aged [estimate = -0.456, $SE = 0.036$, $p < .001$] and younger (-1 SD) participants [estimate = -0.349, $SE = 0.050$, $p < .001$]. Furthermore, there was a significant interaction between EMA time and financial security [estimate = -0.003, $SE = 0.001$, $p < .05$, $r = .084$]. As with age, at higher (+1 SD) levels of financial security there was a greater decline in stress throughout the day [estimate = -0.541, $SE = 0.053$, $p < .001$] compared to mean [estimate = -0.456, $SE = 0.036$, $p < .001$] or lower (-1 SD) levels [estimate = -0.372, $SE = 0.052$, $p < .001$]. None of the other interactions reached significance (all p -values ≥ 0.092). Therefore, both younger age and less financial security were associated with a reduced decline in stress throughout the day (see Figure 2).

Mood valence

The analysis of main effects revealed that EMA time per se was not associated with mood valence ($p = .53$) indicating that mood valence did not fluctuate during the day. While engaging in free time was associated with higher mood valence [estimate = 4.833, $SE = 0.508$, $p < .001$, $r = .345$], chronic stress [estimate = - 0.725, $SE = 0.083$, $p < .001$, $r = .308$], depressive symptoms [estimate = -0.664, $SE = 0.119$, $p < .001$, $r = .204$], and loneliness [estimate = -0.227, $SE = 0.050$, $p < .001$, $r = .201$] were all associated with lower mood valence.

When investigating cross-level interactions between risk factors and EMA time, there was a significant yet rather small (in terms of effect size) interaction effect of gender [estimate = 0.078, $SE = 0.034$, $p < .05$, $r = .086$]. The slope analysis showed no significant fluctuation of mood valence neither for woman ($p = .065$), no for men ($p = .121$).

There was also a significant interaction between EMA time and depressive symptoms [estimate = 0.019, $SE = 0.008$, $p < .05$, $r = .086$]. Those participants scoring higher on depressive symptoms (+1 SD), whilst having lower mood valence, showed no significant change in mood valence throughout the day [estimate = 0.076 $SE = 0.052$, $p = .147$]. In contrast, those with less depressive symptoms (-1 SD) showed a decline in mood valence throughout the day [estimate = -0.120, $SE = 0.053$, $p < .05$]. Those with mean levels of depressive symptoms showed no significant change in mood valence throughout the day [estimate = -0.022, $SE = 0.031$, $p = .477$].

There was a significant interaction between EMA time and loneliness [estimate = - 0.008, $SE = 0.003$, $p < .05$, $r = .089$]. Lonelier participants (+1 SD) showed a decline in mood valence throughout the day [estimate = -0.103, $SE = 0.046$, $p < .05$, but this decline was not seen in those with mean levels of loneliness [estimate = -0.022, $SE = 0.031$, $p = .478$] and less lonely participants (-1 SD) [estimate = 0.059 $SE = 0.046$ $p = .197$]. None of other interactions reached significance (all p -values ≥ 0.13).

Calmness

The analysis revealed that earlier EMA time [estimate = 0.147, $SE = 0.034$, $p < .001$, $r = .165$], not engaging in free time [estimate = 5.461, $SE = 0.535$, $p < .001$, $r = .374$], being male [estimate = -1.067, $SE = 0.518$, $p < .05$, $r = .076$], higher chronic stress [estimate = -0.931, $SE = 0.089$, $p < .001$, $r = .364$], more depressive symptoms [estimate = -0.473, $SE = 0.126$, $p < .001$, $r = .138$], and greater loneliness [estimate = -0.206, $SE = 0.053$, $p < .001$, $r = .142$], were all associated with less calmness.

There was a significant interaction between EMA time and loneliness [estimate = -0.008, $SE = 0.004$, $p < .05$, $r = .078$]. Less lonely participants ($-1\ SD$) showed an increase in calmness throughout the day [estimate = 0.225, $SE = 0.049$, $p < .001$] as did those reporting mean levels of loneliness [estimate = 0.150, $SE = 0.033$, $p < .001$], whereas lonelier participants ($+1\ SD$) did not show such an increase in calmness throughout the day [estimate = 0.075, $SE = 0.049$, $p = .129$] (see Figure 2). None of other interactions reached significance (all p -values ≥ 0.152).

