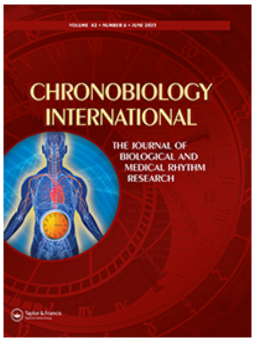

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ORIGINAL ARTICLE

Estimation of sleep shortening and sleep phase advancing in response to advancing risetimes on weekdays

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ABSTRACT
Since the circadian clocks cannot directly respond to the signals of social clocks, earlier risetimes on weekdays lead to loss of certain amount of sleep. However, these clocks can partly reduce this loss by advancing sleep phase due to advancing the pattern of 24-h exposure to light caused by earlier risetimes. In an *in silico* study, a model of sleep-wake regulation was applied to show that the difference between earlier and later weekday risers in weekday risetime is equal to the sum of differences between them in sleep loss and sleep phase advance that can be measured as their differences in weekend-weekday gap in risetime and in weekend risetimes, respectively. Such differences in sleep loss and sleep phase advance were estimated from bed- and risetimes self-reported for weekdays and weekends by 4940 university students and lecturers subdivided into subsamples with different weekday risetimes and chronotypes. We also estimated, for these subsamples, the percentages of weekday sleep insufficiency and circadian misalignment determined as a less than 6 hours in bed on weekdays and a larger than 3-h weekend-weekday gap in risetime, respectively. Additionally, advance phase shifts of the circadian clocks were predicted by model-based simulations of self-reported sleep times.

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Simulation; mathematical modelling; sleep-wake regulating process; morning-evening preference; light-dark cycle; insufficient sleep

Introduction

In the typical environmental conditions, the endogenous circadian clocks are entrained to the external light-dark cycle with 24-h period (Pittendrigh and Daan 1976). These entrained clocks, in turn, interact with the homeostatic drive for sleep to support the 24-h rhythmicity of the sleep-wake cycle (Daan et al. 1984). In today's societies, human preferences for sleep times can be often found to be at odds with their working/school start-times. The term "circadian misalignment" was coined in the field of research on the effects of shiftwork on sleep and circadian rhythms to describe a variety of circumstances, such as inappropriately timed sleep and wake, misalignment of sleep and wake with feeding rhythms, or misaligned central and peripheral rhythms (Baron and Reid 2014). The research of circadian misalignment mostly focuses on misalignment of sleep during shifts to the optimal time for human sleep, i.e., biological night. Particularly, since it is impossible to align morning and night shifts with the circadian clocks and the external 24-h light-dark cycle, both these shifts cause displacement of sleep conceptualized as the misalignments of the sleep-wake cycle in relation to the biological night (Baron and Reid 2014; Boivin et al. 2022; Haus and Smolensky 2006). It was hypothesized that the shift-associated changes in timing of sleep and light-dark exposure can lead to the disturbances of the circadian system and its misalignment with the environment (Boivin and Boudreau 2014; Haus and Smolensky 2013).

The preference for either earlier or later timing of sleep-wake behaviors (Horne and Östberg 1976) termed "chronotype" (Adan 1994) is expected to affect the extent of such misalignment. Moreover, even for day-workers, especially to those preferring a delayed sleep

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timing on free days, the conflict between socially imposed daily schedules and internal circadian clocks can be proposed (Wittmann et al. 2006). This conflict between social and biological clocks usually rests upon the tradition of setting working/school start-times too early. Such a tradition leads to the biasing our work/study culture towards the circadian clocks of early chronotypes and older adults. Consequently, the between social and biological clocks is documented in people preferring late bed- and risetimes on weekends, i.e., as evening types (Merikanto et al. 2012) and in people of certain ages, e.g., late adolescents-early adults (Carskadon 2011; Gradisar et al. 2011; Owens 2014).

