Supplementary Online Content

Taquet M, Quoidbach J, Fried EI, Goodwin GM. Mood homeostasis before and during the coronavirus disease 2019 (COVID-19) lockdown among students in the Netherlands. *JAMA Psychiatry*. Published online July 29, 2020. doi:10.1001/jamapsychiatry.2020.2389

This supplementary material has been provided by the authors to give readers additional information about their work.

eMethods.

1 Participants and data

Details on the demographics and data collection are fully described elsewhere[1]. The data is publicly and openly available as an Open Science Framework project: https://osf.io/mvdpe/

1.1 Recruitment and study setup

Participants were recruited in the week of March 9, via online advertisements on social media, as well as posters and flyers distributed in the Faculty of Social Sciences of Leiden University, or directly approached by researchers. Participants were all students at Leiden University. They were reimbursed for participation with study credits and the chance to win one of four EUR 25 vouchers. Students received credits proportional to completed ecological momentary assessments (EMA) surveys. Out of the 100 initially recruited, 84 participants completed the baseline survey and 79 completed the EMA. One participant provided no EMA data during lockdown (owing to a technical problem with the EMA app) and was excluded from the analysis. We included the 78 participants who provided EMA data before and during lockdown.

1.2 Timeline and lockdown measures

Participants recorded data between March 16 and March 29 (included). March 23 marks the beginning of strict lockdown measures implemented by the Dutch government. These came on top of lighter measures already taken on March 15. Specifically, the relevant timeline of decisions taken by the Dutch government was as follows:

March 12: All events (concerts, sports) and all meetings with more than 100 people were forbidden.

March 15: Additional measures were taken: sex clubs, coffeeshops, cafés, restaurants, sports clubs, schools, and childcare centres were to remain closed until April 6.

March 16: The prime minister announced that the government chooses not to resort to population confinement measures, but to rely on the measures taken earlier in order to try to assert maximum control over the spread of the virus.

March 23: Stricter social distancing rules were announced. These include:

1. All social gatherings are banned (not just social gatherings involving over 100 people).
2. A maximum of three visitors is allowed in each household, and only if it is possible to keep a minimum distance of 1.5 meter between people.
3. If people (groups of three or more) don’t follow the announced measures, including the 1.5 meter distance rule, they may be fined. Companies can get a fine of up to 4000 euros, while civilians can get a fine of up to 400 euros per person.
4. Mayors will get more power to take additional measures, if and when necessary. This includes closing public spaces, such as parks, playgrounds, beaches, etc. If shops don’t follow the rules, they may be closed as well.
5. Hairdressers and nail salons will be closed.
6. If one person in a household has a fever, the whole household should stay indoors.

Therefore, while some lockdown measures were already in place on March 15, by far the largest bulk of additional measures during the study period were implemented on March 23. The latter implied that many activities involving contact with other people became essentially forbidden and that social life was significantly affected. Using the EMA data collected, we were able to follow the same cohort as they went from a situation in which none of the measures specified on March 23 were implemented to a situation where these lockdown measures were taken.

1.3 Data collection

Participants were prompted 4 times a day (at noon, 3pm, 6pm, and 9pm) to report how they had been feeling for the last three hours on an adapted 6-item version of the Depression Anxiety and Stress Scale (DASS)[2]. Specifically, they were asked how much they endorsed 6 specific feelings or behaviors (0=not at all, 1=slightly, 2=moderately, 3=very, 4=extremely) related to depression, anxiety, and stress:

1) I found it difficult to relax.
2) I felt (very) irritable
3) I was worried about different things
4) I felt nervous, anxious or on edge
5) I felt that I had nothing to look forward to
6) I couldn't seem to experience any positive feeling at all

The rationale for adopting a shorter version of the DASS-21 was to reduce participant's burden, increase compliance, and gather more data that are more reliable.

