nature portfolio

https://doi.org/10.1038/s41562-022-01291-0

# Supplementary information

# Sleep during travel balances individual sleep needs

In the format provided by the
authors and unedited

# Sleep during travel balances individual sleep needs

Sigga Svala Jónasdóttir, James Bagrow, and Sune Lehmann

December 22, 2021

## Supplementary Information

### Data Pre-processing

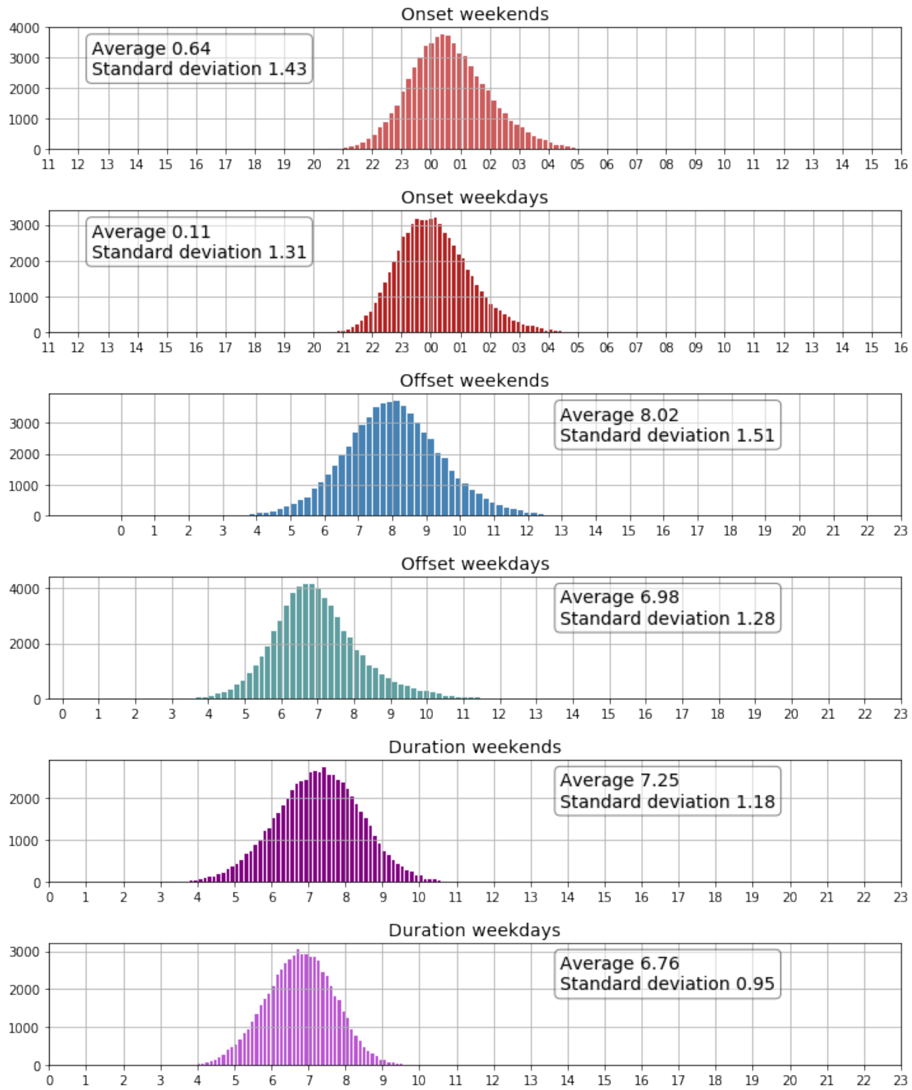
The raw data consists 1-minute epochs of sleep activity which are aggregated into entries with start and end time, in total $\sim$ 820 million rows. In the first pre-processing step we i) merge consecutive sleep activity entries if there are 60 minutes or less between them, ii) impose that entries must start within the time range 19:00-12:00 (day +1), and end within 22:00-15:00 (day +1), iii) if there are multiple entries per day which fulfill these criteria, then we choose the longest entry as nighttime sleep and lastly, iv) we filter entries by sleep duration, and require duration to be within the range 3-13 hours (following Roenneberg et al. (2003)).[9] This step reduces the dataframe down to $\sim$ 30.8 million rows. We note that sleep duration for each entry is calculated as the time from sleep onset to offset, but where we subtract wake-up time after sleep onset (WASO). The entries of nighttime sleep are then matched with stop locations, inferred from GPS traces using the infostop algorithm.[2] The final stop location an individual arrives at, at the end of the day (and before nighttime sleep begins) is marked as the sleep location, but only if the individual does not leave the location until after sleep has ended. After having implemented that, we retain $\sim$ 10.2 million rows. Then we make sure demographic information was reported by the individual, which downsizes the dataframe to $\sim$ 8 million nights (rows).

At this point in the process, we also require individuals to decent data quality or at least 8 nights of data and 70 % should take place at the same location. Furthermore, nights recorded away from home are at least in 20 km distance from home location – leaving us with approximately $\sim$ 6.23 million nights of data.

Then we apply a data-driven filtering to remove outliers based on sleep onset and offset. We look at the distribution of sleep onset and offset separately on weekdays and weekends (Supplementary Figure 1) and set filters to be 3 standard deviation away from the mean, or

- 20:24 $\leq$ onset weekends $\leq$ 04:52 and 03:59 $\leq$ offset weekends $\leq$12:52
- 20:28 $\leq$ onset weekdays $\leq$ 03:59 and 03:21 $\leq$ offset weekdays $\leq$ 11:25

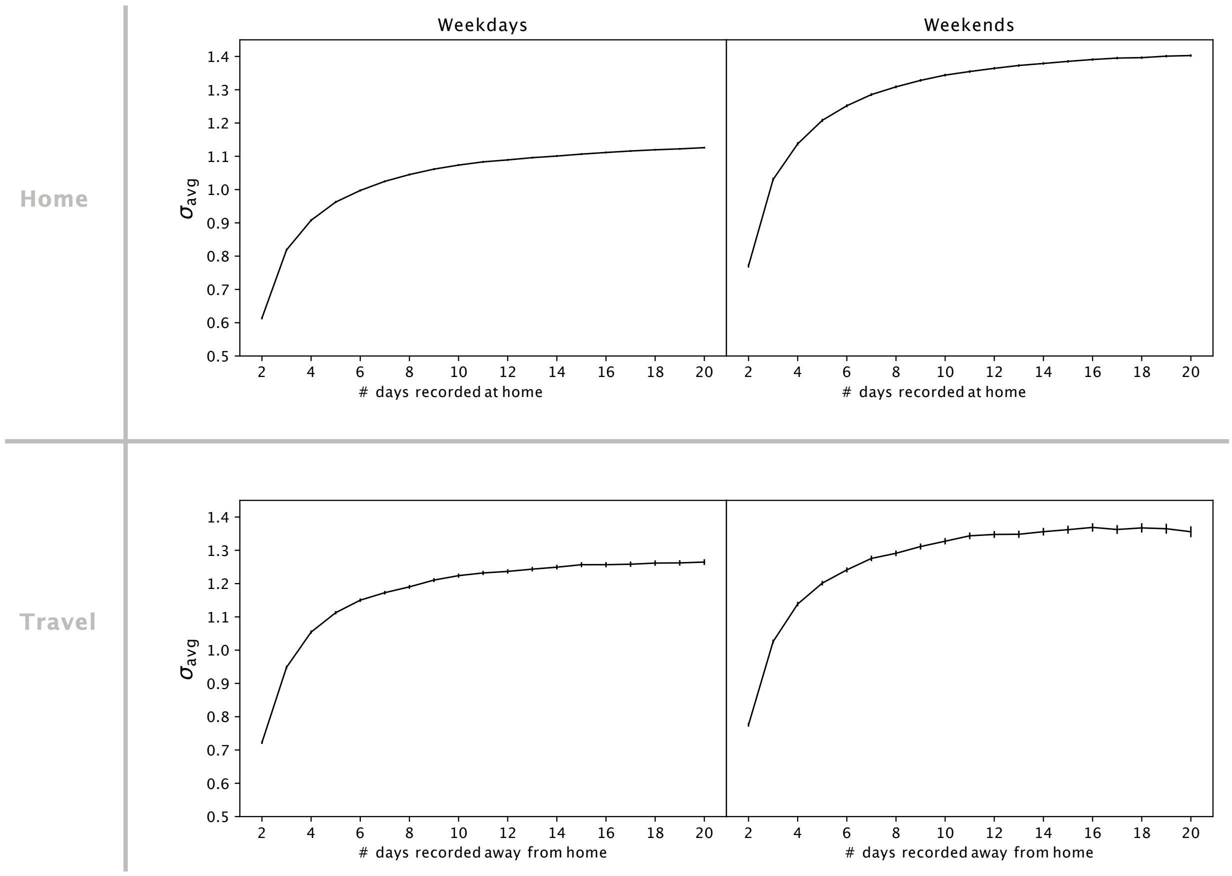
After this step we keep $\sim$ 5.8 million nights. Individuals are then required to have at least 10 nights recorded at home and 2 travel nights (separately on weekends and weekdays) and 70 % of their nights should take place at home. The home location is defined as the most common sleep location. After this step we retain $\sim$ 3.24 million nights and in the final step, we make sure that no variables are missing, leaving us with with $\sim$ 3.17 million nights.




**Supplementary Figure 1:** Distribution of sleep onset, offset duration plotted separately for weekdays and weekends

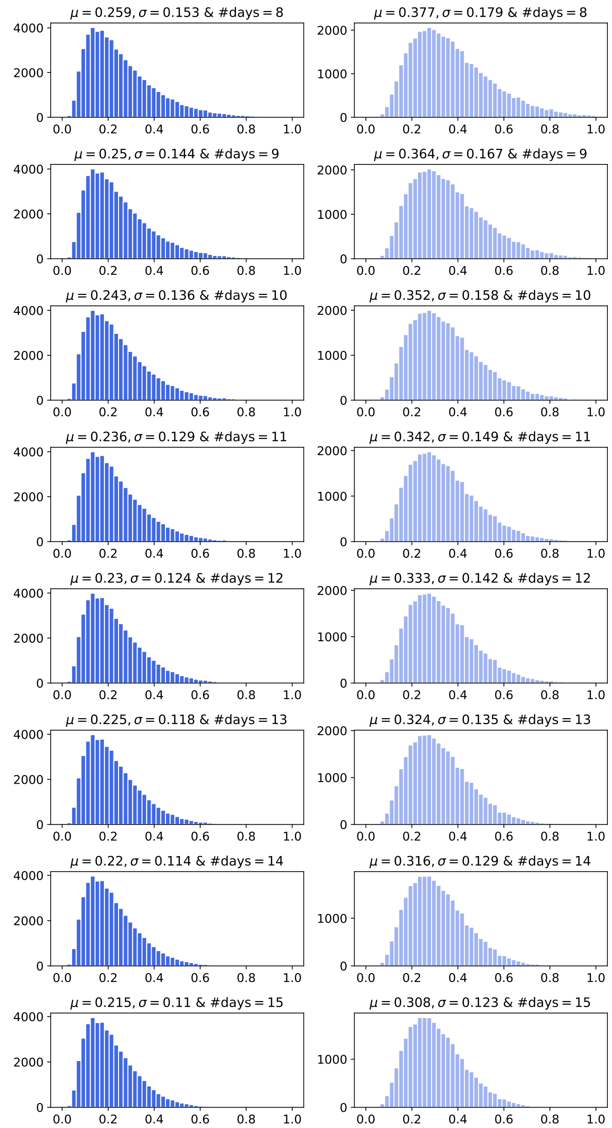
# Filtering & Inclusion Criteria

To motivate our choice for the minimum number of nights required per individual, we examine the development of the standard deviation for sleep duration by the number of days recorded, both at home and away from home (Supplementary Figure 2). The standard deviation seems to stabilize around 10 recorded nights, both at home and away from home. That threshold is reasonable for at nights at home but would eliminate majority of our data (more than 90 %) if applied to travel-nights. Thus, we decided to require individuals of two recorded nights away from home by *day type*. One should pay attention to the fact that individuals can be included for the analysis just on either weekdays or weekends – not necessarily both day types.




