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

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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

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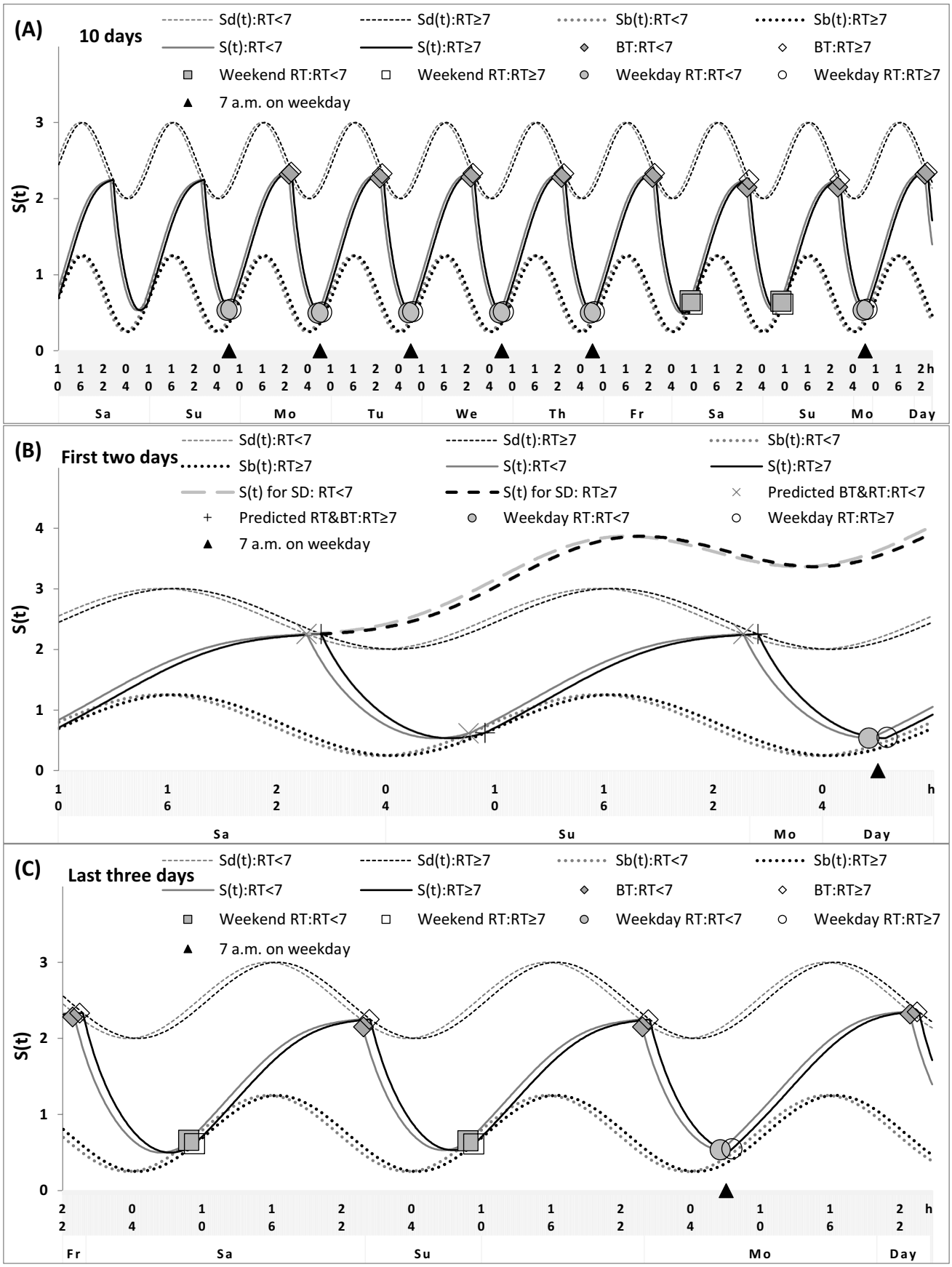
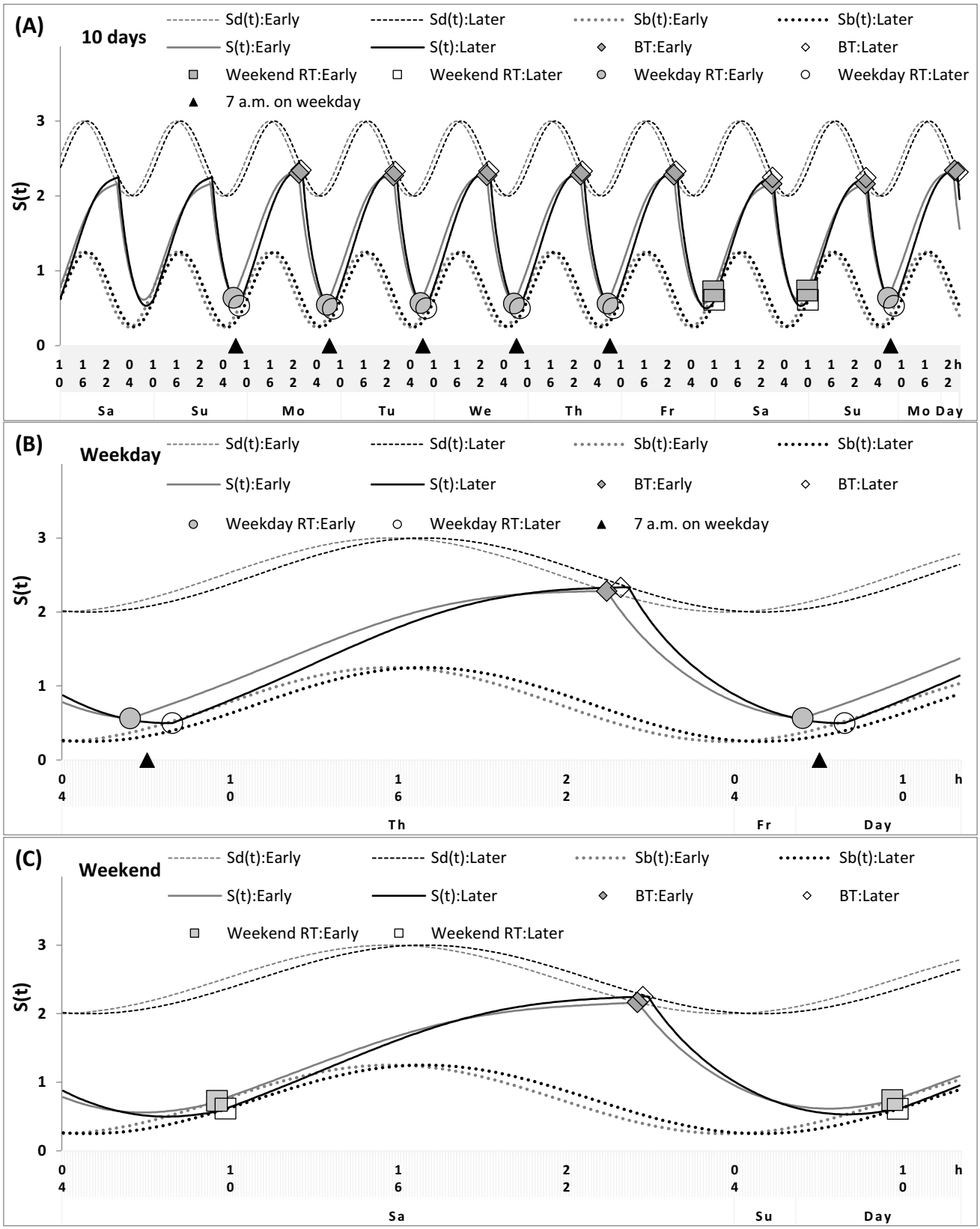