From the DASS (both DASS-21 and DASS-42), items were selected based on their construct validity and factor loadings on domain-specific constructs[3,4]. Items that substantially overlapped, represented physiological symptoms, or related to severe psychopathology were excluded, as they were deemed less relevant for the target population.

A single mood score was obtained by summing up items and subtracting the result from the maximum (i.e. 24) so that 0 corresponded to the lowest mood and 24 to the highest mood. Because the highest value corresponds to the absence of negative affect, it might represent a neutral mood state rather than a particularly high mood state. This has consequences for the interpretation of mood homeostasis: the tendency for individuals to engage in mood-decreasing activities when their mood is particularly high[5] might not be observed in the present study.

Participants were also asked how much time they spent on a certain activity (0 minutes, 1-15 minutes, 15-60 minutes, 1-2 hours, over 2 hours). The eight activities queried were (i) social interaction, (ii) social media, (iii) listening to music, (iv) procrastination, (v) outdoor activity, (vi) being occupied with the coronavirus (e.g. watching news, talking to friends about it, thinking about it), (vii) thinking about own health or that of one's family or close friends in relation to coronavirus, and (viii) being at home.

The dataset was rearranged so that each entry also contained the previous mood (recorded from the previous questionnaire) as well as the change in mood from the previous to the current questionnaire insofar as one such previous answer was recorded on the same day. In other words, observations were arranged in pairs of consecutive observations as long as they were recorded on the same day and not on two consecutive days. So a total of 3 pairs of observations were available per day per participant when they provided 4 records. Given the high compliance of participants with the ecological momentary assessment (see Table 1 in the manuscript), we elected to use a complete case approach rather than imputing the missing records.

For each participant independently, the average change in mood associated with each "dose" (0 min, 1-15min, ...) of each activity was recorded as the pleasantness of that activity at that dose. For instance, to calculate the pleasantness of "being outdoors for 1-2 hours" for one participant, we averaged the change in mood recorded every time that participant mentioned that they had been outdoors for 1-2 hours. This led to individual-specific estimations of the pleasantness of a specific dose of a specific activity.

The pleasantness of a particular moment was calculated as the mean of the pleasantness of the different activities that the participant was engaged in at that moment. So if a participant mentioned that they had just spent 1-2 hours outdoors, 15-60min at home, 1-15min listening to music, etc, then the pleasantness of that moment was recorded as the mean of the pleasantness of being 1-2 hours outdoors, 15-60min at home, 1-15min listening to music, etc.

To assess whether participants had a history of mental illness, the question "Did you suffer from any prior mental health problems and/or take any psychiatric drugs? Please specify" was asked at baseline. Participants' detailed answers were then checked by a clinical psychologist (co-author EIF) who determined whether the answer qualified as a likely previous diagnosis of mental health disorder. This was done before the data was analyzed for this study (and indeed before this study was even designed).

2 Details of statistical analysis

All analyses were conducted in R version 3.4.3.

The relationship between mood in one questionnaire (named "current mood") and the pleasantness of the moment recorded in the next questionnaire (named "pleasantness of subsequent activities") was first observed by grouping mood values into 6 levels: < 12, 12-14, 15-17, 18-20, 21-23, and 24. This is the relationship shown in Fig. 1a-b. The reason for grouping all mood values < 12 into one group is that they represent a small proportion of all records (4.1% vs 5.0% for mood records between 12-14 alone). The reason for grouping the level 24 on its own is that it represents the absence of negative mood (as all items of the DASS represents negative mood items). This grouping was done for visualization only and all subsequent analyses were conducted with the actual mood values (not grouped).