**Supplementary Figure 2:** Development of the standard deviation of sleep duration aggregated by number of nights recorded at home and away from home. $N_{weekdays} = 19\,812$, $N_{weekends} = 13\,515$ and the error bars represent the standard error of the mean (SEM).

In most of our analysis we use the median sleep duration to quantify typical at home behaviour, consequently we also examine how the distributions for the standard error of the median (SEMe) develops as the inclusion criteria changes (Supplementary Figure 3). Naturally, the distributions become tighter, the average and standard deviation decrease in magnitude as the number of days required per individuals is increased. We chose to require individuals of 10 recorded nights at home and by day type.




**Supplementary Figure 3:** Distributions for the standard error of the median (SEMe) by day type while changing the number home-nights required per individual (weekdays are represented in the left column and weekends in the right)

# Comparison of country-level statistics to external large-scale data sets

As a way of ensuring the reliability of our dataset, we assess whether aggregates of sleep estimates in our data converge with prior published data-sets. We note that this comparison was first reported in a previously published paper of ours (*Gender Differences in Sleep Patterns and Variability Across the Adult Lifespan: A Global-Scale Wearables Study*).[5]

Specifically, we compare country-level estimates of sleep metrics from our sample to several previously published sleep studies and surveys. We compare to results from Walch *et al.* (A global quantification of "normal" sleep schedules using smartphone data), Roenneberg *et al.* (Epidemiology of the human circadian clock), Ong *et al.* (Large-scale data from wearables reveal regional disparities in sleep patterns that persist across age and sex) and Ford *et al.* (Trends in Self-Reported Sleep Duration among US Adults from 1985 to 2012).[4,8,10,13]

**Walch *et al.* (2016)** We calculate country level averages of sleep onset, offset and duration from Figures 3A) and B) in the Walch *et al.* paper, thus they may differ marginally from actual estimates.[13] The data in Walch *et al.* paper is collected with self-reports of 'typical bed and wake-time' rounded to the nearest hour for 5450 users. In order to generate comparable statistics, we begin by estimating individual averages by day-type (weekday and weekend-nights separately), and then compute weighted overall averages using a standard weekday-weekend ratio (2/7 weekend-nights and 5/7 weekday nights average). Before reviewing the results, we note that; **i)** there are fewer users (5450) in the Walch *et al.* sample, **ii)** it is uncertain how comparable the samples are in terms of underlying demographics (especially age and gender) at country level and **iii)** we use objective multi-night recordings to obtain country-level averages, while Walch *et al.* used self-reported typical bed and wake-up hours (single estimates), where they did not disclose whether these pertained to weekdays, weekends or overall average behavior.

Supplementary Tables 1-3 illustrate the comparison between the two samples. The estimates of country-level averages for sleep duration are higher in Walch *et al.* sample (0.94 hrs at the most), but the relative order of magnitude by countries matches well between the two samples – e.g. both report the Netherlands to have the highest average sleep duration while Japan and Singapore have the lowest. Similarly, country-level averages of bed and wake time were earlier in Walch *et al.* sample, but the countries with earliest and latest bed and wake-up time are the same across data-sets. We use a statistical measure, the Spearman rank correlation, to quantify how well the three measurements correlate between the two data-sets and find $\rho_{onset} = 0.67$, $\rho_{offset} = 0.74$ and $\rho_{duration} = 0.78$ where all three estimates are statistically significant ($p<0.05$).

| Country | Average sleep duration [hrs] Walch *et al.* | Average sleep duration [hrs] Study sample | Number of users in study sample |
|---|---|---|---|
| Netherlands | 8.14 | 7.49 | 586 |
| Belgium | 8.10 | 7.37 | 202 |
| France | 8.10 | 7.44 | 2409 |
| Australia | 8.10 | 7.34 | 677 |
| Canada | 8.03 | 7.22 | 173 |
| Italy | 7.94 | 7.18 | 898 |
| United Kingdom | 7.94 | 7.41 | 3900 |
| United States | 7.92 | 7.08 | 941 |
| Switzerland | 7.90 | 7.33 | 518 |
| China | 7.89 | 6.96 | 2359 |
| Denmark | 7.87 | 7.32 | 473 |
| Spain | 7.86 | 7.09 | 3394 |
| Mexico | 7.81 | 6.87 | 461 |
| Germany | 7.74 | 7.37 | 7140 |
| Brazil | 7.62 | 6.91 | 201 |
| Japan | 7.50 | 6.47 | 17231 |
| Singapore | 7.48 | 6.72 | 275 |

**Supplementary Table 1:** Comparison of average sleep duration from the study sample to statistics from the data-set in Walch *et al.* study

| Country | Average sleep onset [hh:mm] Walch *et al.* | Average sleep onset [hh:mm] Study sample | Number of users in study sample |
|---|---|---|---|
| Australia | 22:49 | 23:43 | 677 |
| Belgium | 22:53 | 00:03 | 202 |
| United States | 22:57 | 00:11 | 941 |
| Canada | 23:03 | 00:19 | 173 |
| Denmark | 23:05 | 23:42 | 473 |
| Switzerland | 23:09 | 23:49 | 518 |
| Netherlands | 23:09 | 00:03 | 586 |
| United Kingdom | 23:11 | 23:53 | 3900 |
| France | 23:20 | 00:03 | 2409 |
| Germany | 23:21 | 23:42 | 7140 |
| Japan | 23:29 | 00:23 | 17231 |
| Mexico | 23:32 | 00:28 | 461 |
| China | 23:36 | 00:42 | 2359 |
| Brazil | 23:36 | 00:25 | 201 |
| Italy | 23:45 | 00:17 | 898 |
| Singapore | 23:48 | 00:37 | 275 |
| Spain | 23:51 | 00:43 | 3394 |

**Supplementary Table 2:** Comparison of average sleep onset from the study sample to statistics from the data-set in Walch *et al.* study

| Country | Average sleep onset [hh:mm] Walch *et al.* | Average sleep onset [hh:mm] Study sample | Number of users in study sample |
|---|---|---|---|
| Australia | 06:52 | 07:10 | 677 |
| United States | 06:52 | 07:23 | 941 |
| Denmark | 06:53 | 07:09 | 473 |
| Belgium | 06:56 | 07:32 | 202 |
| Japan | 06:58 | 06:58 | 17231 |
| Switzerland | 06:59 | 07:16 | 518 |
| Canada | 07:03 | 07:39 | 173 |
| Germany | 07:07 | 07:11 | 7140 |
| UK | 07:07 | 07:25 | 3900 |
| Brazil | 07:11 | 07:26 | 201 |
| Singapore | 07:15 | 07:26 | 275 |
| Netherlands | 07:15 | 07:40 | 586 |
| Mexico | 07:19 | 07:27 | 461 |
| France | 07:24 | 07:36 | 2409 |
| China | 07:27 | 07:45 | 2359 |
| Italy | 07:39 | 07:36 | 898 |
| Spain | 07:40 | 07:56 | 3394 |

**Supplementary Table 3:** Comparison of average sleep offset from the study sample to statistics from the data-set in Walch *et al.* study

**Roenneberg *et al.* (2007)** Next we compare estimates of sleep duration to those reported by Roenneberg *et al.* (2007). The data-set was collected with the Munich Chronotype Questionnaire therefore consists of retrospective and self-reported estimates of sleep duration on weekdays and weekends separately. Since the users in Roenneberg *et al.* sample are predominantly from Germany, Austria, Netherlands and Switzerland, we only conduct the comparison users from those geographic regions.[10] Supplementary Table 4 reveals that estimates of average sleep duration across the two data-sets closely corresponds, with a weekday average absolute deviation of 3.9% and weekend average absolute deviation of 5.1%. For both weekdays and weekends, our sample has a higher ratio of users in the middle group (7-7.5 hours weekdays, 7.5-8 hours weekends) but fewer are in the group with the longest sleep duration. The percentage of users in the group with shortest sleep duration matches well (1.4% avg. absolute deviation).

| Sleep duration | Roenneberg et al. [% users] | Study sampe [% users] |
|---|---|---|
| **WEEKDAYS** | | |
| < 7.0 hours | 41.0 % | 38.9 % |
| 7.0 - 7.5 hours | 21.0 % | 26.8 % |
| > 7.5 hours | 38.0 % | 34.3 % |
| **WEEKENDS** | | |
| < 7.5 hours | 34.0 % | 34.7 % |
| 7.5 - 8.0 hours | 15.5 % | 22.7 % |
| > 8.0 hours | 50.5 % | 42.6 % |

**Supplementary Table 4:** Ratio (%-point) of users within certain range of sleep duration (separately for weekday and weekend-nights) for Roenneberg *et al.* data-set and study sample

**Ong *et al.* (2019)** Ong *et al.* is a study with nearly half a million objectively measured nights of sleep from $\sim$ 24 000 users living in five different countries. The data-set from Ong *et al.* and study sample might be the most compatible for comparison since they both consist of objective multi-night recordings in-situ from wearable devices. However, they differentiate on couple factors; **i)** there are different types of wearable devices used to measure sleep (Fitbit in Ong *et al.* paper), **ii)** the sample from Ong *et al.* has higher number of users per country but fewer countries, **iii)** there is a higher proportion of female users in Ong *et al.* study and **iv)** a slightly wider age range than in the study sample of this project.

We examine the percentage of users sleeping more than 7 hours by country, separately on weekends and weekdays (see Supplementary Table 5). These proportions correspond closely, with a country-level differences between data-sets averaging at $\sim$ 3.5 percentage points. The smallest national deviation between samples was for Hong Kong (.4%) on weekdays, and the largest difference (7.3 %) was for South Korea on weekdays.

| Country | Australia | Hong Kong | Singapore | South-Korea |
|---|---|---|---|---|
| **WEEKDAYS** | | | | |
| **Ong *et al.*<br>% users w/ duration >7 hrs** | 61.0 % | 34.0 % | 27.0 % | 29.0 % |
| **Study sample<br>% users w/ duration >7 hrs** | 65.7 % | 33.6 % | 25.0 % | 21.7 % |
| **WEEKENDS** | | | | |
| **Ong *et al.*<br>% users w/ duration >7 hrs** | 74.0 % | 58.0 % | 51.0 % | 52.0 % |
| **Study sample<br>% users w/ duration >7 hrs** | 76.5 % | 56.6 % | 57.8 % | 48.6 % |

**Supplementary Table 5:** %-point of users sleeping 7 hours or more (separately on weekday and weekend-nights) for Ong *et al.* and study sample

Furthermore, we compare the average of sleep onset, offset and duration by country and gender between the two samples. The averages for Ong *et al.* data-set are estimated from Figure 2A) in the paper, thus uncertainties might be imposed.[8] In Supplementary Table 6) we see that the deviations between our sample and Ong *et al.* is larger for sleep onset (ranging 18 - 36 minute difference) than for wake times (ranging 2 - 14 minute difference) and sleep duration (ranging from 2-45 minutes). The regional disparities identified in Ong et al. can clearly be identified in our sample as well. The differences for sleep onset and duration across data-sets cannot be explained directly, but the data-sets might differentiate in terms of age and gender representation of users, or the devices measure sleep onset differently.

| | **Australia** | | **Hong Kong** | | **Singapore** | | **South-Korea** | |
|---|---|---|---|---|---|---|---|---|
| **WOMEN** | **Ong *et al.*** | **Study sample** | **Ong *et al.*** | **Study sample** | **Ong *et al.*** | **Study sample** | **Ong *et al.*** | **Study sample** |
| Sleep onset [hh:mm ± mm] | 22:51 | 23:22 ± 4 | 00:14 | 00:50 ±4 | 23:57 | 00:24 ± 7 | 23:51 | 00:21 ± 3 |
| Sleep offset [hh:mm ± mm] | 06:45 | 06:57 ± 3 | 07:34 | 07:45 ±4 | 07:06 | 07:18 ± 7 | 07:11 | 07:13 ± 3 |
| Sleep duration [hours] | 7.28 | 7.46 ±0.05 | 6.09 | 6.84 ± 0.07 | 6.56 | 6.80 ± 0.08 | 6.71 | 6.74 ± 0.03 |
| **MEN** | **Ong *et al.*** | **Study sample** | **Ong *et al.*** | **Study sample** | **Ong *et al.*** | **Study sample** | **Ong *et al.*** | **Study sample** |
| Sleep onset [hh:mm ± mm] | 23:06 | 23:40 ± 3 | 00:27 | 00:45 ± 3 | 00:00 | 00:29 ± 4 | 00:00 | 00:34 ± 1 |
| Sleep offset [hh:mm ± mm] | 06:43 | 06:52 ± 3 | 07:35 | 07:27 ± 3 | 07:00 | 07:04 ± 3 | 07:07 | 07:02 ± 1 |
| Sleep duration [hours] | 7.0 | 7.09 ± 0.04 | 6.5 | 6.6 ± 0.04 | 6.45 | 6.50 ± 0.05 | 6.5 | 6.37 ± 1 |

