Weekend sleep after early and later school start times confirmed a model-predicted failure to catch up sleep missed on weekdays

Arcady A. Putilov

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Abstract

Background Many people believe they sleep for longer time on weekend nights to make up for sleep lost on weekdays. However, results of simulations of risetimes and bedtimes on weekdays and weekends with a sleep–wake regulating model revealed their inability to prolong weekend sleep. In particular, they predicted identical durations of weekend sleep after weeks with relatively earlier and relatively later risetime on weekdays. In the present study, this paradoxical prediction was empirically confirmed.

Methods Times in bed were calculated from weekday and weekend risetimes and bedtimes in pairs of samples of students with early and later school start time and in subsets of samples from 7 age groups with weekday risetime earlier and later than 7:00 a.m.

Results Among 35 pairs of students, mean age ± standard deviation was 14.5 ± 2.9 years and among the age group samples, 21.6 ± 14.6 years. As predicted by the simulations, times in bed on weekends were practically identical in the samples with early and later school start time and in two subsets with earlier and later weekday risetime.

Conclusions The model-based simulations of sleep times can inform an individual about an amount of irrecoverable loss of sleep caused by an advance shift of wakeups on weekdays.

Keywords Simulation · Sleep curtailment · Sleep duration · Sleep timing · Sleep–wake regulation · Two-process model

Introduction

The basic properties of biological time-measuring systems have easily lent themselves to mathematical modeling. Such modeling enriched by model-based simulations of empirical data often works together with other scientific approaches to allow better understanding and predicting findings of future research in the fields of chronobiology and sleep science. In particular, for more than three decades, the two-process model of sleep–wake regulation [1, 2] has become the major contributor to our current understanding of the mechanisms underlying the human 24-h sleep–wake pattern. The two-process model postulates that the timing and duration of sleep is determined by two regulation processes, a sleep homeostatic process and a circadian process. The homeostatic process adjusts sleep intensity and duration as a function of the duration of prior wakefulness and the circadian process represents the influence of the circadian clocks on sleep timing [1]. For instance, this model was applied for evaluation of the contribution of the homeostatic process to the ontogenetic changes in sleep timing and duration. The model-based simulations of experimental and epidemiological data explained these changes during adolescence by the difference between mature and prepubescent adolescents in the kinetics of homeostatic process [3–5]. Similarly, the simulations allowed the conclusion that changes in sleep timing and duration occurring at the age interval from adolescence to elderly can be understood as a consequence of changes in the kinetics of this process [6].

An important measure of usefulness of mathematical modeling and simulation pertains to the ability to turn up

* Arcady A. Putilov
putilov@ngs.ru

1 Laboratory of Sleep/Wake Neurobiology, the Institute of Higher Nervous Activity and Neurophysiology of the Russian Academy of Sciences, Moscow, Russia
2 Research Group for Math-Modeling of Biomedical Systems, Research Institute for Molecular Biology and Biophysics of the Federal Research Centre for Fundamental and Translational Medicine, Novosibirsk, Russia
3 Berlin, Germany
(A) 10 days

(B) First two days

(C) Last three days

7 a.m. on weekday
null
The identical durations of sleep on weekend must be expected after a week with relatively earlier and relatively later weekday RT (Figs. 1 and 2). Such prediction disagrees with a common sense view of lengthening weekend sleep duration for making up missed (weekday) sleep the next (weekend) night. Instead, it suggests a normal duration of weekend sleep that can be neither extended nor reduced in response to a shift of weekday wakeups. If this prediction is not correct, weekend sleep after earlier weekday wakeups (shorter weekday sleep durations) must be longer than after later weekday wakeups (longer weekday sleep durations).

By April 2020, about half of the world’s population was under some form of “lockdown” due to the COVID-19 pandemic. This “lockdown” provided a possibility to demonstrate the predictive power of simulations based on the sleep–wake regulating models. The model-based prediction was that weekend sleep durations reported before, during and after “lockdown” must be practically identical despite a significant increase in weekday sleep duration during “lockdown” compared to sleep duration before or after “lockdown” [10]. This paradoxical model-based prediction [7] was supported by empirical evidence obtained by the comparison of sleep times reported before and during “lockdown”. The results showed that weekend times in bed before and during “lockdown” were practically identical despite the associated with “lockdown” shift to a longer weekday time in bed and a later sleep timing [10]. However, the adverse effects of “lockdown” might also include an increase in stress level, a decrease of the mood level, etc. Such effects can, in turn, modify sleep during “lockdown.” Therefore, it was concluded that the analysis of data of other “natural experiments” might be additionally required for confirmation of the model-based prediction of practically identical duration of weekend sleep after a shorter and a longer weekday sleep [10].