Since the social clocks, such as the morning signals of alarm watches, cannot directly affect the 24-h cycle of light exposure, they cannot shift the phase of human internal clocks on an earlier phase after early weekday risetimes. Instead of following these signals, the phases of circadian body functions, including the positions of sleep and wake phases of the circadian sleep-wake cycle, remain to be set by the ex-ternal 24-h pattern of light exposure (Czeisler and Gooley 2007; Skeldon and Dijk 2021). Therefore, when late weekend risers are forced to arrive at their work/study place at the morning type-oriented working/school start-times, they sacrifice a much large amount of sleep on weekdays than early weekend risers. The lack of response of the internal clocks to the signals of social clocks in the condition of day-to -day stability of this external 24-h cycle can lead to irrecoverable loss of a large fraction weekday sleep (Putilov 2023). It was shown that university students preferring late bed- and risetimes report significantly lower general health score and weekday sleep insufficiency, i.e., spending less than 6 hours in bed due to a large, more than three hours, advancing shift of weekday wakeups (Putilov et al. 2023).

However, the likelihood of weekday sleep insufficiency can be associated not only with chronotype and the extent of advancing shift of weekday risetime relative to risetime after the following *ad lib* sleep. The circadian clocks can cause a reduction, albeit only partial, of the amount of sleep lost on weekdays. For instance, a small but significant advancing shift of the weekend sleep-wake cycles on earlier clock times was previously documented in simulations of sleep times reported before lockdown than after lockdown and after early school start time than after later school start time (Putilov 2023). These shifts can be explained by the advance of the circadian clocks leading to the advance of the sleep-wake cycle in response to the advance of the 24-h pattern of light exposure on weekdays (Putilov 2023).

Given that, as it was previously stressed by Skeldon and Dijk (2021), the sun's position in the sky, unlike the observed circadian phase, remains unaffected during such natural experiments on human sleep timing, changes in self-exposure to light emitted by artificial rather than natural lighting sources can account for these advances of the circadian phase of the sleep-wake cycle after earlier risetimes. Paradoxically, although such artificial light sources can be blamed for the delay of circadian phase observed in modern post-industrial societies (Wright et al. 2013; Stothard et al. 2017), they, on the other hand, can help to partially reduce this delay due to earlier weekday wakeups (Putilov 2023). The experimental human studies confirmed the substantial influence the wakeup time, likely via the associated morning light exposure, on the timing of the human circadian clocks (Burgess and Eastman 2006; Crowley and Carskadon 2010). The findings of these experimental studies were additionally supported by the results of "natural experiments" on weekday shifts of risetimes relative to weekend risetimes (Hasler et al. 2025; Zerbini et al. 2021, 2022).

Here, the previously proposed methodology for model-based simulation of sleep times (Putilov 1995, 2023) was applied to guide the estimations of sleep loss and advance of sleep timing in response to the shift of weekday risetimes on an earlier hour. We tried to answer to the following question about these estimates: How large is such an advance compared to such sleep loss in people of different age and chronotype? First, we reported the results of an *in silico* study aimed on applying a model of sleep-wake regulation to propose a methodology for calculation of sleep loss and advance of sleep timing in response to the shift of weekday risetimes on an earlier hour. Second, we showed that this methodology can be implicated in an analysis of weekday and weekend sleep times collected in a survey for estimation of such sleep loss and such advance of sleep timing. Third, we applied the same model in a simulation study aimed on demonstrating that, although the shifts of phase of the circadian clocks cannot be directly measured from sleep times self-reported for weekdays, evidence for such shifts can be provided by simulation of the processes underlying weekday and weekend sleep timing and duration in people of different age and chronotype.

Materials and Methods

In Silico and Simulation Studies: Model

In the present *in silico* study, we applied a model of sleep-wake regulation to propose the methodology of calculation of sleep loss and advance of sleep timing in response to the shift of weekday risetimes on an earlier hour. The calculations are based on the rhythmostatic version (Putilov 1995) of the two-process model of sleep-wake regulation (Daan et al. 1984). The model of rhythmostatic regulator explains the 24-h period of the human sleep-wake cycle by the modulating influence of the circadian clocks on the parameters of the sleep homeostatic process suggested by the classical version of the two-process model (Borbély et al. 2016; Daan et al. 1984). In the present model-based calculations, this modulating influence is represented by the simplest (sine) periodic function with a circadian period.