2.1 Definition of mood homeostasis

As in our previous study[5], we define mood homeostasis as the extent to which a person preferentially engages in mood-increasing activities at time $t+1$ when her mood is low at time t and saves the mood-decreasing activities for when her mood is higher. Mood homeostasis is therefore high if there is a strongly negative correlation between current mood (denoted M_t) and future pleasantness (denoted P_{t+1}). Specifically, the following multivariate linear regression was estimated:

$$P_{t+1} = P_0 + \beta_m M_t + \beta_t T + \beta_d D \qquad [1]$$

where, as in our previous studies[5–7], the covariate T is the time of day (recorded as a categorical variable representing the time at which the participant was prompted and taking on 4 possible values: noon, 3pm, 6pm, or 9pm) and D represents the day of the week (recorded as a categorical variable taking on 3 possible values: weekday, Saturday, or Sunday). Mood homeostasis was then calculated as -1 times the coefficient β_m :

$$\text{MH} = -\beta_m.$$

To guarantee that mood homeostasis varies between -1 and 1, the value of future pleasantness P_{t+1} and current mood M_t were standardized (i.e., their mean was subtracted and the result was divided by the standard deviation). To account for potential clustering of the data owing to multiple observations of P_{t+1} and M_t for each participant, a multilevel approach was used in which a random intercept P_0 was estimated.

Note that the formula that we used to calculate mood homeostasis is slightly different from that in our previous study[5] as we wanted to account for the inter-individual differences in the hedonic response to different activities (e.g., some people find it more pleasurable to go out for a walk while others prefer to listen to music). In our previous study, owing to the large sample size and the fact that it was a case-control study (rather than a cohort study such as here), inter-individual differences were thought to matter less and were largely ignored. As a result the actual value of mood homeostasis may not be directly comparable with previously reported values and the focus should be on group differences or within-subject differences.

2.2. Changes in mood homeostasis between before and during lockdown

To test whether mood homeostasis varies between before and during lockdown, a dichotomous variable (called the "lockdown" variable, I_L) was used to indicate which records were collected until March 22, 2020 (I_L=0) and which records were collected from March 23, 2020 onwards (I_L=1). Using an interaction term between current mood (M_t) and lockdown (I_L) in the regression model allowed us to calculate a coefficient in M_t (and hence a value of MH) separately for the measurements before and the measurements during lockdown:

$$P_{t+1} = P_0 + (\beta_{m,0} + \beta_L I_L)M_t + \beta_t T + \beta_d D \quad [2]$$

MH = $-\beta_{m,0}$ before lockdown

MH = $-\beta_{m,0} - \beta_L$ during lockdown

The null hypothesis that there is no difference between mood homeostasis before and during lockdown was then tested as the null hypothesis that the coefficient of the interaction term is equal to zero (i.e., β_L=0). The corresponding two-tailed P-value was returned by the nlme package (version 3.1-131) in R 3.4.3.

2.3 Mediation analysis of the change in mood homeostasis with range of activities

Mood homeostasis could decrease without a change in the range of activities that people engage in. As an example, imagine that before lockdown, Julia often went outdoors for a walk with a friend whenever her mood was low (in order to boost it) and she preferred keeping grimmer activities like discussing her concerns about COVID-19 and her grandfather's health for when her mood was higher (which invariably decreased her mood). This would help her maintain mood homeostasis. If, during lockdown, she was starting her day with a walk outdoors (even though her mood was already high) and worried about her grandfather's health after the lunchtime news even though her mood was already low, her mood homeostasis would be reduced. But this drop in mood homeostasis would not involve any difference in the range of activities.

On the other hand, imagine that Lucas used to go and play football with his friends whenever his mood was low and go on dates to meet a romantic partner (which tended to generate anxiety and sometimes painful rejections!) whenever his mood was higher. During lockdown, he found it more difficult to do either of those things and his mood homeostasis decreased as a result. This change in mood homeostasis would be in part mediated by a change in the range of activities that he engaged in (both mood-increasing and mood-decreasing activities).