Consequently, the purpose of the present report was to provide new empirical evidence supporting this paradoxical prediction. Two new datasets were used to examine significance of the difference between weekend sleep durations after the earlier and later weekday wakeups leading to a shorter and a longer weekday sleep duration, respectively. The 1st (whole) dataset consists of 810 samples that were divided into two subsets in accord with weekday RT, either earlier than 7 a.m. or later. Another dataset includes 35 pairs of samples of school students attending classes in the same school at different, either early or later, school start times (it has been well-documented that, due to confrontation between early school times and biological tendency to delay timing of their sleep on weekends, a dramatic weekday sleep loss occurs in these adolescents when they are forced to attend school in early morning hours [4, 11–15]).

The following two alternative hypotheses were tested:

- If, as many people believe, the body is able to make up missed sleep the next night, a weekend time in bed is longer after a shorter weekday sleep than after a longer weekday sleep;

- Alternatively, if the body has no way of dealing with sleep loss on weekdays, the weekend times in bed are practically identical after a shorter and a longer weekday sleep.

### Materials and methods

Information about RT and bedtime on weekdays and weekends was taken from journal papers (see the references in Appendix A). Data on less than a half of the total set of 810 samples were previously analyzed for predicting possible effects of installation of perennial Daylight Saving Time on sleep timing and duration [8] and as an input to the model of sleep–wake regulating processes in the simulations of weekday and weekend sleep times [5, 9]. For the vast majority of newly added samples, the date of publication was not earlier than 2019. No exclusion criteria were applied for the samples listed in Appendix A, and see Appendix B for the details on the rules applied for merging or separate reporting samples from some of the publications.

The whole set of 810 samples was divided into two subsets with earlier and later weekday RT, < 7:00 a.m. and ≥ 7:00 a.m. (443 and 367 samples, respectively). Since sleep times drastically vary with age, mean age reported for a sample was used to further subdivide the samples into 7 age groups. Among 810 samples, there were 35 pairs of students’ samples from the same school who differed on school start times, either early or more or less delayed (Table 1, right). The 2nd page of Appendix A contains the whole list of bedtimes and risetimes for these 35 pairs of samples. Only samples with early school start times were included in the whole dataset of 810 samples at the 1st page of Appendix A (Table 2).

Statistical analyses were performed with the Statistical Package for the Social Sciences (SPSS23, IBM, Armonk,
NY, USA). For comparison of paired samples with early and later school start times, paired \( t \)-test was applied (Table 1, right). Sleep times in the samples with earlier and later weekday RT were compared with independent samples \( t \)-test (Table 1, left) and with one- or two-way ANOVAs (Table 2, right). The 2nd independent factor was “Age” (Table 2, right, see also Fig. 3 for the results obtained for each of 7 age groups).