(A)
10 days
Sd(t):RT<7
Sd(t):RT≥7
Sb(t):RT<7
Sb(t):RT≥7
S(t):RT<7
S(t):RT≥7
BT:RT<7
BT:RT≥7
Weekend RT:RT<7
Weekend RT:RT≥7
Weekday RT:RT<7
Weekday RT:RT≥7
7 a.m. on weekday
S(t)
Sa Su Mo Tu We Th Fr Sa Su Mo Day
(B)
First two days
Sd(t):RT<7
Sd(t):RT≥7
Sb(t):RT<7
Sb(t):RT≥7
S(t):RT<7
S(t):RT≥7
S(t) for SD: RT<7
S(t) for SD: RT≥7
Predicted BT&RT:RT<7
Predicted RT&BT:RT≥7
Weekday RT:RT<7
Weekday RT:RT≥7
7 a.m. on weekday
S(t)
Sa Su Mo Day
(C)
Last three days
Sd(t):RT<7
Sd(t):RT≥7
Sb(t):RT<7
Sb(t):RT≥7
S(t):RT<7
S(t):RT≥7
BT:RT<7
BT:RT≥7
Weekend RT:RT<7
Weekend RT:RT≥7
Weekday RT:RT<7
Weekday RT:RT≥7
7 a.m. on weekday
S(t)
Fr Sa Su Mo Day