**Supplementary Table 6:** Average sleep onset, offset and duration (with SEM for the study sample) by country and gender separately for Ong *et al.* data-set and study sample

**Ford *et al.* (2015)** Lastly, we compare measures of average sleep duration by gender and age group for a subset users residing in the US to self-report data from the US National Health Interview Survey conducted in 2012. The results are listed in Supplementary Table 7. The estimates for men differentiate the most for the youngest and oldest groups (18-24 and 55-65), while the standard error of the mean overlaps for other age groups (except slight deviation for age group 35-44). The differences across the two data-sets is larger for women, but there are fewer women in the sample than men ($N_{women} = 317$ and $N_{men} = 624$). Furthermore, we can not know how well the sociodemographic composition of the two samples correspond.

| **Age group** | **18-24** | **25-34** | **35-44** | **45-54** | **55-64** |
|---|---|---|---|---|---|
| Men NHIS data-set [hrs ± hrs] | 7.45 ± 0.05 | 7.08 ± 0.03 | 6.99 ± 0.03 | 6.94 ± 0.04 | 7.09 ± 0.03 |
| Men study sample [hrs ± hrs] | 7.08 ± 0.07 | 7.08 ± 0.05 | 6.86 ± 0.06 | 6.84 ± 0.04 | 6.82 ± 0.1 |
| Women NHIS data-set [hrs ± hrs] | 7.46 ± 0.04 | 7.13 ± 0.03 | 7.05 ± 0.03 | 6.98 ± 0.03 | 7.05 ± 0.03 |
| Women study sample [hrs ± hrs] | 7.31 ± 0.2 | 7.53 ± 0.08 | 7.41 ± 0.08 | 7.37 ± 0.08 | 6.94 ± 0.1 |

**Supplementary Table 7:** Comparison of average sleep duration (with SEM) by gender and age group for users in the study sample residing in the US to estimates from the US National Health Interview survey sample (2012)

## Calculation of Social Jetlag

Wittman et al. (2006) developed a concept to describe this misalignment between the biological clock and social clock called *social jetlag*, and is estimated by calculating the difference between midsleep on free days (proxied with weekends) and work days (proxied with weekdays).[15]

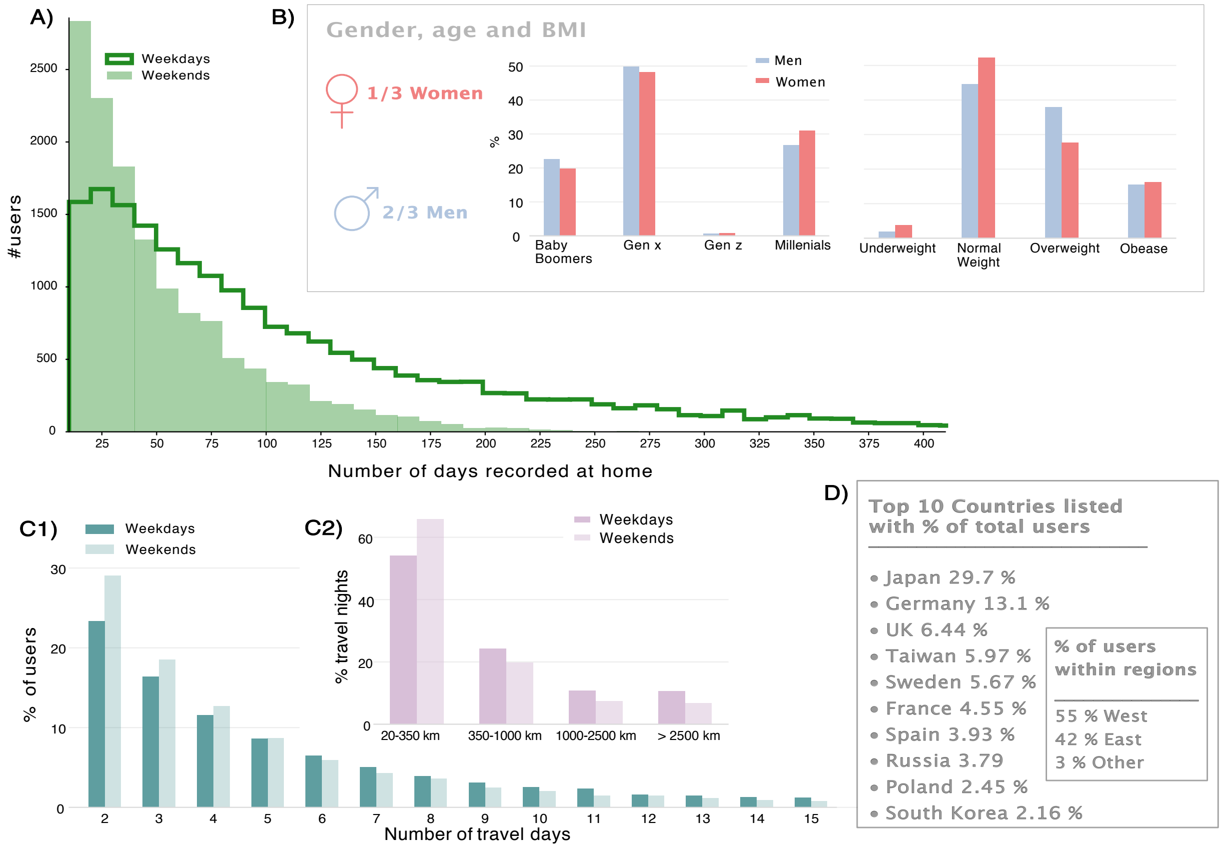
$$Social\ jetlag = MSF - MSW \tag{1}$$

where $MSF$ denotes midsleep on free days (weekends) and $MSW$ midsleep on work days (weekdays).

## Data Coverage & Demographics

Sleep behaviour is dependent on internal and external processes and differentiates by demographic variables such as gender, age, cultural context and day type. To explore those effects we use individual-level covariates; gender (female/male), generations (Baby Boomers born 1946-64, Gen X born 1965-80, Millennial's born 1981-96 and Gen Z born 1997 or later) and BMI categories (underweight/normal weight/overweight/obese) which were labelled according to the World Health Organization classification.[3,14] There are multiple studies which connect weight gain, and higher BMI-level with shorter sleep duration and poorer sleep quality.[11,12] There are large disparities in sleep patterns across cultures, especially the contrast between Eastern (Asia) and Western (Europe and North America) regions. Studies have shown that sleep duration is shorter and bed times later among people residing in the East than those living in the West.[6–8,13] Thus, we use region of residence (also called `East/West`) as a covariate where East represents residents in Asia and West for those living N-America and Europe. All plots and models are implemented separately for weekdays and weekends because of likely differences in the social structure over the course of the week. Since we do not directly observe schedules, we assume the likelihood of work days is highest on weekdays and work-free days is highest on weekends.[15] We define weekdays (work-days) and weekends (work-free days) differently based on country of residence. In Supplementary Table 8 we list countries with different work-free weekdays than Saturday and Sunday.[1]

Supplementary Figure 4 visualises 1) the distribution of the number days users have recorded at home and away from home, 2) how individuals distribute by gender, BMI categories and generations, 3) lists out the ten largest geographic regions and 4) shows how far away from home travel-nights typically are. Approximately 1/3 of the sample is women and 2/3 men. Most individuals are either normal weight or overweight and from generation x or millennial's. Individuals distribute similarly by age and BMI for both genders. Most travel-nights are 1000 km or less away from home. There are dominant geographic regions in the sample, where more than 60 % of individuals live in 5 countries. We do explore and control for the effect of *all* demographic variables in our analysis.

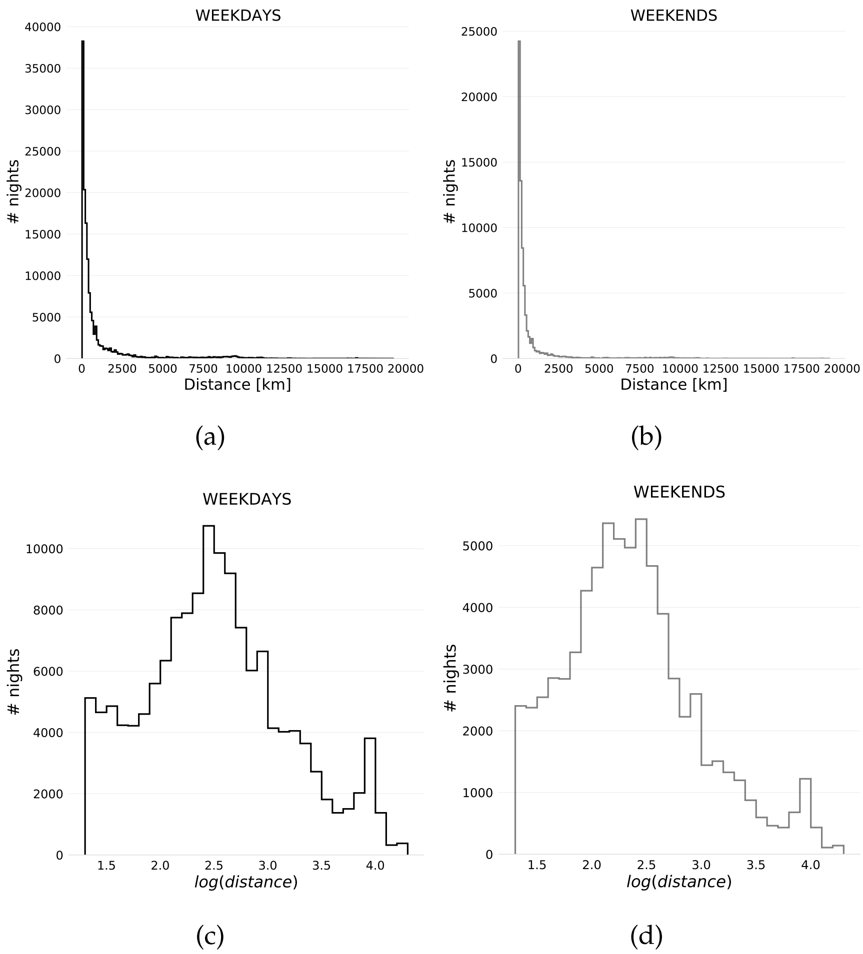



**Supplementary Figure 4: A)** Displays the distribution of number of days individuals have recorded at home on weekends and weekdays. **B)** Illustrates the ratio of female and male individuals and how they distribute by BMI categories and generations. **C1)** Shows the percentage of individuals by number of travel days, separately on weekdays and weekends. **C2)** Displays how travel-nights distribute by distance categories separately on weekends and weekdays. **D**) Lists the top ten countries with most residence and the percentage of individuals living there, as well as the percentage of individuals living within the three regions (East/West/Other)

| **Weekends or work-free days:** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Thursday & Friday** | Algeria | Bahrain | Bangladesh | Djibouti | Egypt | Iran | Iraq | Israel |
| | Jordan | Kuwait | Libya | Maldives | Nepal | Oman | Palestine | |
| | Qatar | Saudi Arabia | Sudan | Suriname | Syria | United Arab Emirates | Yemen | |
| **Wednesday & Thursday** | Afghanistan | | | | | | | |
| **Sundays** | India | Malaysia | | | | | | |

**Supplementary Table 8:** List of countries with weekends or work-free days on other days than Saturday and Sunday

We visualise the distribution of distance travelled in Supplementary Figures 5 a) and b) for weekday and weekend nights separately. The plot shows that the distribution is approximately log-normal. This can verified by visual inspection in Supplementary Figure 5 c) and d) that illustrate the distribution of $log_{10}(distance)$. Notably, one can observe the 20 km cutoff (minimum distance for travel nights) on the left side of the distributions in Supplementary Figures 5 c) and d).