Table 1 Results of comparison of school age students with \( t \)-test

| Samples of school students | Age 15-year group (128 samples) | School start times (70 samples) |
|----------------------------|---------------------------------|--------------------------------|
|                            | RT < 7                          | RT ≥ 7                          | Early                      | Later                     |
|                            | Mean   | SEM   | Mean   | SEM   | \( t \)126 | Mean   | SEM   | Mean   | SEM   | \( t \)34 |
| Sleep times                |        |       |        |       |            |        |       |        |       |            |
| Bedtime                    |        |       |        |       |            |        |       |        |       |            |
| Weekday                    | 22.82  | 0.07  | 23.36  | 0.10  | \( -4.30^{***} \) | 23.06  | 0.95  | 23.57  | 1.16  | \( -5.13^{***} \) |
| Weekend                    | 24.14  | 0.08  | 24.53  | 0.13  | \( -2.61^{*} \)   | 24.45  | 1.24  | 24.60  | 1.34  | \( -1.33 \) |
| Difference                 | 1.32   | 0.08  | 1.17   | 0.08  | 1.21      | 1.39   | 0.59  | 1.03   | 0.77  | 3.15^{**}   |
| Weekly averaged            | 23.19  | 0.06  | 23.69  | 0.11  | \( -4.18^{***} \) | 23.46  | 1.01  | 23.86  | 1.16  | \( -4.63^{***} \) |
| Risetime                   |        |       |        |       |            |        |       |        |       |            |
| Weekday                    | 6.49   | 0.04  | 7.35   | 0.05  | \( -13.58^{***} \) | 6.42   | 0.42  | 7.98   | 1.02  | \( -7.57^{***} \) |
| Weekend                    | 9.40   | 0.10  | 9.54   | 0.16  | -0.76     | 9.72   | 1.20  | 9.86   | 1.27  | \( -2.31^{*} \) |
| Difference                 | 2.91   | 0.10  | 2.19   | 0.16  | 4.05^{***} | 3.29   | 1.30  | 1.88   | 1.05  | 7.51^{***} |
| Weekly averaged            | 7.32   | 0.04  | 7.98   | 0.06  | \( -8.88^{***} \) | 7.36   | 0.44  | 8.51   | 0.99  | \( -7.43^{***} \) |
| Time in bed                |        |       |        |       |            |        |       |        |       |            |
| Weekday                    | 7.67   | 0.08  | 7.99   | 0.11  | \( -2.33^{*} \)  | 7.36   | 1.00  | 8.40   | 0.84  | \( -7.33^{***} \) |
| Weekend                    | 9.26   | 0.07  | 9.02   | 0.14  | 1.72      | 9.26   | 0.61  | 9.26   | 0.85  | 0.01       |
| Difference                 | 1.59   | 0.08  | 1.02   | 0.14  | 3.70^{***} | 1.90   | 0.86  | 0.86   | 0.94  | 5.68^{**}   |
| Weekly averaged            | 8.13   | 0.07  | 8.28   | 0.10  | -1.30     | 7.91   | 0.82  | 8.65   | 0.73  | \( -7.04^{***} \) |

Table 2 Results of one- and two-way ANOVAs of the whole set of 810 samples

| ANOVAs | One-way | Two-way |
|--------|---------|---------|
|        | RT < 7  | RT ≥ 7  | “RT” |        | “RT” | “Age” | Interaction |
| Sleep times | Mean   | SEM   | Mean   | SEM   | \( F \)1/808 | Mean   | SEM   | Mean   | SEM   | \( F \)6/796 | \( F \)6/796 | \( F \)6/796 |
| Bedtime Weekday    | 22.69  | 0.05  | 23.29  | 0.06  | 55.67^{***} | 70.28^{***} | 204.9^{***} | 2.49^{*}     |
| Weekend            | 23.74  | 0.06  | 24.19  | 0.07  | 26.20^{***} | 34.38^{***} | 188.1^{***} | 2.89^{**}    |
| Difference         | 1.05   | 0.03  | 0.90   | 0.03  | 10.23^{**}  | 4.64^{*}     | 32.85^{***} | 0.42       |
| Weekly averaged    | 22.99  | 0.05  | 23.55  | 0.06  | 48.29^{***} | 65.48^{***} | 222.2^{***} | 2.91^{**}    |
| Risetime Weekday   | 6.52   | 0.02  | 7.49   | 0.02  | 1229.5^{***} | 931.7^{***} | 8.21^{***}  | 3.17^{**}    |
| Weekend            | 8.77   | 0.05  | 9.19   | 0.06  | 28.27^{***} | 43.27^{***} | 80.85^{***} | 1.89       |
| Difference         | 2.25   | 0.05  | 1.69   | 0.06  | 54.38^{***} | 49.80^{***} | 80.16^{***} | 3.32^{**}    |
| Weekly averaged    | 7.16   | 0.02  | 7.98   | 0.03  | 591.5^{***} | 569.6^{***} | 37.94^{***} | 1.45       |
| Time in bed Weekday| 7.83   | 0.05  | 8.21   | 0.06  | 23.78^{***} | 60.23^{***} | 183.5^{***} | 3.26^{**}    |
| Weekend            | 9.04   | 0.05  | 9.00   | 0.05  | 0.30      | 1.97     | 170.7^{***} | 6.83^{***}   |
| Difference         | 1.21   | 0.04  | 0.79   | 0.04  | 61.07^{***} | 52.19^{***} | 45.50^{***} | 5.79^{***}   |
| Weekly averaged    | 8.17   | 0.05  | 8.43   | 0.05  | 12.95^{**} | 44.35^{**} | 208.6^{***} | 3.80^{**}   |