In the model, rhythmostatic version of the two-process model (Putilov 1995), *t1* and *t2* are the initial times for the buildup and decay phases of this sleep-wake regulating process (e.g. rise- and bedtime on vocation days with *ad lib* sleep at any day of the week, vRT and vBT, respectively). Given these initial times, the process $S(t)$ can be described as the following:

$$S(t) = [S_u + C(t)] - \{[S_u + C(t)] - S_b\} * e^{-\frac{t-t1}{[Tb-k*C(t)]}} \tag{1a}$$

$$S(t) = [S_l + C(t)] - \{S_d - [S_l + C(t)]\} * e^{-\frac{t-t2}{[Td-k*C(t)]}} \tag{1b}$$

where

$$C(t) = A * sin(2\pi * t/\tau + \varphi_0) \tag{2}$$

is the sine function with the circadian period τ representing the modulating influence of the circadian clocks, $C(t)$, on $S(t)$. In the present calculations and simulations, this period was assigned to 24 hours (Table S1), because it is well-known that the circadian clocks remain under control of (i.e. are entrained to) the external light-dark cycle with 24 h period throughout the whole week.

In Silico Study: Parameters of the Model Used for Comparison of Sleep Times

The "initial" parameters of this model (see Table S1) were derived in Putilov (1995) from data on the durations of recovery sleep after 6 gradually increasing intervals of extended wakefulness and from data on the levels of slow-wave activity calculated for 10 naps after various intervals of preceding wakefulness and after two recovery sleep episodes following two different intervals of sleep deprivation. The results of the simulation of these "initial" parameters are included in Supplementary Materials (in doc file). These parameters derived from data of experimental studies were previously slightly modified in Putilov (2023) to simulate data on bed- and risetimes reported in the literatures for weekdays and weekends (i.e. the dataset included 1048 samples divided into two halves with earlier and later weekday risetimes (6.5 h and 7.5 h, respectively). In the present *in silico* study, the same parameters as in Putilov (2023) were used to determine the way of calculation of relative measures of sleep loss and sleep phase advance after the shift wRT from later to earlier hour (Tables S1 and S2). The standard Excel software was used to perform all calculations and simulations. Moreover, the empirical results of the previous study (Putilov 2023) on sleep loss and sleep phase advance after earlier and later weekday risetimes were compared in Discussion with the present survey results on the response of sleep to such a shift.

Survey: Participants

In winter seasons, lecturers from several Russian universities invited their students, colleagues and some other workers of their departments to respond from the smartphones to questions concerning their sleep – wake habits and behavior. The responses from 1271 male and 3075 female students, and from 138 male and 456 female older participants, i.e. lecturers, were collected via web sites ($n = 4940$ in total).

The mean ages ± standard deviation calculated for these students and lecturers of two genders were 19.2 ± 2.0 and 19.4 ± 1.7 years, and 41.0 ± 13.7 and 42.5 ± 12.2 years, respectively.

Survey: Assessment of Chronotype, Sleep Times, and Wake- and Sleepabilities

In order to divide survey participants into morning, other, and evening chronotypes, the following questionnaire tools were used: (1) the Single-Item Chronotyping (SIC) designed for self-choosing chronotype from 7 response options (Putilov et al. 2021); (2) the reduced (60-item) version (Putilov et al. 2022) of the Sleep-Wake Adaptability test (SWAT) designed to self-report sleep-wake adaptability; and (3) a slightly modified version (Putilov et al. 2021, 2022) of the 19-time point Visuo-verbal Judgment Task (VJT) developed by Marcoen and other (Marcoen et al. 2015) for self-reporting sleepiness levels expected for 19 time points on the 1.5-day interval of permanent wakefulness staring from 8 a.m. Moreover, rise- and bedtimes for weekdays and weekends were reported by survey participants and they provided a possibility to calculate 5 other sleep times listed and explained in Table 1.