◂**Fig. 1** Model-based simulation of sleep–wake cycles with earlier and later weekday risetimes. **A**–**C** Simulations of the sleep–wake cycles in samples with weekday risetime (RT) earlier than 7:00 a.m. and at 7:00 a.m. or later (RT < 7 and RT ≥ 7, $n = 443$ and 367, respectively) on the interval of 10 days (**A**) and two subintervals (**B**, **C**). Two alternating phases of the sleep–wake regulating process (i.e., wake and sleep states) are simulated as exponential buildups and decays of S(t) with additional modulation of the parameters of these exponential buildups and decays (1) by sine-form function with 24-h period (2). The risetimes and bedtimes on free days serve as the initial times for the buildup and decay phases of the 24-h sleep–wake cycle. They resemble empirical data averaged for weekends in Fig. 3, but additionally suggest the full compensation of the earlier weekday wakeups by the advance shift of the circadian phase and sleep timing in earlier risers. The whole list of parameters of the model is given in supplementary Table A1 of Appendix B. Sd(t) and Sb(t) refer to the highest expected buildup and lowest expected decay of S(t) predicted by these simulations (1)–(2). As shown in the simulations (**A**), at any of 10 days, a switch from buildup phase to decay phase occurs exactly at Sd(t). In other words, throughout the whole interval of 10 cycles (Sa-Su, Mo-Fr, Sa-Su, and Mo), S(t) does not build up above Sd(t), including the subinterval of 5 weekdays between Mo and Fr (i.e., when, near the end of the weekday decay phase, S(t) does not reach Sb(t) due to early morning wakeups). S(t) for SD: the hypothetical case of sleep deprivation from the first night the first Mo (**B**). Only such SD caused by prolongation of wakefulness on night hours can lead to a further buildup of S(t) above Sd(t). This hypothetical further buildup might be associated with the accumulation of "sleep debt" that must be "paid back" during the following recovery night. Evidence for such a further buildup was not provided by the simulations of sleep times in samples with RT < 7 and RT ≥ 7 (Table 2 and Fig. 3). Throughout 5 weekdays, S(t) does not build up above Sd(t), even when weekday RT < 7 due to earlier wakeups. The simulations suggested that weekend sleep duration is identical in these subsets, even in the cases when weekday sleep duration is shorter after earlier weekday RT than after later weekday RT. At any of the simulated days, there exists the difference between two subsets of samples in the circadian phase (**C**). Symbols additionally illustrate bedtimes and risetimes (BT&RT) predicted for free days and empirical data on weekday and weekend rise-and bedtimes (BT and RT) for these two subsets of samples (Fig. 3)