Energetic arousal

The analysis revealed that later EMA time [estimate = -2.063, $SE = 0.059$, $p < .001$, $r = .793$], younger age [estimate = 0.069, $SE = 0.028$, $p < .05$, $r = .090$], being female [estimate = 1.013, $SE = 0.369$, $p < .01$, $r = .102$], higher chronic stress [estimate = -0.162, $SE = 0.063$, $p < .05$, $r = .096$], having more depressive symptoms [estimate = -0.397, $SE = 0.09$, $p < .001$, $r = .163$], and greater loneliness [estimate = -0.142, $SE = 0.038$, $p < .001$, $r = .137$] and engaging not in free-time [estimate = 6.367, $SE = 0.591$, $p < .001$, $r = .392$] were all associated with lower energetic arousal.

There was a significant interaction between EMA time and gender [estimate = 0.149, $SE = 0.06$, $p < .05$, $r = .093$]. Female participants showed a steeper decline in energetic arousal throughout the day [estimate = -2.166, $SE = 0.065$, $p < .001$] compared to male participants [estimate = -1.868, $SE = 0.100$, $p < .001$]. There was a significant interaction

between EMA time and depressive symptoms [estimate = 0.091, $SE = 0.015$, $p < .001$, $r = .227$]. Those participants with less severe depressive symptoms ($-1\ SD$), whilst reporting greater energetic arousal overall, showed a steeper decline in energetic arousal throughout the day [estimate = -2.547, $SE = 0.094$, $p < .001$], compared to participants with more severe ($+1\ SD$) depressive symptoms [estimate = -1.610, $SE = 0.092$, $p < .001$] or with mean levels of depressive symptoms [estimate = -2.078, $SE = 0.055$, $p < .001$]. Similarly, there was a significant interaction between EMA time and loneliness [estimate = 0.014, $SE = 0.006$, $p < .05$, $r = .082$]. Those with lower loneliness scores ($-1\ SD$), whilst reporting greater energetic arousal overall, showed a steeper decline in energetic arousal throughout the day [estimate = -2.210, $SE = 0.081$, $p < .001$], compared to participants with higher ($+1\ SD$) loneliness scores [estimate = -1.947, $SE = 0.081$, $p < .001$] and mean loneliness scores [estimate = -2.078, $SE = 0.055$, $p < .001$]. There was also a significant interaction between EMA time and financial security [estimate = -0.006, $SE = 0.002$, $p < .001$, $r = .118$]. Participants reporting greater financial security ($+1\ SD$) showed a steeper decline in energetic arousal throughout the day [estimate = -2.262, $SE = 0.080$, $p < .001$] compared to participants with less ($-1\ SD$) financial security [estimate = -1.895, $SE = 0.079$, $p < .001$] and mean financial security [estimate = -2.078, $SE = 0.055$, $p < .001$]. None of the other interactions reached significance (all p -values $\geq .054$).

Figure 2. An overview of the interactions between EMA time and the person-related characteristics. Only significant interactions are shown. Higher values correspond to a higher level of either perceived stress, mood valence, calmness, or energetic arousal.

Hair cortisol concentration (HCC)

A 1.2 pg/mg average increase in HCC was found in a previous study, which employed a similar methodology and investigated changes as a result of the COVID-19 pandemic (Rajcani et al. 2021). In our study, 24 (17.14%) participants showed an increase in HCC of at least 1.2 pg/mg following the lockdown restrictions compared to before, whereas 39 (27.86%) participants showed a decrease of at least 1.2 pg/mg, leaving 77 participants (55%) with relatively stable HCC across hair segments (See Figure 3B). Overall, we found that HCC was higher before lockdown (pre-lockdown median = 4.98 pg/mg, min = 0.54, 1st quartile = 3.12, 3rd quartile = 7.35, max = 28.69) compared to during lockdown (lockdown median = 4.14 pg/mg, min = 0.79, 1st quartile = 2.79, 3rd quartile = 7.26, max = 25.78) and a paired Wilcoxon signed-rank test revealed that this difference was significant ($p < .05$; Figure 3A).