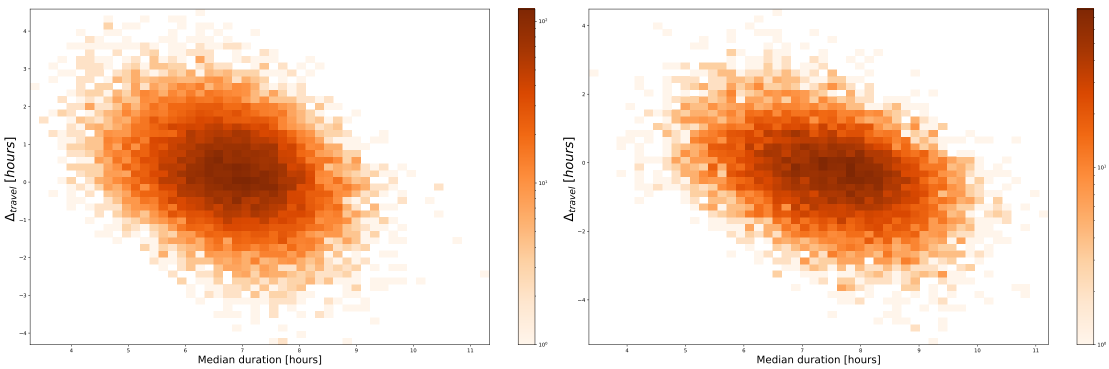

**Supplementary Figure 5: a)** Distribution of distance travelled for weekday travel nights. **b)** Distribution of distance travelled for weekend travel nights. **c)** Distribution of $log_{10}(distance)$ for weekday travel nights. **b)** Distribution of $log_{10}(distance)$ for weekend travel nights.

Our data includes in total 66 distinct time zone changes during travel nights. In Supplementary Table 9 we list the top 20 pairs (separately for weekday and weekend nights) for readers to inspect.

| WEEKDAYS | | WEEKENDS | |
|---|---|---|---|
| **Time zone changes** | **# nights** | **Time zone changes** | **# nights** |
| -1.0 | 6665 | 1.0 | 2337 |
| 1.0 | 6553 | -1.0 | 2197 |
| -2.0 | 1880 | -2.0 | 574 |
| -6.0 | 1102 | 2.0 | 395 |
| 2.0 | 1089 | -6.0 | 332 |
| -7.0 | 895 | -7.0 | 254 |
| 6.0 | 576 | 6.0 | 191 |
| -8.0 | 565 | 7.0 | 182 |
| 7.0 | 543 | -8.0 | 179 |
| 3.0 | 499 | -5.0 | 157 |
| -5.0 | 495 | -3.0 | 150 |
| -3.0 | 461 | -9.0 | 143 |
| -9.0 | 427 | 3.0 | 141 |
| 4.0 | 330 | 5.0 | 126 |
| 5.0 | 312 | 4.0 | 112 |
| 8.0 | 291 | 8.0 | 106 |
| -4.0 | 244 | -4.0 | 100 |
| -16.0 | 196 | -16.0 | 66 |
| -19.0 | 143 | -13.0 | 54 |
| -14.0 | 177 | -15.0 | 53 |

**Supplementary Table 9:** Number of travel nights with time zone changes for the top 20 one most common (separately for weekday and weekend nights)

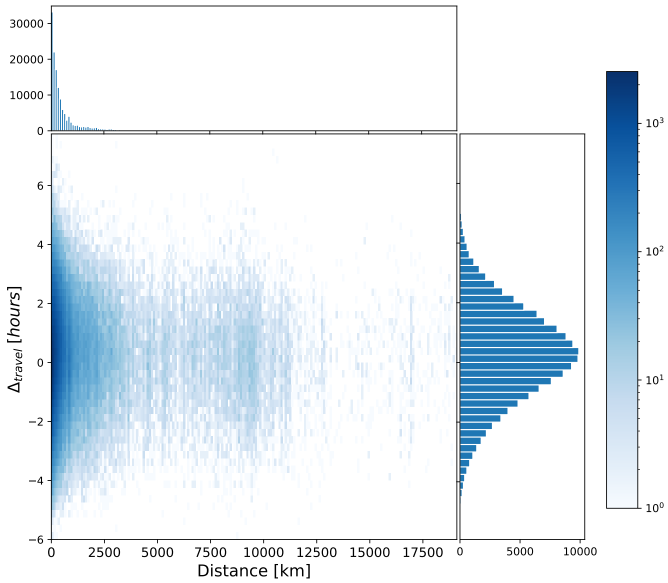
## Scatter plot: $\Delta_{travel}$ and median sleep duration



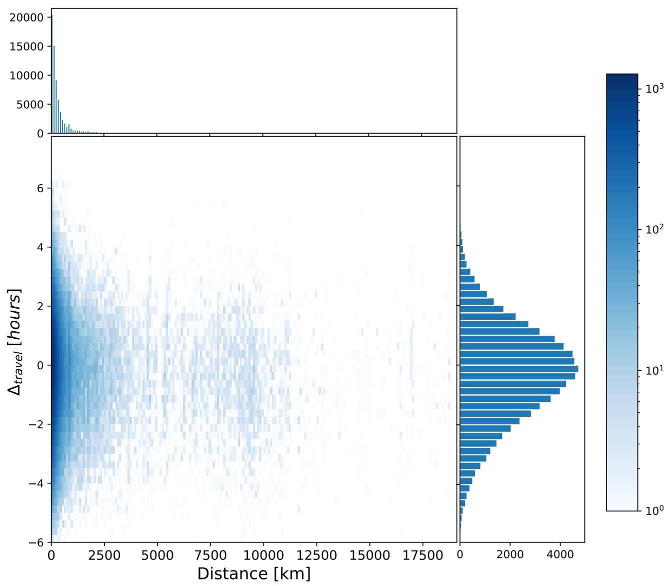

(a) (b)

**Supplementary Figure 6: a)** $\Delta_{travel}$ plotted against median sleep duration on weekdays. **b)** $\Delta_{travel}$ plotted against median sleep duration on weekends.

## Scatter plot: $\Delta_{travel}$ (daily estimate) and distance travelled



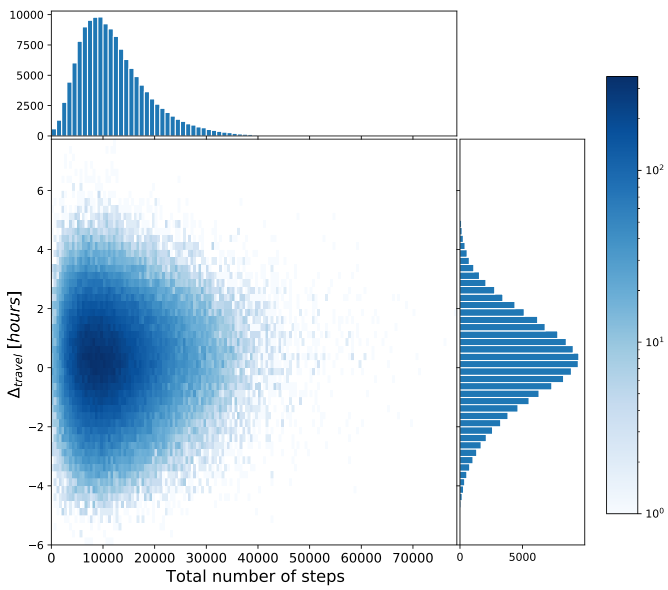

(a)



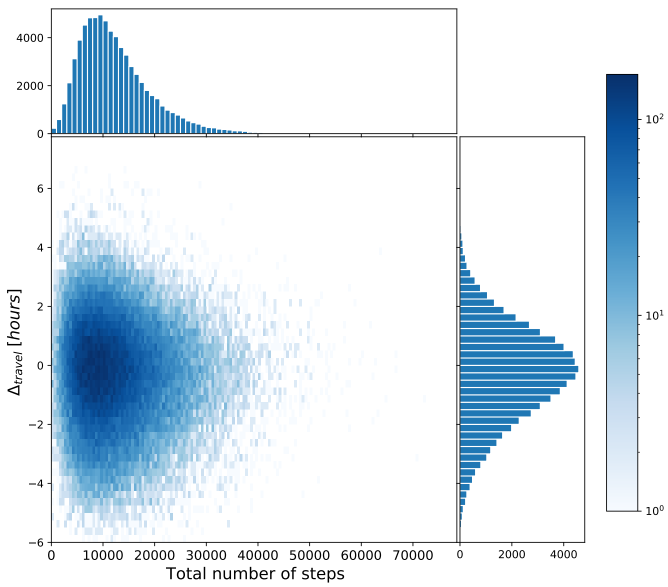

(b)

**Supplementary Figure 7: a)** $\Delta_{travel}$ (not averaged across individuals but nightly estimates) plotted against distance travelled on weekdays. **b)** $\Delta_{travel}$ (not averaged across individuals but nightly estimates) plotted against distance travelled on weekends.

185 ## Scatter plot: $\Delta_{travel}$ and number of steps (daily estimates)




(a)

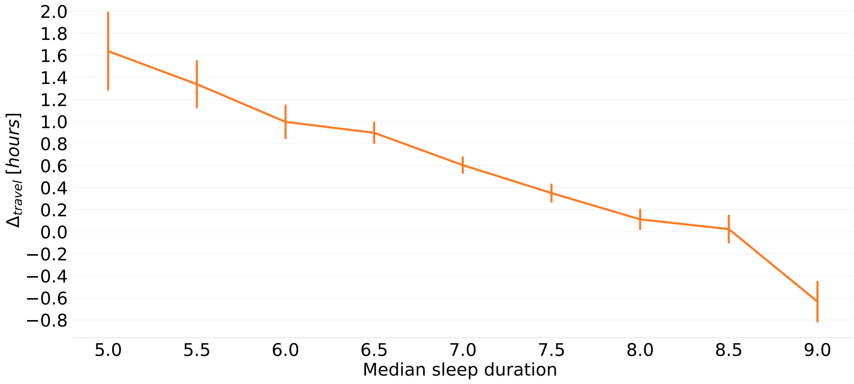



(b)

**Supplementary Figure 8: a)** $\Delta_{travel}$ (not averaged across individuals but nightly estimates) plotted against daily number of steps (proxy for physical activity) on weekdays. **b)** $\Delta_{travel}$ (not averaged across individuals but nightly estimates) plotted against daily number of steps (proxy for physical activity) on weekends

## Travel during official holidays

We wanted to control for when travel takes place during national holidays. However, we could not identify any reliable official records of public holidays by country and therefore it is difficult to incorporate these in our analysis. In order to explore this effect, we consider travel in the days between Christmas and new year's (Dec 26-30) for the countries that celebrate these holidays (N-America and Europe). We find $N_{days} = 2316$ for 1348 individuals during this period. We plotted $\Delta_{travel}$ averaged by sleep groups on Figure 9. We observe a similar pattern as for the analysis of all travel nights.

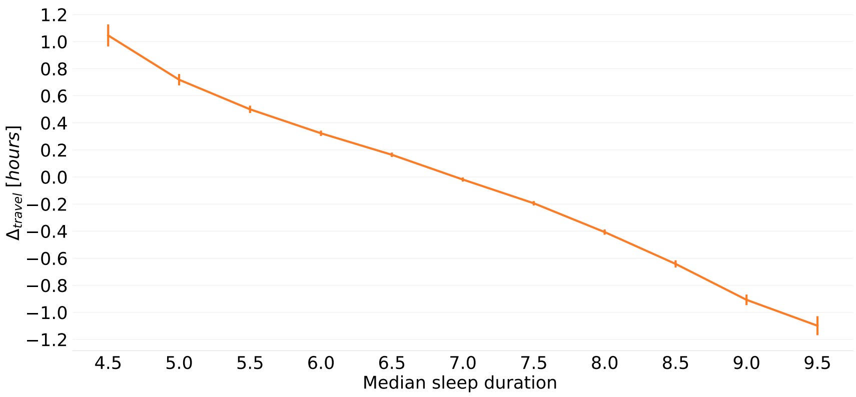



**Supplementary Figure 9:** Average $\Delta_{travel}$ by sleep groups (median sleep duration rounded to half hour bins) for individuals from Europe or N-America travelling during 27-30th of December (holiday season). Errorbars correspond to standard error of the mean for the $n = 1\,348$ individuals.