novel insights into human rhythmic behavior that are not simply intuitive. The present study aimed on empirical confirmation of one of such insights. This is a model-predicted failure of catching up sleep missed on weekdays by prolongation of weekend sleep. Many people believe that they are able to make up missed sleep the next night. For example, when they sleep in the night between Friday and Saturday, they hope to recover, at least partly, their sleep missed after getting up early on a Friday morning (e.g., due to the necessity to attend their work/school). Intuitively, this ability might be explained in the words resembling the terms used in the descriptions of results of applying the two-process model of sleep regulation to simulation of the responses of sleep to its deprivation [1]. The intensification and extension of sleep after sleep deprivation during the previous night seems to be the most known prediction of the two-process model [1]. However, such intensification and extension were not predicted by the model-based simulations of weekend sleep after the reduction of sleep caused by early morning wakeups in the previous weekdays [5]. As shown in Fig. 1B, the model postulates an accumulation of "sleep debt" after the prolongation of wakefulness at night and next day hours. Consequently, a longer and deeper sleep must be expected during the following (recovery) night (i.e., because the accumulated "sleep debt" must be "paid back" during this recovery sleep, it is longer and more intensive compared to a baseline sleep after wakefulness of "normal" duration). In quantitative terms, such an accumulation of "sleep debt" is described as an additional buildup of the sleep–wake regulating process occurring in the course of prolongation of wakefulness after the habitual bedtime set by the sleep–wake regulating mechanism (Fig. 1B). However, when we applied one of the versions of this model [7] to simulate data on bedtimes and risetimes on weekdays and weekends, we did not find that it is necessary to refer to the phenomenon of "banking sleep" for explaining why sleep duration on weekend is longer than sleep duration on weekdays [8, 9]. The simulations suggested that, in any of 5 work/school days, the sleep–wake regulating process builds up exactly to the upper threshold, i.e., to the level at which the buildup of the sleep–wake regulating process during wakefulness must be terminated by the sleep–wake regulating mechanism to allow the initiation of the decay of this process during sleep (Fig. 1A). Despite the earlier wakeups leading to the longer intervals of wakefulness on these 5 work/school days, this process does not build up above this upper threshold in these 5 days. Since the accumulation of "sleep debt" does not occur, the zero amount of this "debt" cannot be "paid back" on weekends (Fig. 1A, B). Therefore, when people try to sleep for longer time on weekend night to make up for sleep lost during weekday nights, they fail to prolong their sleep beyond its normal duration [5, 8, 9]).

In other words, the everyday evening switches from the buildup to decay phases (i.e., from the previous wakefulness to night sleep episode, respectively) occur spontaneously throughout the whole 7-day interval of the week, irrespective of risetime (RT) on weekdays. Bedtimes are always set at the upper threshold of the sleep–wake regulating process, not later (Figs. 1 and 2). Since the accumulation of "sleep debt" indicated by the further buildup of this process above the upper threshold does not occur during weekdays (Fig. 1), people cannot catch up even a bit of sleep missed during these days. This implies that the weekend sleep has nothing to do with the recovery sleep. If the "debt" was not accumulated in the course of weekday wakefulness, it cannot be "paid" back during the following weekend sleep. Consequently, a duration of sleep on weekends can be viewed as a normal (adequate) sleep duration, not as a duration of recovery (lengthened) sleep.

Particularly, these results of simulations led to a rather paradoxical prediction. If a weekend sleep is not a recovery


(A)
10 days
Sd(t):Early
Sd(t):Later
Sb(t):Early
Sb(t):Later
S(t):Early
S(t):Later
BT:Early
BT:Later
Weekend RT:Early
Weekend RT:Later
Weekday RT:Early
Weekday RT:Later
7 a.m. on weekday
S(t)
Sa
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Tu
We
Th
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(B)
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(C)
Weekend
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◂**Fig. 2** Model-based simulation and bedtimes and risetimes in students with early and later school start times. **A**–**C** Simulations of the interval of 10 days (**A**) and two subintervals of this interval, weekday night between Wednesday and Thursday (**B**), and weekend night between Saturday and Sunday (**C**). Symbols additionally illustrate empirical data on bedtimes and risetimes from Table 1 (right) for students with early and later school start times (mean values for 35 pairs of samples). Despite a shorter weekday sleep duration in students with early school start time (B), these simulations suggested the identical duration of weekend sleep after early and later school start times (**A**, **C**). Since the advance shift of weekday wakeups differed after early and later school start times (i.e., it was larger after early school start time), this difference leads to the difference in the timing of light exposure that, in turn, leads to the difference in the circadian phase. The difference in the advance shift also explains the difference in weekday sleep duration (i.e., weekday sleep was shorter after early school start time)

sleep, 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 lost 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 $\geq$ 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 ($SPSS_{23}$, IBM, Armonk,

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		
Sleep times		Mean	SEM	Mean	SEM	*t*126	Mean	SEM	Mean	SEM	*t*34
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***

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

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	*F*1/796	*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: Samples with weekday risetime earlier than 7:00 and at 7:00 or later ($n = 443$ and 367, respectively, mean ages of 22.6 and 20.4 years, and standard deviations of 16.4 and 12.3 years, respectively). Mean and SEM: mean sleep time obtained by averaging over samples of each of two subsets and standard error of this Mean; "RT," "age," interaction: *F*-ratios yielded by one- and two-way ANOVAs for main effects of independent factors "RT" (two subsets of samples with weekday RT < 7 and ≥ 7) and "age" (7 age groups), and for interaction between these factors; *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ for *F*. Figure 3 also show averaged sleep times from two-way ANOVAs

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).