RT < 7 and ≥ 7: the subsets of 88 and 40 samples with mean weekday risetime earlier than 7:00 and at 7:00 or later from age 15-year group (age > 14 but ≤ 16 years); early and later: 35 paired samples with early and later school start time, mean age of 14.5 years and standard deviation of 2.9 years. Mean and SEM: mean sleep time obtained by averaging over samples of a subset and standard error of this Mean; \( t \)126 and \( t \)34: Independent samples Student’s \( t \)-test and paired Student’s \( t \)-test for the samples of Age 15-year group with weekday RT < 7 and ≥ 7 and for the students with early and later school start time, respectively; \(* p < 0.05, ** p < 0.01, *** p < 0.001 \) for \( t \). See also Fig. 2 for the results of simulation of paired samples and Fig. 3 for sleep times in subsets of 88 and 40 samples from age 15-year group.
The parameters of the model [7] were initially derived from data of Åkerstedt and Gillberg [16] on the experimentally determined durations of recovery sleep after 6 gradually increasing intervals of extended wakefulness and from data of Dijk and co-workers on the relative (compared to baseline sleep episode) levels of SWA in 10 naps [17] (Dijk et al., 1987) and in two recovery sleep episodes scheduled at different circadian times [18, 19]. This version of two-process model predicted, in particular, the modulation of sleep times in the present study simulations. Notably, both the results of simulations with earlier and later RT were practically identical on weekend time in bed (Fig. 3, Table 1A, left, and Fig. 3). This reduction was larger by a quarter of hour after earlier wakeups (Table 2, left, and see also the comments on a more reliable method of evaluation of actual sleep loss in Appendix B).

Thus, despite inadequate duration of weekday sleep caused by earlier wakeups, the samples with earlier and later RT were practically identical on weekend time in bed (Fig. 3C, Table 1, right, and Table 2, left). This implies that, irrespective of age and amount of sleep lost on weekdays, people are not capable to sleep for longer periods of time on weekends to compensate any reduction of their weekday sleep. In other words, their body has no way of dealing with loss of sleep caused by earlier weekday wakeups. This seems to be an irrecoverable loss.

In the whole set of samples, the difference between subsets of samples with earlier and later RT in weekday RT was associated with an earlier weekend sleep timing in the former compared to the latter (Table 2, left, and Fig. 3A, B). This difference in the sleep timing led to the difference in the circadian modulation of the sleep–wake cycle as illustrated in the simulations of the sleep-regulating processes in subsets with earlier and later weekday RT (Fig. 1 and Table 1A). However, such a compensating shift of the circadian modulation and sleep timing in response to 5 days of early morning light exposure was not universal. The exceptions were the same groups of late adolescents and early adults with the most profound reduction of weekday sleep duration and the latest sleep timing compared to younger and older age groups (Fig. 3A, B). Similarly, a small advance of weekend sleep timing was found in the analysis of the samples of students with early and later school start time (Table 1, right). Such an advance cannot compensate a much bigger advance of weekday wakeups. As illustrated by the simulations of their sleep–wake cycles in Fig. 2, the difference in students with early and later school start time was more pronounced on the parameters of the circadian modulation and less pronounced on the weekend sleep timing (Fig. 2 and Table A1).
Weekly average

(A) Bedtime

(B) Risetime

(C) Time in Bed

(D) Difference
Thus, it seemed that those ages that suffer most from early weekday wakeups cannot compensate sleep loss caused by early weekday wakeups by the profound advance of their weekend sleep timing (Figs. 3 and 4D). Possibly, such a failure was caused by two counterbalancing influences, the morning light exposure caused by early weekday wakeups, on the one hand, and the voluntary exposure to artificial lighting in the late weekend evening and early weekend night, on the other hand. Consequently, the reduction of sleep in these ages appeared to be much larger compared to its reduction in other ages (Fig. 3C, D, and Tables 1 and 2), i.e., because people in these earlier and later ages might more successfully compensate a relatively small shift of weekday wakeups by almost identical shifts of both weekend sleep timing and circadian phase.

**Discussion**

The present study was aimed at empirical confirmation of a model-based prediction [5, 8–10] of a failure to catch up sleep missed on weekdays by prolongation of weekend sleep. Simulations predicted that the durations of weekend sleep must be practically identical after a larger and a smaller weekday sleep losses caused by earlier weekday wakeups.

The statistical analysis of empirical data supported these simulations’ results. This allows the conclusion that the body has no a way of dealing with sleep lost on weekdays. Similar results were also obtained in the previous study aimed at comparison of weekend times in bed before and during “lockdown” [10].