## First night effect?

In order to know the order of a travel night during a trip, one must have the previous night recorded. We added the order to all travel nights (if possible), and found that only 27% travel nights in our data-set contain that information.

Furthermore, for those nights, 93% are either 1st, 2nd or 3rd night. To explore the first night effect, we provide a plot in Supplementary Figure 10 of $\Delta_{travel}$ averaged by sleep groups (individual median sleep duration rounded to the nearest half hour bin) to illustrate that we observe the same pattern as for the analysis of all travel nights.




**Supplementary Figure 10:** Average $\Delta_{travel}$ by sleep groups (median sleep duration rounded to half hour bins) for nights that are either the first or second night of a trip. Error bars correspond to the standard error of the mean and $n = 13\,157$ individuals

# Down-sampling nights at home

As mentioned in the manuscript - one of the limitations of this study is the disproportionate number of nights recorded away from home in comparison to nights at home (6% of weekdays and 9.3% of weekends are travel-nights). One might consider that the change in sleep behaviour away from home could be happening incidentally – meaning that if we randomly choose the same amount of nights at home as number of nights recorded away from home, then the sample distributions for $\Delta_{home}$ and $\Delta_{travel}$ would look more alike.

To contest to that presumption, we perform down-sampling such that we randomly select nights at home to be equal to the number of nights recorded away from home (for each individual) and compare the sample distributions (both visually and by percentiles) for $\Delta_{home\ DS}$ and $\Delta_{home}$. The process is described step-by-step;

- Repeat 50 times;
  - For each individual we randomly choose $N_{travel}$ nights recorded at home
  - For those randomly drawn nights, we estimate $\Delta_{home}$ and store it for each individual
- Estimate $\Delta_{home\ DS}$ for each individual from the 50 trials
- Estimate the quartiles for the sample distribution of $\Delta_{home\ DS}$

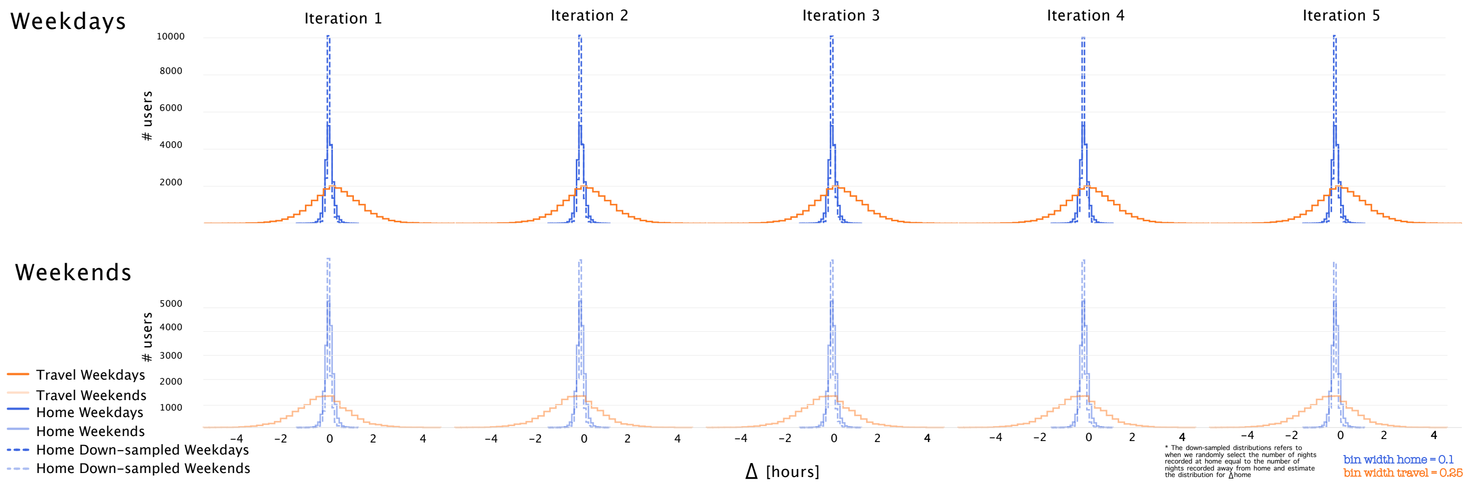
Results are listed in Supplementary Tables 10 and 11 and distributions also visualised in Supplementary Figure 11. The distribution for $\Delta_{home\ DS}$ is actually narrower than for the full sample. That can be rationalized by the fact that 70 % of individuals have 5 or less days recorded away from home but when we examined the development of the standard deviation by number of data-points (see section *Filtering & Inclusion Criteria* in SI) – the standard deviation increases and is not stabilized until there are about 10 recorded nights. The distribution for $\Delta_{home\ DS}$ moves further away from the distribution $\Delta_{travel}$ when down-sampled.

| Iteration | 1 | 2 | 3 | 4 | 5 | Full sample – Home | Full sample – Travel |
|---|---|---|---|---|---|---|---|
| **Minimum** | -0.565 | -0.588 | -0.596 | -0.619 | -0.617 | -1.39 | -5.25 |
| **Lower quartile** | -0.0532 | -0.0515 | -0.0533 | -0.0524 | -0.0534 | -0.110 | -0.417 |
| **Median** | 0 | 0 | 0 | 0 | 0 | -0.0140 | 0.239 |
| **Upper quartile** | 0.0342 | 0.0340 | 0.0340 | 0.0363 | 0.0346 | 0.086 | 0.933 |
| **Maximum** | 0.726 | 0.754 | 0.711 | 0.735 | 0.766 | 1.16 | 5.98 |

**Supplementary Table 10:** Sample quartiles of $\Delta_{home\ DS}$ [hours] home-nights are randomly selected and equal to the number of travel-nights on weekdays

| Iteration | 1 | 2 | 3 | 4 | 5 | Full sample – Home | Full sample – Travel |
|---|---|---|---|---|---|---|---|
| **Minimum** | -0.692 | -0.841 | -0.680 | -0.752 | -0.746 | -1.39 | -5.25 |
| **Lower quartile** | -0.0763 | -0.0783 | -0.0777 | -0.0785 | -0.0789 | -0.110 | -0.417 |
| **Median** | 0 | 0 | 0 | 0 | 0 | -0.0140 | 0.239 |
| **Upper quartile** | 0.0114 | 0.0110 | 0.0117 | 0.0112 | 0.0134 | 0.086 | 0.933 |
| **Maximum** | 0.712 | 0.604 | 0.586 | 0.6454 | 0.6322 | 1.16 | 5.98 |

**Supplementary Table 11:** Sample quartiles of $\Delta_{home\ DS}$ [hours] home-nights are randomly selected and equal to the number of travel-nights on weekends

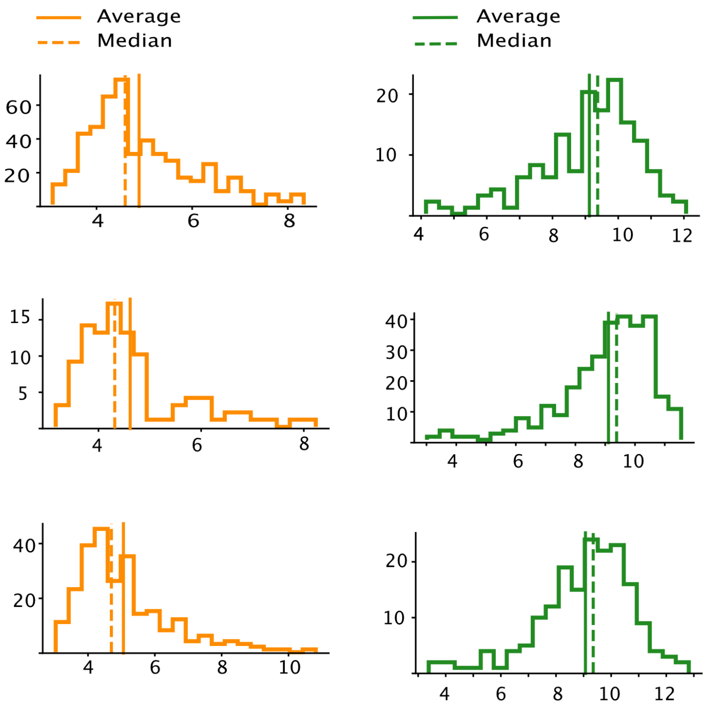



**Supplementary Figure 11:** Distributions of $\Delta_{home\ DS}$ on weekdays and weekends (from the five iterations described above) with $\Delta_{home}$ and $\Delta_{travel}$

# The baseline effect at home

| Sleep groups | 4.5 | 5.0 | 7.0 | 9.0 | 9.5 |
|---|---|---|---|---|---|
| % users where $\mu > M$ * | 95.2 % | 86 % | 40 % | 19 % | 7 % |
| % users where $\mu \leq M$ * | 4.8 % | 14 % | 60 % | 81 % | 93 % |
| $\mu_{skew}$ * | 1.02 | 0.67 | -0.12 | -0.73 | -0.66 |

*$\mu$ denotes average, M denotes median




**Supplementary Figure 12:** Here we illustrate how the asymmetry of an individual's distribution emerges due to homeostasis. In the table the majority of individuals who regularly have shorter nighttime sleep at home (4.5 or 5.0 hours) have a median larger than the mean and a positively skewed distribution – indicating heavier right tail. The opposite can be observed for individuals typically obtaining longer nighttime sleep – where majority of the individuals have an averages smaller than the median and a negative skew suggesting disproportional tendency for shorter nights. The distributions on the bottom of the figure are representative for six randomly selected individuals, 3 of which have low sleep duration (orange color) and 3 who have high sleep duration (green color).

# Controlling for demographic heterogeneity with mixed effects model

We analyse the data with mixed effects model with a three-way interaction term between home (True/False), every demographic variable and median duration (centered around the mean). Measurements are nested within individual (random effect) and the model is defined in equation below.

$$\begin{aligned} Y_i \;=\; & \mu + \alpha(\text{duration\_center}_i) + \beta(\text{home}_i) + \delta(\text{bmi\_cat}_i) + \epsilon(\text{east\_west}_i) + \\ & \zeta(\text{gender}_i) + \eta(\text{generation}_i) + \theta(\text{home}_i \times \text{duration\_center}_i) + \iota(\text{home}_i \times \text{bmi\_cat}_i) + \\ & \kappa(\text{home}_i \times \text{east\_west}_i) + \lambda(\text{home}_i \times \text{gender}_i) + \nu(\text{home}_i \times \text{generation}_i) + \\ & \xi(\text{duration\_center}_i \times \text{bmi\_cat}_i) + \pi(\text{duration\_center}_i \times \text{east\_west}_i) + \\ & \rho(\text{duration\_center}_i \times \text{gender}_i) + \sigma(\text{duration\_center}_i \times \text{generation}_i) + \\ & \tau(\text{duration\_center}_i \times \text{home}_i \times \text{bmi\_cat}_i) + \upsilon(\text{duration\_center}_i \times \text{home}_i \times \text{east\_west}_i) + \\ & \phi(\text{duration\_center}_i \times \text{home}_i \times \text{gender}_i) + \chi(\text{duration\_center}_i \times \text{home}_i \times \text{generation}_i) + \\ & + y(\text{user}_i) + \epsilon_i \text{ where } i = 1, \ldots 664\,130 \; or \; i = 1, \ldots 2\,146\,499 \\ & \text{ Furthermore } y(\text{user}_i) \sim N(0, \sigma_w^2), \text{ and } \epsilon_i \sim N(0, \sigma^2) \end{aligned}$$