Apart from pre-lockdown HCC which strongly predicted HCC during lockdown (estimate = 0.811, $SE = 0.046$, $t = 17.84$, $p < .001$), no other person related variable was significantly associated with HCC during lockdown (all $ps > 0.14$). When we included the difference between HCC pre- vs. during lockdown as the dependent variable, again, no variables significantly predicted changes in HCC (all $ps > 0.29$). Additional exploratory analysis revealed that changes in HCC did not predict levels of EMA stress or mood.

Figure 3. A boxplot showing hair cortisol concentration (HCC) for each subject before lockdown (pre) and after the lockdown restrictions were implemented (post) (A). The change in HCC after the lockdown restrictions were implemented (post) compared to before (pre) per subject (B). Yellow bars indicate a decrease (28% of participants), and red bars (17%) an increase, of at least 1.2 pg/mg (Rajcani et al. 2021). Most participants (55%) showed no change of at least 1.2 pg/mg as shown by the grey bars.

Discussion

We conducted a large ecological momentary assessment study during COVID-19 lockdown and were able to gain novel insights into the diurnal dynamics of perceived stress and mood during this psychologically taxing period. We found that important person-related characteristics, including age, gender, financial security, depressive symptoms, and loneliness modulated the diurnal dynamics of participants' stress, mood, and arousal. We found an overall decrease in HCC following lockdown in a subsample of participants who provided hair samples, but these changes were neither related to any of the person-related characteristics nor to the EMA measures.

Perceived stress dynamics during lockdown

Overall, perceived stress varied throughout the day with higher values in the morning and a decline towards the evening. This pattern is in line with the findings reported before lockdown in healthy participants (Zawadzki et al. 2019). The diurnal variation in stress was modulated by two person-related characteristics: age and financial security. Younger individuals, besides displaying higher stress levels, showed a less marked decline in their perceived stress throughout the day compared to older participants. A similar effect was seen in less financially secure individuals, as participants with below average financial security also showed a blunted daily decline in perceived stress.

Being younger and more financially insecure could act as a risk factor for perceived stress particularly in the evenings, which is usually an important time of recovery and relaxation (Sonnentag, Binnewies, and Mojza 2008). Income and socioeconomic status have previously been targeted in the cross-sectional studies as factors that contributed to higher mental distress following the COVID-19 pandemic onset (e.g., Bu, Mak, and Fancourt 2021; O'Connor et al. 2020), but this is the first finding that suggests financially insecure individuals display higher perceived stress levels towards the evening. When it comes to the factor of age, our findings of altered diurnal fluctuations in stress add to previous cross-sectional

findings of more adverse effects of lockdown on stress in younger compared to older participants (Banks and Xu 2020; Birditt et al. 2020; Kalaitzaki 2020; Nwachukwu et al. 2020). Findings that link both financial insecurity and younger age to overall higher stress levels, and in our study also to alterations in diurnal stress dynamics, call for further investigation of factors that contribute and prevent adverse responses to the COVID-19 pandemic in these sociodemographic groups. In this regard, younger and/or financially insecure individuals might benefit from engaging in stress-reducing activities that can be easily done at home and in isolation, particularly during the evening or before going to bed. This could include meditation, progressive muscle relaxation, or listening to music which can purposefully downregulate perceived stress levels.

Depressive symptoms, loneliness, and chronic stress did not modulate the effect of time of day on perceived stress, but individuals with more depressive symptoms, loneliness, and chronic stress did report higher overall momentary perceived stress. This findings is in line with previous studies performed during COVID-19 lockdown (e.g., Bu et al. 2021; Holingue et al. 2020; O'Connor et al. 2020; Taquet et al. 2020), which found that individuals with existing mental problems and loneliness showed an increase in their symptomatology and overall distress following the COVID-19 outbreak.