To test whether the change in mood homeostasis was mediated by the range of activities that participants engaged in, we first defined a "range of activities" variable by summing the answers to the questions asking participants the time they spent doing each of the 6 activities (all but "being at home" and "procrastination" which were thought to reflect a decrease in the range of activities): 0 minutes = 0, 1-15 minutes = 1, 15-60 minutes = 2, 1-2 hours = 3, over 2 hours = 4. For instance, if a participant at a particular time reported that they spent 1-2 hours outdoors (scoring 3), over 2 hours in social interaction (scoring 4), 15-60 discussing with friends about the coronavirus (scoring 2), and 1-15 minutes on social media (scoring 1), their range of activities at that time would be 10 points. We then ran a mediation analysis using the lavaan package[8] in R in which the range of activities was a mediator, the lockdown variable was an independent variable, and mood homeostasis was a dependent variable. Note that technically, as mood homeostasis is itself a coefficient in a regression model and the lockdown is a moderator in that regression, the mediation model is actually a mediated moderation[9] but the analysis of the coefficients involved is the same. As is standard in mediation analysis[10], the range of activities was deemed to mediate the association between lockdown and mood homeostasis if the indirect path (i.e., the association between lockdown and mood homeostasis via range of activities) was significantly different from zero. We also report the proportion of the association that is mediated by the range of activities (which is simply the ratio of the indirect effect on the total effect[11]).

2.4 Moderation of the change in mood homeostasis by history of mental illness status

To test whether differences in mood homeostasis were moderated by the presence or absence of a history of mental illness, another dichotomous variable (I_H) was used to indicate which records were collected among participants with a history of mental illness ($I_H=1$) vs not ($I_H=0$). This was used as a second interaction term in the multivariate linear regression model so that, in this part of the analysis, 4 coefficients β_m (and hence 4 values of MH) were calculated: one value before lockdown among participants without a history of mental illness, one value during lockdown among participants without a history of mental illness, one value before lockdown among participants with a history of mental illness, and one value during lockdown among participants with a history of mental illness. Mathematically, the regression model for this analysis thus reads:

$$P_{t+1} = P_0 + (\beta_{m,0} + \beta_{11}\, I_L I_H + \beta_{10}\, I_L \bar{I}_H + \beta_{01}\, \bar{I}_L I_H)M_t + \beta_t T + \beta_d\, D \quad [3],$$

where $\bar{I}_L$ and $\bar{I}_H$ are the opposite of I_L and I_H respectively (i.e., equal to 1 before the lockdown and in the absence of a mental illness respectively). This leads to four values of mood homeostasis:

MH = $-\beta_{m,0}$	before lockdown in participants without a history of mental illness
MH = $-\beta_{m,0} - \beta_{10}$	during lockdown in participants without a history of mental illness
MH = $-\beta_{m,0} - \beta_{01}$	before lockdown in participants with a history of mental illness
MH = $-\beta_{m,0} - \beta_{11}$	during lockdown in participants with a history of mental illness

The association of mental illness status on the change in mood homeostasis was assessed using an F-test in an ANOVA. Pairwise t-tests were also performed to test for differences in mood homeostasis between participants with (vs without) a history of mental illness before lockdown and during lockdown.

2.5 Association between changes in mood homeostasis and changes in mood states

If impaired mood homeostasis is implicated in the mechanisms by which lockdown impacts mental health, then we would expect to observe that larger changes in mood homeostasis are associated with larger changes in mood states. We represented changes in mood states by the change in mean mood Δ_μ of a participant (i.e., the difference between the mean mood during lockdown and the mean mood before lockdown for that individual).

We estimated the association between changes in mood homeostasis and changes in mood states by including the change in mean mood as an interaction term in the regression model (exactly as we did for the association with mental illness status in model [3] except that change in mean mood is a continuous variable rather than a dichotomous one):

$$P_{t+1} = P_0 + (\beta_{m,0} + \beta_L I_L + \beta_{1\mu} I_L \Delta_\mu + \beta_{0\mu} \bar{I}_L \Delta_\mu) M_t + \beta_t T + \beta_d D \qquad [4],$$

and the values of mood homeostasis are therefore given by:

MH = $-\beta_{m,0} - \beta_{0\mu} \Delta_\mu$ before lockdown (i.e., when I_L= 0 and $\bar{I}_L$=1)