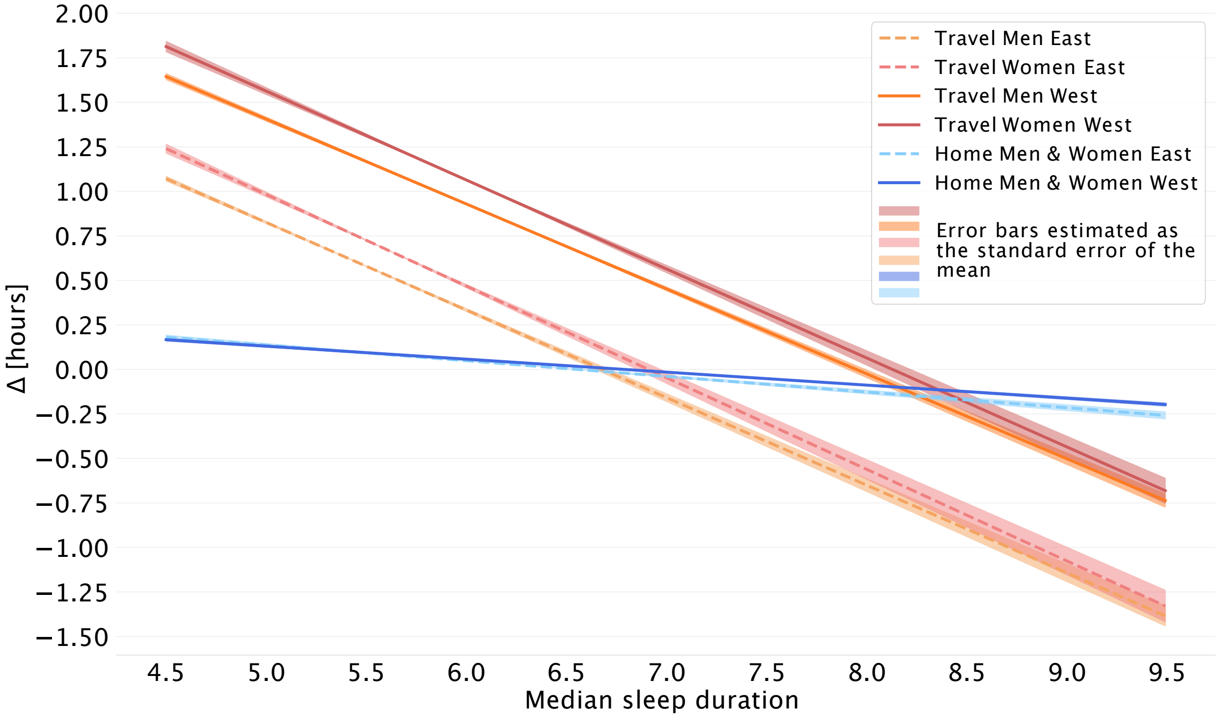
We note that the reference categories for each covariate here below:

- `home`: True
- `gender`: MALE
- `bmi_cat`: 1 (normal weight)
- `east_west`: west
- `generations`: gen x

## Model A Weekdays: Fixed effects

| Fixed Effect | Estimate | Std. Error | P-value |
|---|---|---|---|
| (Intercept) | -2.770e-03 | 2.854e-03 | 0.331746 |
| dur_C | -7.297e-02 | 3.322e-03 | <2e-16 *** |
| homeFalse | 5.520e-01 | 8.072e-03 | <2e-16 *** |
| east_westeast | -2.065e-02 | 2.747e-03 | 5.84e-14 *** |
| genderFEMALE | 2.599e-03 | 2.707e-03 | 0.337063 |
| bmi_cat2 | -3.644e-03 | 2.647e-03 | 0.168699 |
| bmi_cat3 | -9.225e-03 | 3.558e-03 | 0.009531 ** |
| generationbaby boomers | -1.998e-02 | 2.915e-03 | 7.42e-12 *** |
| generationmillenials | 1.214e-02 | 2.935e-03 | 3.54e-05 *** |
| dur_C:homeFalse | -4.041e-01 | 7.586e-03 | <2e-16 *** |
| homeFalse:east_westeast | -5.868e-01 | 8.031e-03 | <2e-16 *** |
| homeFalse:genderFEMALE | 1.166e-01 | 8.233e-03 | <2e-16 *** |
| homeFalse:bmi_cat2 | -4.469e-02 | 7.709e-03 | 6.78e-09 *** |
| homeFalse:bmi_cat3 | -1.403e-01 | 1.036e-02 | <2e-16 *** |
| homeFalse:generationbaby boomers | -6.877e-02 | 8.432e-03 | 3.46e-16 *** |
| homeFalse:generationmillenials | -5.380e-02 | 8.617e-03 | 4.27e-10 *** |
| dur_C:east_westeast | -1.496e-02 | 2.987e-03 | 5.49e-07 *** |
| dur_C:genderFEMALE | 3.973e-03 | 3.020e-03 | 0.188338 |
| dur_C:bmi_cat2 | -1.436e-03 | 2.888e-03 | 0.619102 |
| dur_C:bmi_cat3 | 5.399e-03 | 3.797e-03 | 0.155105 |
| dur_C:generationbaby boomers | 1.222e-03 | 3.101e-03 | 0.693443 |
| dur_C:generationmillenials | -1.009e-02 | 3.331e-03 | 0.002451 ** |
| dur_C:homeFalse:genderFEMALE | -2.272e-02 | 8.914e-03 | 0.010802 * |
| dur_C:homeFalse:bmi_cat2 | 2.933e-02 | 8.466e-03 | 0.000532 *** |
| dur_C:homeFalse:bmi_cat3 | 6.585e-02 | 1.113e-02 | 3.33e-09 *** |
| dur_C:homeFalse:generationbaby boomers | 4.872e-02 | 9.126e-03 | 9.33e-08 *** |
| dur_C:homeFalse:generationmillenials | -8.210e-02 | 9.874e-03 | <2e-16 *** |

**Supplementary Table 12:** Estimates of fixed effects from mixed effects model A for home and travel-nights on weekdays. The dependent variable is $\Delta_s$ where $s \in \{travel, home\}$, unit hour. Linear mixed model fit by REML. Two sided t-tests with Satterthwaite's method.

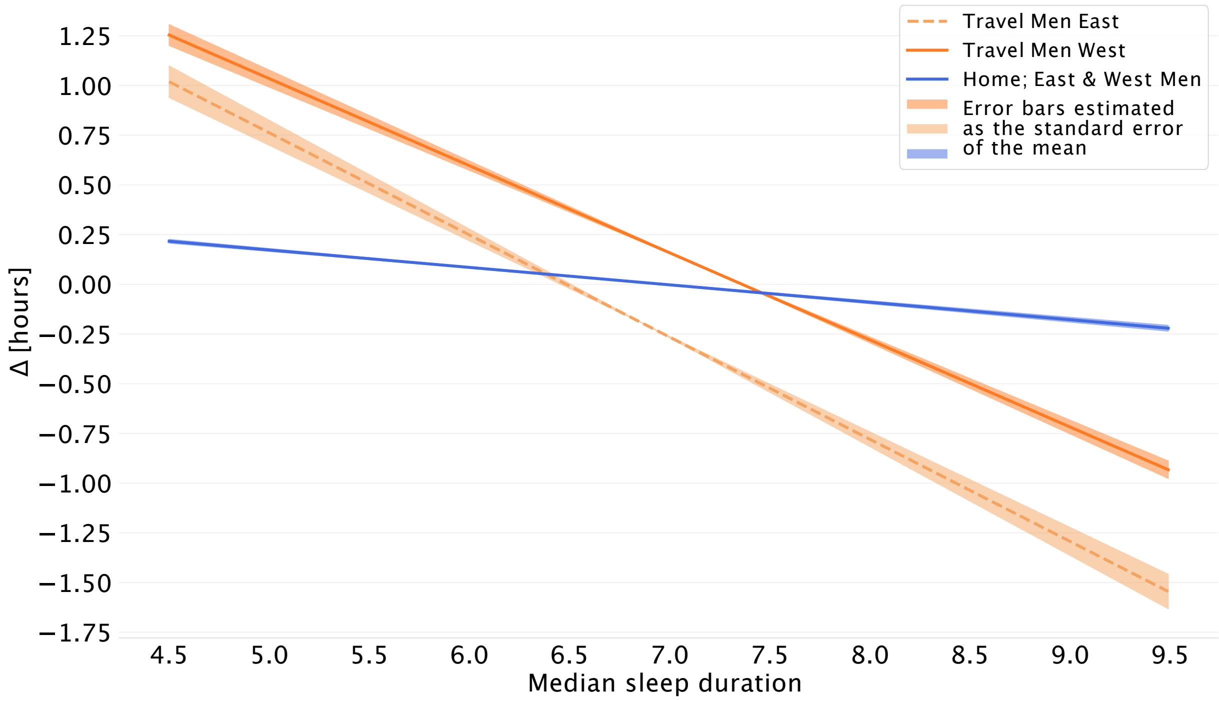



**Supplementary Figure 13:** Illustration for the mixed effect model A for the most important fixed effects in terms of significance and effect size on weekdays. The shaded area represents the standard error of the mean (SEM).

## Model A Weekends: Fixed effects

| Fixed effects | Estimaates | Std. Error | P-value |
|---|---|---|---|
| (Intercept) | -4.365e-02 | 4.751e-03 | <2e-16 *** |
| dur_C | -8.757e-02 | 4.835e-03 | <2e-16 *** |
| homeFalse | 7.815e-04 | 1.443e-02 | 0.956796 |
| east_westeast | 3.288e-03 | 4.560e-03 | 0.470930 |
| genderFEMALE | -4.162e-03 | 4.342e-03 | 0.337830 |
| bmi_cat2 | -7.358e-03 | 4.304e-03 | 0.087358 . |
| bmi_cat3 | -6.093e-03 | 5.865e-03 | 0.298910 |
| generationbaby boomers | -2.386e-02 | 4.676e-03 | 3.40e-07 *** |
| generationmillenials | 1.514e-02 | 4.957e-03 | 0.002260 ** |
| dur_C:homeFalse | -3.480e-01 | 1.452e-02 | <2e-16 *** |
| homeFalse:east_westeast | -4.642e-01 | 1.447e-02 | <2e-16 *** |
| homeFalse:genderFEMALE | -2.686e-02 | 1.372e-02 | 0.050337 . |
| homeFalse:bmi_cat2 | -7.017e-02 | 1.351e-02 | 2.05e-07 *** |
| homeFalse:bmi_cat3 | -1.214e-01 | 1.802e-02 | 1.59e-11 *** |
| homeFalse:generationbaby boomers | 1.180e-02 | 1.496e-02 | 0.430232 |
| homeFalse:generationmillenials | 9.730e-03 | 1.503e-02 | 0.517398 |
| dur_C:east_westeast | -7.787e-03 | 4.524e-03 | 0.085227 . |
| dur_C:genderFEMALE | 2.603e-03 | 4.355e-03 | 0.550038 |
| dur_C:bmi_cat2 | -4.310e-04 | 4.217e-03 | 0.918601 |
| dur_C:bmi_cat3 | 4.230e-03 | 5.635e-03 | 0.452857 |
| dur_C:generationbaby boomers | 5.185e-03 | 4.516e-03 | 0.251022 |
| dur_C:generationmillenials | -1.252e-02 | 5.059e-03 | 0.013335 * |
| dur_C:homeFalse:east_westeast | -7.880e-02 | 1.416e-02 | 2.63e-08 *** |
| dur_C:homeFalse:genderFEMALE | -5.599e-02 | 1.357e-02 | 3.67e-05 *** |
| dur_C:homeFalse:bmi_cat2 | 3.334e-02 | 1.319e-02 | 0.011499 * |
| dur_C:homeFalse:bmi_cat3 | 6.028e-02 | 1.732e-02 | 0.000502 *** |
| dur_C:homeFalse:generationbaby boomers | 4.159e-02 | 1.444e-02 | 0.003982 ** |
| dur_C:homeFalse:generationmillenials | -5.755e-02 | 1.515e-02 | 0.000146 *** |

**Supplementary Table 13:** Estimates of fixed effects from mixed effects model A for home and travel-nights on weekends. The dependent variable is $\Delta_s$ where $s \in \{travel, home\}$, unit hour. Linear mixed model fit by REML. Two sided t-tests with Satterthwaite's method.




**Supplementary Figure 14:** Illustration for the mixed effect model A for the most important fixed effects in terms of significance and effect size on weekends. The shaded area represents the standard error of the mean (SEM).