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 time course of SWA by the circadian pacemaker [7] that was experimentally confirmed in later experiments [20].

If *t1* and *t2* are the initial times for the buildup and decay phases of the 24-h sleep–wake cycle (i.e., the risetimes and bedtimes on free days, respectively), the process of sleep–wake regulation, *S(t)*, can be simulated using the following equations:

$$S(t) = \left[S_u + C(t)\right] - \left\{\left[S_u + C(t)\right] - S_b\right\} * e^{-(t-t1)/[Tb-k^*C(t)]} \quad (1)$$

$$S(t) = \left[S_l + C(t)\right] - \left\{S_d - \left[S_l + C(t)\right]\right\} * e^{-(t-t2)/[Td-k^*C(t)]} \quad (2)$$

where

$$C(t) = A * sin\left(2\pi * t/\tau + \varphi_0\right) \quad (3)$$

is a periodic function with a period τ assigned to 24 h (i.e., this term represents the modulating effect of the circadian process on the parameters of homeostatic process).

For simulation of sleep times in the present study (Figs. 1 and 2), slightly modified initial parameters of this model of the processes of sleep–wake regulation [5, 9] were used to account for the differences from the originally simulated sample [7] in sleep duration and timing (Tables 1, left, and Fig. 3). Table A1 of Appendix B provides information on all such similarities and differences between the parameters of the model in the initial and present study simulations.

Results

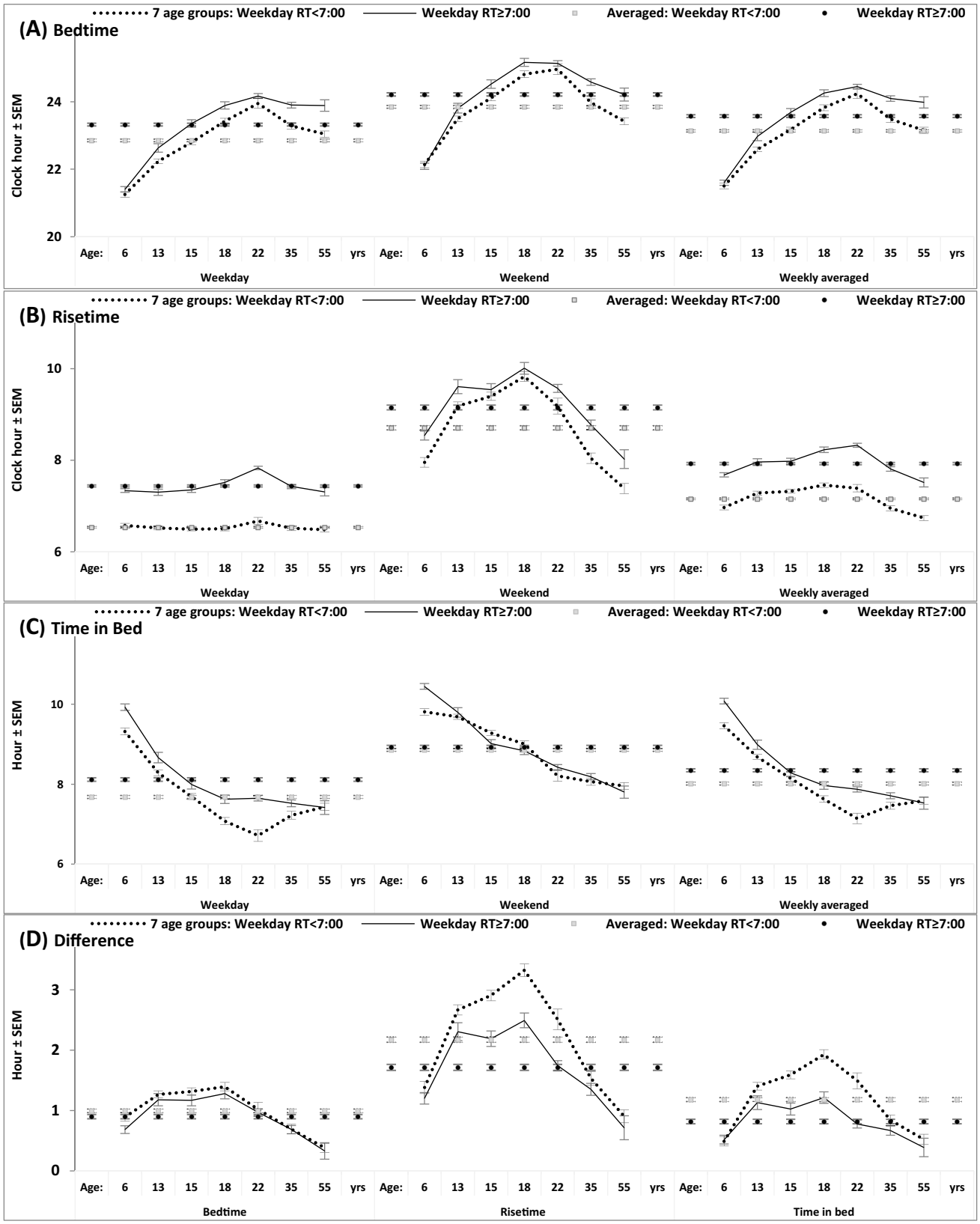
As reported in Tables 1 and 2, statistical tests did not reveal any significant difference between weekend times in bed reported for subsets of samples with earlier and later weekday RT and with early and later school start times. These results were in full agreement with the model-based prediction illustrated in Figs. 1 and 2. Notably, both the results of *t*-test and ANOVA (e.g., Table 1, right, and Table 2, right, respectively) pointed at the weekend time in bed as the only estimate among 12 different sleep times that consistently suggested statistical non-significance of the difference between two subsets of samples with either earlier or later weekday wakeups.