Previous findings have shown women to suffer from greater distress and risk of adverse mental health outcomes during the COVID-19 pandemic (e.g., Gómez-Salgado et al. 2020; O'Connor et al. 2020). In contrast, we found that men reported higher perceived stress than women. Previous (pre-pandemic) research indicates gender/sex-related differences in the use of coping strategies and stress appraisal: while women seem to appraise stressors as more severe, they also use more coping strategies overall and engage in social support seeking more than men (Tamres, Janicki, and Helgeson 2002). Thus, the result of higher stress levels in the daily life of men compared to women might be explained by a lower resilience (Sánchez-Teruel, Robles-Bello, and Valencia-Naranjo 2021) or by a use of less efficient coping strategies during the first lockdown period (Prowse et al. 2021).

However, more research is needed to tease apart sex/gender-related differences in terms of the effect of the COVID-19 pandemic on perceived stress levels.

Mood dynamics during lockdown

Participants reported greater calmness later in the day, whereas mood valence remained stable across measurement time points (Figure 1). A recent review that addressed diurnal variations of well-being measures reported mixed results. Some studies showed increases in mood valence and calmness during the day whilst others did not (see de Vries et al. 2020). The review argued that the effects of time of day on mood tend to disappear when the situational factors such as momentary activity are controlled for, which is a potential explanation for our different results for mood valence and calmness. Furthermore, energetic arousal was higher in the morning and decreased during the day, and showed the biggest change throughout the day compared to the other measures. This pattern is in line with previous studies showing that energetic arousal was higher in the morning and early afternoon and steeply decreased towards the evening (Giurgiu et al. 2019; Stone et al. 1996; Wood and Magnello 1992).

Participants with more depressive symptoms and higher trait loneliness, in addition to displaying lower energetic arousal throughout the study, showed a flattened diurnal curve of energetic arousal (Figure 2, bottom row). This could indicate a state of *hypoarousal* in the mornings and *hyperarousal* in the evenings. Potential underlying causes may be sleep disturbances, as lower social connectedness and higher depressive symptoms have already been related to poorer sleep quality in times of the pandemic (Ernstsen and Havnen 2021; Grey et al. 2020). This is a relevant avenue for future research, as recent findings suggest that feeling sleepy predicts expressing less motivation to initiate social contact, which could lead to further isolation in already vulnerable individuals, resulting in a vicious cycle (Holding et al. 2020; Simon and Walker 2018). Our results also show that lower financial security is related to a less marked decline in energy throughout the day, suggesting that the lower socioeconomic status could act as a risk factor for alterations in diurnal arousal, similarly to

loneliness and depressive symptoms. Interestingly, financial insecurity, depression, and loneliness were associated both with prolonged states of arousal in evenings *and* increased perceived stress levels. Thus, certain more vulnerable individuals may benefit most from relaxing activities, such as mindfulness, music, meditation, in the evenings.

Alterations in the diurnal dynamics of mood valence and calmness were also identified in participants with higher depressive symptomatology and loneliness. Participants who had more depressive symptoms, whilst having lower mood valence overall, tended to show a slight increase as the day progressed. This finding, although somewhat paradoxical at first, fits with previous work showing that individuals with more depressive symptoms tend to show a diurnal peak in positive mood later in the day (Peeters et al. 2006). Greater trait loneliness predicted a decline in mood valence and a diminished increase in calmness throughout the day. Also, more lonely participants reported lower mood valence and calmness across all measurement points. This indicates that individuals with higher trait loneliness tended to be less calm and in a less positive mood, and this was particularly the case later in the day. One potential explanation for this finding is that in the evenings these participants became more aware of their loneliness and/or ruminated more due to the lack of distractions, such as work or studying, which presumably kept them occupied earlier in the day. This could have been particularly important during COVID-19 lockdown where social connectedness was shown to be an important resilience factor (Nitschke et al. 2020). Given that loneliness modulated diurnal dynamics of all three mood measures in a consistent manner, showing a blunted increase of mood valence and calmness and a blunted decrease of energy during the day, our findings suggest that lonely individuals may be a particularly vulnerable group for experiencing diurnal disruptions in mood fluctuations in the context of lockdown restrictions. Thus, besides showing that lonely individuals are a particularly important group that might need supportive interventions in the context of the pandemic (Buecker et al. 2020), we additionally showed that interventions could be most needed towards the evening.