MH = $-\beta_{m,0} - \beta_L - \beta_{1\mu} \Delta_\mu$ during lockdown (i.e., when I_L= 1 and $\bar{I}_L$=0)

The relationship between the change in mood homeostasis and the change in mean mood is then:

$$\Delta \text{MH} = -\beta_L - (\beta_{1\mu} - \beta_{0\mu}) \Delta_\mu.$$

The change in mood homeostasis is thus composed of a term related to the lockdown ($-\beta_L$) regardless of mean mood and a term related to the mean mood ($\Delta \text{MH}_\mu = -(\beta_{1\mu} - \beta_{0\mu})\Delta_\mu$).

This allows us to calculate the additional change in mood that occurs for any additional change in mood homeostasis. As an illustration of the effect, we set ΔMH_μ to 0.1 and calculate the corresponding Δ_μ. To provide more insight into the effect size of that association, we also assess what the corresponding change in mean mood would imply for a hypothetical individual who would start with a mean mood equal to that of the mean of the population. An ANOVA applied to model [4] allows us to assess whether there is a significant interaction between change in mood and change in mood homeostasis, i.e., whether the terms in $\Delta_\mu \times I_L \times M_t$ (which have two degrees of freedom) explain a significant part of the variance.

Of note, mood homeostasis was thus calculated as a single multilevel regression model (model [1]) and its associations with other variables are tested using interaction terms (model [2], model [3], and model [4]). This approach means that the control for covariates is pooled at the population level and that individual participants with fewer pairs of observations contribute less to the fixed effect on which the analysis is focused. This approach does not require to set a cut-off on the number of observations recorded per individual which is necessarily arbitrary and results in information loss. This is in contrast with an analytic approach in which a mood homeostasis coefficient is calculated for each individual independently and then subsequently analyzed as if all coefficients were equally reliable (while those calculated from fewer data points are clearly not).

3 Dynamic simulations

As in our previous study[5], dynamic simulations were used to model the mood timelines of 100 simulated subjects with high mood homeostasis (taken as the value of mood homeostasis before lockdown in the whole cohort) and 100 simulated subjects with low mood homeostasis (taken as the value of mood homeostasis during lockdown in the whole cohort). For each simulated subject, a 5-year timeline was simulated with 3 records per day. The dynamic simulation proceeded by estimating the next pleasantness (pleasantness at time $t+1$, i.e., P_{t+1}) from the current mood (mood at time t, i.e., M_t) and then estimating the next mood by adding the pleasantness (as it is a measurement of the change in mood resulting from engaging in a particular set of activities) to the current mood.

Estimating the next pleasantness from the current mood was achieved using the regression model [1] in which the coefficients were those estimated from the data. To account for the uncertainty in the estimated coefficients of model [1], their values were randomly drawn at each iteration of the dynamic simulation from a normal distribution with a mean equal to their estimated value and a standard deviation equal to the standard deviation of the estimate.

Each timeline thereby generated for each of the 200 simulated subjects was tested for the presence of episodes of depressed mood defined based on a quantitative interpretation of the DSM-V/ICD-11 criteria (as was done in our previous study[5]): mood records that are constantly at least one standard deviation below the individual's mean mood for at least 14 consecutive days.

The results from this simulation process allows to translate differences in mood homeostasis into incidence of episodes of depressed mood which are more clinically meaningful. As with any mathematical model, they are based on several assumptions whose validity in the real world needs to be critically appraised. In particular, the following assumptions are made in the simulation process:

1) The relationship between current mood and future pleasantness can be accurately represented by the linear regression model [1].
2) The pleasantness of activities for each individual is stable over time and does not depend on other contextual variables.
3) Future mood can be accurately estimated from current mood by adding the contribution to mood of a combination of activities that the participant engaged in between two questionnaires.
4) The activities that were not recorded as part of this study were either not mood-modifying or would affect mood in a way that is compatible with the calculated values of mood homeostasis.

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