The samples with early and later school start time showed approximately 1-h difference in weekday time in bed (Table 1, right). This difference was larger than the difference between the samples with earlier and later weekday RT, especially in younger or older ages (Tables 1 and 2, left, and Fig. 3).

As expected, earlier weekday RT resulted in a statistically significant increase in the extent of reduction of time in bed on weekdays compared to that after later weekday RT (Fig. 3C, D, and Tables 1 and 2). This reduction was the largest in school students with early school start time (Table 1, right) and in the samples from the same age groups, late adolescence and young adulthood (Fig. 3C, D). On average, the inability to catch up on all the sleep lost during 5 workdays resulted in the reduction of weekly averaged time in bed in any samples, but 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).


7 age groups: Weekday RT<7:00
Weekday RT≥7:00
Averaged: Weekday RT<7:00
Weekday RT≥7:00
(A) Bedtime
Clock hour ± SEM
24
22
20
Age: 6 13 15 18 22 35 55 yrs
Weekday
Weekend
Weekly averaged
(B) Risetime
10
8
6
(C) Time in Bed
Hour ± SEM
(D) Difference
3
2
1
0
Bedtime
Risetime
Time in bed

◂**Fig. 3** Sleep times in 443 and 367 samples with earlier and later weekday risetimes. **A**–**D** 12 sleep times. Age: sleep times in samples with earlier and later weekday risetime (RT either < 7 or ≥ 7) were calculated separately for 7 age groups (0–11, 11–14, 14–16, 16–19, 19–25, 25–45, and 45–85 years, $n = 140$, 124, 128, 109, 115, 120, and 74, respectively). Additionally, the lines paralleled X-axis illustrate mean sleep times for earlier and later RT obtained by averaging over 7 age groups in two-way ANOVAs. Clock hour or hour ± SEM: mean sleep time for the subsets of samples with earlier and later weekday RT and standard error of this mean. See Table 2 (right) for the results of statistical comparison of two subsets of the whole set of samples with earlier and later weekday RT, and Table 1 (left) for the results of comparison of samples from one of age groups (> 14 and ≤ 16 years)

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 weekday 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 either 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.

Consent for publication N/A

Conflict of interest The author declares no competing interests.

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