## The effect of time zone changes, direction of travel and distance

To explore the effect of time zone changes, distance travelled and the direction of journey (eastward or westward travel) we use mixed effects model.

For time zone changes we define a new covariate with aggregates of absolute timezone changes:

- 0 hours
- >0-1 hours
- >1-3 hours
- >3-6 hours
- >6 hours

See the number of nights within each interval in Supplementary Table 14. The boundaries are defined with two main objectives; define reasonable intervals and keep the distribution of data between intervals or subgroups as equal as possible. However, the distribution between groups will never be equal since 85 % of the data has no time zone changes and $\sim$ 8 % have one hour of absolute time zone change. We note that Supplementary Table 9 lists the top 20 time zone changes separately for weekday-and weekend nights

| Time zone changes | Weekdays #nights | Weekends #nights |
|---|---|---|
| 0 hours | 119342 | 64222 |
| >0-1 hours | 13335 | 4591 |
| >1 -3 hours | 4143 | 1321 |
| >3 - 6 hours | 3461 | 1136 |
| >6 hours | 4596 | 1467 |

**Supplementary Table 14:** Number of nights within each interval of time zone changes (for the covariate used in the mixed effects model)

Now, by observing the distribution of distance for travel nights separately on weekends and weekdays (see Supplementary Figure 5 a) and b)), it is evident that they are skewed where majority of nights are within relatively short distance from home and few nights in long distance from home. The distribution for $\log_{10}(distance)$ for weekday- and weekend travel nights (see supplementary Figure 5 c) and d)) confirms that distance is approximately log-normally distributed and therefore we log-transform distance and centre around the population mean (320 and 250 km on weekend and weekday nights respectively) to include in the mixed effects model. We also include demographic covariates used before: generations (Millenials, Gen X & Baby Boomers), gender (Male/Female), East/West (Asia/North America & Europe) and BMI category (Normal Weight/Overweight/Obese). All of these categories are defined formally above (see *Data Coverage & Demographics*). The mixed effects model is defined with a two-way interaction term between; i) each demographic covariate and median sleep duration (centred around the population mean) and ii) time zone changes and direction of journey and, iii) log(distance) and median sleep duration (if the relative change in sleep duration due to distance travelled is dependent on individual's typical sleep duration at home, and vice versa). The model is implemented separately for weekday and weekend travel nights, and the framework defined in equation below.

$$
\begin{aligned}
Y_i \;=\; & \mu + \alpha(\text{duration\_center}_i) + \beta(\text{log\_distance\_center}_i) + \delta(\text{bmi\_cat}_i) + \epsilon(\text{east\_west}_i) + \\
& \zeta(\text{gender}_i) + \eta(\text{generation}_i) + \theta(\text{tz\_cat}_i) + \iota(\text{east\_west\_journey}_i) + \\
& +\lambda(\text{duration\_center}_i \times \text{bmi\_cat}_i) + \nu(\text{duration\_center}_i \times \text{east\_west}_i) + \\
& \xi(\text{duration\_center}_i \times \text{gender}_i) + \pi(\text{duration\_center}_i \times \text{generation}_i) + \\
& \omega(\text{tz\_cat}_i \times \text{east\_west\_journey}_i) + \phi(\text{log\_distance\_c}_i \times \text{duration\_center}_i) + y(\text{user}_i) + \epsilon_i \\
& \text{where } i = 1, \ldots 137\,617 \; or \; i = 1, \ldots 69\,299. \\
& \text{Furthermore } y(\text{user}_i) \sim N(0, \sigma_w^2), \text{ and } \epsilon_i \sim N(0, \sigma^2)
\end{aligned}
$$

We note that the reference categories for each covariate here below:

- `home`: True
- `gender`: MALE
- `bmi_cat`: 1 (normal weight)
- `east_west`: west
- `generations`: gen x
- `east_west_journey`: west
- `tz_diff_cat`: 0

## Model B Weekdays: Fixed effects

| Fixed effect | Estimate | Std. Error | P-value |
|---|---|---|---|
| (Intercept) | 6.424e-01 | 1.674e-02 | <2e-16 *** |
| dur_C | -4.738e-01 | 1.631e-02 | <2e-16 *** |
| east_westeast | -6.203e-01 | 1.548e-02 | <2e-16 *** |
| generationbaby boomers | -1.069e-01 | 1.653e-02 | 1.02e-10 *** |
| generationmillenials | -4.601e-02 | 1.600e-02 | 0.004040 ** |
| bmi_cat2 | -6.912e-02 | 1.477e-02 | 2.91e-06 *** |
| bmi_cat3 | -1.650e-01 | 1.954e-02 | <2e-16 *** |
| genderFEMALE | 1.016e-01 | 1.503e-02 | 1.45e-11 *** |
| tz_diff_cat>0-1 | -1.272e-01 | 2.387e-02 | 9.90e-08 *** |
| tz_diff_cat>1-3 | -3.217e-01 | 3.972e-02 | 5.58e-16 *** |
| tz_diff_cat>3-6 | -3.033e-01 | 4.252e-02 | 9.99e-13 *** |
| tz_diff_cat>6 | -5.059e-01 | 3.639e-02 | <2e-16 *** |
| east_west_journeyeast_journey | -3.313e-02 | 1.046e-02 | 0.001544 ** |
| log_distance_c | 1.684e-01 | 1.017e-02 | <2e-16 *** |
| dur_C:east_westeast | -4.086e-02 | 1.621e-02 | 0.011719 * |
| dur_C:generationbaby boomers | 3.413e-02 | 1.748e-02 | 0.050971 . |
| dur_C:generationmillenials | -1.116e-01 | 1.799e-02 | 5.50e-10 *** |
| dur_C:bmi_cat2 | 2.976e-02 | 1.600e-02 | 0.062907 . |
| dur_C:bmi_cat3 | 7.278e-02 | 2.078e-02 | 0.000462 *** |
| tz_diff_cat1:east_west_journeyeast_journey | -1.071e-01 | 3.196e-02 | 0.000801 *** |
| tz_diff_cat>1-3:east_west_journeyeast_journey | 9.562e-02 | 5.882e-02 | 0.104044 |
| tz_diff_cat>4-6:east_west_journeyeast_journey | -1.984e-01 | 6.268e-02 | 0.001548 ** |
| tz_diff_cat>6:east_west_journeyeast_journey | -2.140e-01 | 6.049e-02 | 0.000403 *** |

**Supplementary Table 15:** Estimates of fixed effects from mixed effects model B for travel-nights on weekdays. The dependent variable is $\Delta_{travel}$, unit hour. Linear mixed model fit by REML. Two sided t-tests with Satterthwaite's method.

## Model B Weekends: Fixed effects

| Fixed effect | Estimate | Std.Error | P-value |
|---|---|---|---|
| (Intercept) | -8.033e-03 | 2.097e-02 | 0.701617 |
| dur_C | -4.605e-01 | 1.960e-02 | <2e-16 *** |
| east_westeast | -4.898e-01 | 1.965e-02 | <2e-16 *** |
| generationbaby boomers | -1.704e-02 | 2.054e-02 | 0.406904 |
| generationmillenials | 2.399e-02 | 2.007e-02 | 0.231892 |
| bmi_cat2 | -7.839e-02 | 1.834e-02 | 1.93e-05 *** |
| bmi_cat3 | -1.395e-01 | 2.437e-02 | 1.07e-08 *** |
| genderFEMALE | -2.174e-02 | 1.849e-02 | 0.239595 |
| tz_diff_cat>0-1 | -1.395e-01 | 3.000e-02 | 3.31e-06 *** |
| tz_diff_cat>1-3 | -1.610e-01 | 5.448e-02 | 0.003120 ** |
| tz_diff_cat>3-6 | -2.726e-01 | 5.783e-02 | 2.44e-06 *** |
| tz_diff_cat>6 | -4.265e-01 | 5.383e-02 | 2.35e-15 *** |
| east_west_journeyeast_journey | -2.828e-02 | 1.330e-02 | 0.033481 * |
| log_distance_c | 3.165e-02 | 1.485e-02 | 0.033049 * |
| dur_C:east_westeast | -6.800e-02 | 1.893e-02 | 0.000329 *** |
| dur_C:generationbaby boomers | 6.045e-02 | 1.946e-02 | 0.001897 ** |
| dur_C:generationmillenials | -6.938e-02 | 1.996e-02 | 0.000510 *** |
| dur_C:bmi_cat2 | 2.697e-02 | 1.774e-02 | 0.128380 |
| dur_C:bmi_cat3 | 7.901e-02 | 2.280e-02 | 0.000531 *** |
| dur_C:genderFEMALE | -6.215e-02 | 1.811e-02 | 0.000604 *** |
| dur_C:log_distance_c | -2.257e-02 | 1.091e-02 | 0.038501 * |

**Supplementary Table 16:** Estimates of fixed effects from mixed effects model B for travel-nights on weekends. The dependent variable is $\Delta_{travel}$, unit hour. Linear mixed model fit by REML. Two sided t-tests with Satterthwaite's method.

## Model B1: Time zone changes as covariate without aggregation

To ensure that aggregating time zone changes into categories for the covariate in the model B, does not influence the results, we run the same model again, but now with time zone changes as a covariate without aggregation and only include the top 10 time zone changes for weekday-and weekend nights separately (see listed in Supplementary Table 9). The model framework is defined formally below:

$$\begin{aligned} Y_i \;=\;& \mu + \alpha(\text{duration\_center}_i) + \beta(\text{log\_distance\_center}_i) + \delta(\text{bmi\_cat}_i) + \epsilon(\text{east\_west}_i) + \\ & \zeta(\text{gender}_i) + \eta(\text{generation}_i) + \iota(\text{time\_zone\_changes}_i) + \\ & +\lambda(\text{duration\_center}_i \times \text{bmi\_cat}_i) + \nu(\text{duration\_center}_i \times \text{east\_west}_i) + \\ & \xi(\text{duration\_center}_i \times \text{gender}_i) + \pi(\text{duration\_center}_i \times \text{generation}_i) + \\ & y(\text{user}_i) + \epsilon_i \text{ where } i = 1, \ldots 132\,682 \; or \; i = 1, \ldots 67\,673. \\ & \text{Furthermore } y(\text{user}_i) \sim N(0, \sigma_w^2), \text{ and } \epsilon_i \sim N(0, \sigma^2) \end{aligned}$$

The fixed effects for the weekday and weekend models are presented in Supplementary Table 17 and 18. The estimates of fixed effects are effectively the same as in model: people on average lose more sleep as time zone changes increase in magnitude and more sleep loss during east ward travel than westward.

| Fixed Effect | Estimate | Std. Error | P-value |
|---|---|---|---|
| (Intercept) | 6.333e-01 | 1.617e-02 | <2e-16 *** |
| dur_C | -4.717e-01 | 1.659e-02 | <2e-16 *** |
| east_westeast | -6.238e-01 | 1.566e-02 | <2e-16 *** |
| generationbaby boomers | -1.066e-01 | 1.674e-02 | 2.01e-10 *** |
| generationmillenials | -5.067e-02 | 1.622e-02 | 0.001790 ** |
| bmi_cat2 | -6.964e-02 | 1.496e-02 | 3.26e-06 *** |
| bmi_cat3 | -1.680e-01 | 1.980e-02 | <2e-16 *** |
| genderFEMALE | 9.617e-02 | 1.523e-02 | 2.75e-10 *** |
| tz_diff_hour-8 | -5.281e-01 | 7.542e-02 | 2.54e-12 *** |
| tz_diff_hour-7 | -4.415e-01 | 5.925e-02 | 9.29e-14 *** |
| tz_diff_hour-6 | -2.487e-01 | 5.415e-02 | 4.36e-06 *** |
| tz_diff_hour-2 | -2.574e-01 | 4.365e-02 | 3.72e-09 *** |
| tz_diff_hour-1 | -1.117e-01 | 2.355e-02 | 2.11e-06 *** |
| tz_diff_hour1 | -2.582e-01 | 2.405e-02 | <2e-16 *** |
| tz_diff_hour2 | -1.913e-01 | 5.578e-02 | 0.000606 *** |
| tz_diff_hour6 | -5.639e-01 | 7.217e-02 | 5.61e-15 *** |
| tz_diff_hour7 | -8.436e-01 | 7.868e-02 | <2e-16 *** |
| log_distance_c | 1.704e-01 | 1.018e-02 | <2e-16 *** |
| dur_C:east_westeast | -4.239e-02 | 1.644e-02 | 0.009949 ** |
| dur_C:generationbaby boomers | 3.551e-02 | 1.772e-02 | 0.045031 * |
| dur_C:generationmillenials | -1.134e-01 | 1.823e-02 | 5.15e-10 *** |
| dur_C:bmi_cat2 | 3.006e-02 | 1.621e-02 | 0.063701 . |
| dur_C:bmi_cat3 | 7.183e-02 | 2.108e-02 | 0.000655 *** |