An earlier weekday RT is mostly set by social clocks, while other sleep times (weekday bedtime and weekend bedtime and risetime) are mostly determined by human biology (e.g., they reflect the result of entrainment of the biological clocks by the 24-h periodicity of light and darkness). The present and previously published results on simulations and empirical analysis of sleep times in people with early and late weekday wakeups [10, 21] can be additionally supported by findings of some other “natural experiments” in which sleep durations were studied with and without a socially imposed 1-h shift of weekday RT. First, our results seemed to be in agreement with the results of comparison of sleep durations before and after retirement. An increase of sleep duration by 21 min was observed after retirement, but the changes in duration and timing of sleep were driven by weekend sleep, whereas weekend sleep stayed about the same [22]. Second, approximately 1-h difference in weekday RT is also expected between people living in close proximity to one another on the right and left sides from the border between two time zones. Giuntella and Mazzonna [23] reported the results of comparison of employed people living on the late and early sunset side of a time zone border (on the right and on the left from the border). They found that employed people living in the US counties located on the right side of the border slept, on average, 19 fewer minutes than employed people living in the counties on the left side of the border. In agreement with this result, the study of school students living in India [24] revealed a reduced sleep duration at the late sunset side of a time zone as compared to duration of sleep at the early sunset side.

Getting enough sleep is essential for maintaining optimal health and well-being (see, e.g., [25] for review). Therefore, negative consequences for health and performance might be expected after an additional reduction of sleep caused by a 1-h advance of weekday wakeups. For example, such consequences were reported in the cited above study of the effect of the side of time zone [23]. Health index dropped by 0.3 standard deviations when people were living on the late sunset side of the border of time zone compared to the index of people living on the early sunset side. Moreover, risks for total and several specific cancers were found to increase within a time zone in the direction from the east to the west [26], and it was also reported that an increase in longitude when moving east to west within a time zone significantly increases the risk of development of hepatocellular carcinoma [27]. Moreover, later sunset times were found to be associated with poorer academic performance in school students [24], and even a small, 20-min reduction of total sleep time had negative effect on children’s attention and emotional regulation [28]. Therefore, in light of results of such studies, it comes as no surprise that even a week of recovery sleep subsequent to 10 days of sleep restriction was insufficient for full recovery of human functioning [29].

Overall, the analysis of data on sleep times supported the model-based prediction of peoples’ inability to sleep for longer on weekend to make up for weekday sleep loss. This suggested that weekend sleep is an adequate rather than extended sleep, and this result challenged the conventional view of weekend sleep as a compensatory (e.g., [30]) or catch-up sleep (e.g., [31]) that has a longer duration than the duration of “ideal” sleep (e.g., [32]) because it aimed on dissipation of weekday “sleep debt” during the weekend.
(e.g., [33]). Of practical importance, the model allows the calculation of irrecoverable sleep loss caused by early weekday RT. Therefore, the model-based simulations might be recommended for the estimation of weekday sleep loss of an individual with a particular pattern of sleep and wakefulness on free days.

**Conclusions**

A failure to extend weekend sleep after earlier wakeups in the previous 5 weekdays was predicted by the simulations of weekday and weekend sleep times in the framework of two-process conceptualization of sleep–wake regulation [1, 2, 7]. This prediction was confirmed by the results of analysis of sleep times reported by people practicing earlier or later weekday wakeups. Both the present and previous [10] simulations of empirical data obtained in “natural experiments” provided evidence for the human inability to catch up on missed weekday sleep during weekend nights. Some of the results also suggested that an advance of weekend sleep timing may prevent sleep loss caused by an advance of weekday RT. However, such an advance seems not to be large and, therefore, cannot compensate sleep loss in people with extremely late weekend sleep timing (e.g., late adolescents and young adults). The model-predicted empirical evidence of identical durations of weekend sleep after earlier and later weekday wakeups further demonstrated the capability of mathematical models to serve as powerful tools for understanding the mechanisms governing our everyday transitions between sleep and wake states and for predicting findings of future studies. The model-based simulations of sleep times can be recommended for the estimation of irrecoverable loss of sleep after early weekday wakeups.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11325-022-02648-5.

**Data availability** All data analyzed in the present article were included in one of supplementary files (Appendix A).

**Code availability** Formula and parameters for data simulations were included as one of supplementary files (Appendix B).

**Declarations**

**Ethical approval** This article does not contain any studies with human participants or animals performed by the author.

**Consent to participate** Individual data were not used in the present study. For the present analysis, only group-averaged values of sleep times were taken from the previously published papers. These collected mean values were included in one of supplementary files (Appendix A), and all these previously published papers were cited in this Appendix A. Each of these previously published papers contains the necessary information on compliance of those studies with ethical standards.

**Conflict for publication** N/A

**Conflict of interest** The author declares no competing interests.

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