Gender also modulated diurnal dynamics of mood. Although women did not have lower mood across all measurement points, their mood valence tended to decrease during the day, while remaining stable in men. These results partially align with cross-sectional studies that showed women experienced more negative affect during lockdown (De Pasquale et al. 2021; Gismero-González et al. 2020; Pérez-Fuentes et al. 2021). However, although women showed a decrease in mood valence during the day and lower energetic arousal overall, men were less calm and showed heightened energetic arousal in the evenings. Together with the finding that men were more stressed than women, this is in contrast to previous findings that lockdown affected women's mental health more severely (e.g., Gómez-Salgado et al. 2020; O'Connor et al. 2020). However, as mentioned above, studies also showed that women had higher resilience during lockdown than men (Sánchez-Teruel et al. 2021) and that they used more efficient coping strategies (Prowse et al. 2021), which is a possible explanation for our findings.

Finally, we found that chronic stress was related to lower mood, calmness, and energetic arousal overall, but did not modulate their diurnal variation. Also, participants with higher COVID-19 concern did not show any changes in mood but they did report higher perceived stress, and this factor did not affect diurnal variation of either stress or mood. Given that chronic stress and COVID-19 concerns were referring to shorter time periods before the assessment than the other person-related characteristics, we can speculate that either longer-lasting (such as loneliness), more stable (such as financial security), and/or more severe (such as depressive symptoms) person-related characteristics modulate diurnal changes of perceived stress and mood in a consistent manner.

Hair cortisol before and during lockdown

Although there was great variation in the extent to which HCC changed following lockdown, our results show a slight decrease of HCC levels during the lockdown, compared to a pre-lockdown period. However, none of the person-related characteristics were associated with HCC. Thus, although individuals with certain characteristics displayed higher perceived

stress levels, lower mood and altered diurnal fluctuations therein, they did not show marked alterations in biological stress levels in response to the first lockdown overall. Previous studies performed on nurses (Rajcani et al. 2021) and health workers (Ibar et al. 2021) reported an increase in HCC following the pandemic which is in contrast to our findings. Given that frontline health workers are an exceptionally vulnerable and burdened group during the pandemic, it is understandable that the effects of the pandemic on cumulated cortisol levels were more pronounced in this group, compared to the sample in the present study. However, this does not explain the opposite trend of reduced HCC, which was also not modulated by any of the risk factors assessed in the present study.

Two possible and mutually not exclusive explanations for the present finding are seasonal variations in HCC as well as changes in amounts of physical activity during lockdown. Previous research is still inconclusive regarding seasonal variation in HCC, with studies reporting lower HCC during winter and higher HCC levels in summer (Staufenbiel et al. 2015; as well as the opposite Abell et al. 2016). Nonetheless, hair segments represented the period of February/early March 2020 (pre-lockdown) and mid-March/April 2020 (lockdown), thus changes in daylight and/or temperature might have partly influenced the results. Moreover, the present finding can be explained by reduced physical activity during lockdown, given that most of our participants were constrained in their homes and were forced to engage in a more sedentary lifestyle. This idea is supported by research showing that HCC and physical activity levels are positively correlated in young adults (Garcia-Banda et al. 2011; Gerber et al. 2013). Importantly, changes in HCC and its association to potential risk factors were analyzed over the whole sample, which most likely averaged out some of the potential effects in specific subgroups. Although 55% of our sample showed a change in HCC lower than the average change in the previous study performed on nurses (Rajcani et al. 2021), our results indicate that approximately 17% of the participants displayed at least a 1.2 pg/mg increase in HCC, whereas 28% displayed at least a 1.2 pg/mg decrease in response to the lockdown. This raises the question about additional factors (see e.g., Engert et al. 2021) or a cumulative effect of several factors of vulnerability and resilience that might

be related to psychobiological stress responses in certain individuals confronted with lockdown restrictions and the COVID-19 pandemic, which should be examined in future studies.