**Supplementary Table 17:** Estimates of fixed effects from mixed effects model B1 for travel-nights on weekdays. The dependent variable is $\Delta_{travel}$, unit hour. Linear mixed model fit by REML. Two sided t-tests with Satterthwaite's method.

| Fixed Effect | Estimate | Std. Error | P-value |
|---|---|---|---|
| (Intercept) | -1.654e-02 | 2.018e-02 | 0.412684 |
| dur_C | -4.617e-01 | 1.983e-02 | <2e-16 *** |
| east_westeast | -4.906e-01 | 1.991e-02 | <2e-16 *** |
| generationbaby boomers | -2.034e-02 | 2.078e-02 | 0.327872 |
| generationmillenials | 1.755e-02 | 2.027e-02 | 0.386536 |
| bmi_cat2 | -7.794e-02 | 1.853e-02 | 2.62e-05 *** |
| bmi_cat3 | -1.468e-01 | 2.460e-02 | 2.46e-09 *** |
| genderFEMALE | -2.074e-02 | 1.869e-02 | 0.267029 |
| tz_diff_hour-7 | -2.908e-01 | 1.090e-01 | 0.007646 ** |
| tz_diff_hour-6 | -2.167e-01 | 9.517e-02 | 0.022806 * |
| tz_diff_hour-5 | -3.276e-01 | 1.360e-01 | 0.016006 * |
| tz_diff_hour-2 | -2.543e-01 | 7.738e-02 | 0.001016 ** |
| tz_diff_hour-1 | -8.625e-02 | 3.973e-02 | 0.029933 * |
| tz_diff_hour1 | -2.034e-01 | 3.905e-02 | 1.91e-07 *** |
| tz_diff_hour2 | -1.429e-02 | 9.288e-02 | 0.877702 |
| tz_diff_hour6 | -3.699e-01 | 1.240e-01 | 0.002841 ** |
| tz_diff_hour7 | -2.734e-01 | 1.350e-01 | 0.042771 * |
| log_distance_c | 3.335e-02 | 1.486e-02 | 0.024813 * |
| dur_C:east_westeast | -6.290e-02 | 1.915e-02 | 0.001026 ** |
| dur_C:generationbaby boomers | 6.531e-02 | 1.969e-02 | 0.000911 *** |
| dur_C:generationmillenials | -6.432e-02 | 2.015e-02 | 0.001417 ** |
| dur_C:bmi_cat2 | 2.383e-02 | 1.791e-02 | 0.183346 |
| dur_C:bmi_cat3 | 7.467e-02 | 2.301e-02 | 0.001180 ** |
| dur_C:genderFEMALE | -6.218e-02 | 1.832e-02 | 0.000688 *** |

**Supplementary Table 18:** Estimates of fixed effects from mixed effects model B1 for travel-nights on weekends. The dependent variable is $\Delta_{travel}$, unit hour. Linear mixed model fit by REML. Two sided t-tests with Satterthwaite's method.

# Robustness in terms of varying number of minimum travel days per individual

$$\begin{aligned} Y_i \quad = \quad & \mu + \alpha(\text{duration\_center}_i) + \beta(\text{home}_i) + \delta(\text{bmi\_cat}_i) + \epsilon(\text{east\_west}_i) + \\ & \zeta(\text{gender}_i) + \eta(\text{generation}_i) + \theta(\text{home}_i \times \text{duration\_center}_i) + \\ & \iota(\text{home}_i \times \text{bmi\_cat}_i) + \kappa(\text{home}_i \times \text{east\_west}_i) + \\ & \lambda(\text{home}_i \times \text{gender}_i) + \nu(\text{home}_i \times \text{generation}_i) + \\ & y(\text{user}_i) + \epsilon_i, \text{ where i varies by inclusion criteria.} \\ & \text{ Furthermore } y(\text{user}_i) \sim N(0, \sigma_w^2), \text{ and } \epsilon_i \sim N(0, \sigma^2) \end{aligned}$$

299 ## Model C Weekdays: Fixed effects

| Fixed Effect | travel days $\geq$ 2 | travel days $\geq$ 4 | travel days $\geq$ 6 | travel days $\geq$ 8 | travel days $\geq$ 10 | travel days $\geq$ 12 |
|---|---|---|---|---|---|---|
| | **Estim. $\pm$ SEM** | **Estim. $\pm$ SEM** | **Estim. $\pm$ SEM** | **Estim. $\pm$ SEM** | **Estim. $\pm$ SEM** | **Estim. $\pm$ SEM** |
| **Intercept** | -0.00083 $\pm$ 0.0028 | -0.00256 $\pm$ 0.0035 | -0.00446 $\pm$ 0.0041 | -0.00559 $\pm$ 0.0048 | -0.00558 $\pm$ 0.0056 | -0.00690 $\pm$ 0.0064 |
| **dur_C** | -0.0809 $\pm$ 0.0014 | -0.0788 $\pm$ 0.0018 | -0.0769 $\pm$ 0.0023 | -0.00754 $\pm$ 0.0028 | -0.00742$\pm$ 0.0031 | -0.00734 $\pm$ 0.0036 |
| **home=false** | 0.550 $\pm$ 0.0081 | 0.546 $\pm$ 0.0086 | 0.529 $\pm$ 0.0093 | 0.515 $\pm$ 0.0099 | 0.517 $\pm$ 0.011 | 0.509 $\pm$ 0.011 |
| **dur_C and home=false** | -0.393 $\pm$ 0.0043 | -0.390 $\pm$ 0.0047 | -0.384 $\pm$ 0.0051 | -0.379 $\pm$ 0.0055 | -0.379 $\pm$ 0.0059 | -0.373 $\pm$ 0.0064 |
| **east_west=east and home=false** | -0.584 $\pm$ 0.008 | -0.581 $\pm$ 0.0086 | -0.573 $\pm$ 0.0093 | -0.569 $\pm$ 0.010 | -0.572 $\pm$ 0.011 | -0.576 $\pm$ 0.012 |

**Supplementary Table 19:** Estimates of most important fixed effects for model C (in terms of significance and effect size) with increasing number minimum of travel days required per individual on weekdays. The dependent variable is $\Delta_s$ where $s \in \{travel, home\}$, unit hour. Linear mixed model fit by REML. Two sided t-tests with Satterthwaite's method.

300 ## Model C Weekends: Fixed effects

| Fixed Effect | travel days $\geq$ 2 | travel days $\geq$ 4 | travel days $\geq$ 6 | travel days $\geq$ 8 | travel days $\geq$ 10 | travel days $\geq$ 12 |
|---|---|---|---|---|---|---|
| | **Estim. $\pm$ SEM** | **Estim. $\pm$ SEM** | **Estim. $\pm$ SEM** | **Estim. $\pm$ SEM** | **Estim. $\pm$ SEM** | **Estim. $\pm$ SEM** |
| **Intercept** | -0.0421 $\pm$ 0.0046 | -0.0445 $\pm$ 0.0060 | -0.0427 $\pm$ 0.0074 | -0.0355 $\pm$ 0.0089 | -0.060$\pm$ 0.0077 | -0.0317 $\pm$ 0.011 |
| **dur_C** | -0.0912 $\pm$ 0.0022 | -0.0896 $\pm$ 0.0029 | -0.0826 $\pm$ 0.0038 | -0.080 $\pm$ 0.0046 | -0.0758$\pm$ 0.0055 | -0.0771 $\pm$ 0.0064 |
| **home=false** | 0.0115 $\pm$ 0.0013 | 0.0249 $\pm$ 0.0014 | 0.0185 $\pm$ 0.016 | 0.00912 $\pm$ 0.016 | -0.0198 $\pm$ 0.014 | 0.0398 $\pm$ 0.020 |
| **dur_C and home=false** | -0.380 $\pm$ 0.0067 | -0.367 $\pm$ 0.0078 | -0.350 $\pm$ 0.0091 | -0.348 $\pm$ 0.010 | -0.342 $\pm$ 0.012 | -0.329 $\pm$ 0.013 |
| **east_west=east and home=false** | -0.0454 $\pm$ 0.014 | -0.439 $\pm$ 0.016 | -0.415 $\pm$ 0.019 | -0.40 $\pm$ 0.021 | -0.369 $\pm$ 0.023 | -0.338 $\pm$ 0.026 |

**Supplementary Table 20:** Estimates of most important fixed effects for model C (in terms of significance and effect size) with increasing number minimum of travel days required per individual on weekends. The dependent variable is $\Delta_s$ where $s \in \{travel, home\}$. Linear mixed model fit by REML. Two sided t-tests with Satterthwaite's method..

# References: SI


[1] Workweek and weekend, Mar 2021.

[2] Ulf Aslak and Laura Alessandretti. Infostop: Scalable stop-location detection in multi-user mobility data. *arXiv preprint arXiv:2003.14370*, 2020.

[3] WHO Consultation. Obesi'i'y: Preventing and managing the global epidemic. 2000.

[4] Earl S Ford, Timothy J Cunningham, and Janet B Croft. Trends in self-reported sleep duration among us adults from 1985 to 2012. *Sleep*, 38(5):829–832, 2015.

[5] Sigga Svala Jonasdottir, Kelton Minor, and Sune Lehmann. Gender differences in nighttime sleep patterns and variability across the adult lifespan: A global-scale wearables study. *Sleep*, 2020.

[6] L Kuula, M Gradisar, K Martinmäki, C Richardson, D Bonnar, K Bartel, C Lang, L Leinonen, and AK Pesonen. Using big data to explore worldwide trends in objective sleep in the transition to adulthood. *Sleep Medicine*, 62:69–76, 2019.

[7] June C Lo, Ruth LF Leong, Kep-Kee Loh, Derk-Jan Dijk, and Michael WL Chee. Young adults' sleep duration on work days: differences between east and west. *Frontiers in neurology*, 5:81, 2014.

[8] Ju Lynn Ong, Jesisca Tandi, Amiya Patanaik, June C Lo, and Michael WL Chee. Large-scale data from wearables reveal regional disparities in sleep patterns that persist across age and sex. *Scientific reports*, 9(1):3415, 2019.

[9] Till Roenneberg, Karla V Allebrandt, Martha Merrow, and Céline Vetter. Social jetlag and obesity. *Current Biology*, 22(10):939–943, 2012.

[10] Till Roenneberg, Tim Kuehnle, Myriam Juda, Thomas Kantermann, Karla Allebrandt, Marijke Gordijn, and Martha Merrow. Epidemiology of the human circadian clock. *Sleep medicine reviews*, 11(6):429–438, 2007.

[11] Perla A Vargas, Melissa Flores, and Elias Robles. Sleep quality and body mass index in college students: the role of sleep disturbances. *Journal of American College Health*, 62(8):534–541, 2014.

[12] Robert D Vorona, Maria P Winn, Teresa W Babineau, Benjamin P Eng, Howard R Feldman, and J Catesby Ware. Overweight and obese patients in a primary care population report less sleep than patients with a normal body mass index. *Archives of internal medicine*, 165(1):25–30, 2005.

[13] Olivia J Walch, Amy Cochran, and Daniel B Forger. A global quantification of "normal" sleep schedules using smartphone data. *Science advances*, 2(5):e1501705, 2016.

[14] Expert Consultation Who. Appropriate body-mass index for asian populations and its implications for policy and intervention strategies. *Lancet (London, England)*, 363(9403):157, 2004.

[15] Marc Wittmann, Jenny Dinich, Martha Merrow, and Till Roenneberg. Social jetlag: misalignment of biological and social time. *Chronobiology international*, 23(1-2):497–509, 2006.