Strengths and limitations

The present study is one of the few that applied an ecologically valid research approach to examine diurnal dynamics of perceived stress and mood concurrently to biological stress markers during the COVID-19 pandemic in the general population. Moreover, our sample is exceptionally large and covers a wide range of individuals with different sociodemographic characteristics. Importantly, by considering various previously identified risk factors simultaneously, we were able to provide evidence for their unique substantial impact on overall levels of stress and mood and their impact on their diurnal variations. In addition, we included HCC as a stress-related biomarker to gain insight into potential endocrine alterations following the lockdown restrictions. The discrepancy between self-reported and endocrine measures of stress indicates that both capture different aspects of individuals' stress experiences (Nater 2018).

Despite the above-mentioned strengths, the following limitations need to be addressed. Just like many other studies conducted during the COVID-19 pandemic, our study lacks a 'baseline' assessment, which would have allowed us to establish the extent to which the results from the present study are specific to the lockdown period. In this regard, we plan to conduct an additional data collection after the global health crisis is over (or has eased considerably), to follow up on the current findings. Moreover, although the sample covered a high number and wide range of individuals, it was not fully representative of the Austrian and Italian populations. We cannot rule out a potential self-selection bias as participants freely chose to participate in the study and furthermore, only individuals with an Android device could participate. In addition, we did not assess certain variables related to participants' health behaviour or lifestyle (e.g., physical activity, sleep), which otherwise could provide more in-depth explanations for the present findings. In our analyses, we

included all person-related factors simultaneously into the models. While this permitted us to determine each factor's unique contribution to the diurnal dynamics of stress and mood while controlling for all other included factors, we did not determine individuals which combine several of the identified risk factors altogether. Finally, our sampling regime, which started relatively late in the morning (10 a.m.), may have missed early morning changes in perceived stress and mood that have been found to be relevant in some previous studies (Peeters et al. 2006) and a higher sampling rate throughout the day might have revealed a more fine-grained analysis of diurnal dynamics. However, we opted for a moderate sampling protocol to accommodate the study to personal schedules as best as possible and to keep participant burden low during this unusual period.

Conclusions and future directions

The present study emphasizes the need to consider diurnal dynamics of mental health indicators during psychologically taxing periods. The fact that certain person-related characteristics, such as younger age, loneliness, depressive symptoms, were associated with changes in diurnal fluctuations raises the question about underlying psychobiological and behavioural mechanisms on the one hand (e.g., sleep patterns, (mal)adaptive coping behaviours) and hints towards specific time windows of opportunity for the implementation of intervention and prevention strategies on the other hand. These risk factors were unrelated to HCC although HCC decreased following lockdown restrictions. Future research might reveal additional risk factors characteristic for certain vulnerable subgroups that display long-term increases in HPA axis activation in the context of the COVID-19 pandemic. Finally, treatments aiming to improve mental health in individuals suffering from lockdown restrictions might be particularly effective when delivered contingent on individuals' momentary needs. In this regard, investigations into the interplay of individual characteristics, (disrupted) daily stress/mood dynamics, and time point of treatment delivery seems an appealing avenue for future research in the context of precision medicine.

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Author contributions

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 679 draft: A.C.F., P.A.G.F., G.P., E.P., A.S.; Writing – review & editing: C.L., U.M.N., G.S., N.S.
 680 All authors approved the final version of the paper for submission.

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Conflicts of Interests

682 The authors declared no conflicts of interest with respect to the authorship or the publication
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