Table 1. Sleep times of later and earlier weekday risers and their differences.

Sleep time (abbreviation)			Either later or earlier wRT		Difference between them	
			Interpretation	Reported or calculated as	Interpretation as the difference in	Equal to the difference in
Bedtime	weekday	(wBT)	Early bedtime	wBT, (wBT-24)	early bedtime	wRT-wTiB
	weekend	(fBT)	Sleep phase	fBT, (fBT-24)	sleep phase advance	**fRT**
Risetime	weekday	(wRT)	Early risetime	wRT	early risetime	**fRT+fwRT**
	weekend	(fRT)	Sleep phase	fRT	sleep phase advance	**wRT-fwRT**
Time in bed	weekday	(wTiB)	Reduced sleep	wRT-wBT	reduced sleep	fTiB-fwTiB
	weekend	(fTiB)	*Ad lib* sleep	fRT-fBT	*ad lib* sleep	***fRT-fBT = 0***
Weekend-weekday gap	time in bed	(fwTiB)	Sleep reduction	fTiB-wTiB	sleep reduction	fwRT-fwBT
	bedtime	(fwBT)	Sleep gain	fBT-wBT	sleep gain	fwRT-fwTiB
	risetime	(fwRT)	Sleep loss	fRT-wRT	sleep loss	**wRT-fRT**

Equal to the difference in: The difference in sleep time can be equal to the sum of the differences between two other sleep times or another difference or zero; wBT and fBT, wRT and fRT, and wTiB and fTiB: Weekday and weekend bedtime, risetime and time in bed, respectively; fwBT, fwRT, and fwTiB: Gaps between weekends and weekdays in these sleep times. Printed in ***bold italic***: Since the duration and timing of *ad lib* sleep at night between Saturday and Sunday are endogenously determined, they are predicted to be the same after any (e.g. either later or earlier) wRT, and, therefore, the difference in fTiB = fRT − fBT = 0. Printed in bold: The difference in wRT is equal to the sum of differences in fRT = fBT and fwRT = fwBT + fwTiB, i.e. the difference in weekday risetime (a relative advance of weekday wake-ups) is equal to the difference in sleep phase advance (a relative advance of sleep phase on weekends) plus the difference in sleep loss (an additional loss of sleep on weekdays). These interpretations of sleep times and differences between them in later and earlier weekday risers are illustrated in Figures S1 and S2.

Survey: Categorization of Morningness-Eveningness and Weekday Risetimes

The $SPSS_{26.0}$ statistical software package (IBM, Armonk, NY, USA) was used for statistical analyses. Factor analysis was applied to obtain scores on the 1st (the largest) principal component (PC1) of variation in three following self-assessments of chronotype, (1) chronotype self-chosen with SIC was scored as – 1 and + 1 for morning and evening types, respectively, and as 0 for other types, (2) sum of scores on 10-item scales of Morning Sleepability and Nighttime Wakeability of the SWAT were calculated, and (3) the difference in mean KSS (Karolinska Sleepiness Scale) scores expected for morning and evening-early night time points (i.e. the responses to the VJT for 8:00, 9:00, 10:00, and 11:00 and for 21:00, 22:00, 23:00, 24:00, 2:00, and 4:00, respectively). In accord with PC1 score, the subsamples of students and lecturers were further divided into three groups of approximately equal size (see Results).

The responses on the questions about clock hours for rise- and bedtimes on weekdays and weekends were used to calculate the sets of 9 sleep times (Tables 1 and S3-S5). The times reported by late and earliest weekday risers (wRT >7.0 h and <6.5 h, respectively) were used to calculate the differences between them in sleep times (Table 1 and S6-S9). Additionally, responses to three 10-item scales of the SWAT designed to assess Nighttime Sleepability, Daytime Sleepability, and Daytime Wakeability were compared in such subdivisions.

Survey: Percentages of Sleep Insufficiency and Circadian Misalignment

Weekend-weekday gaps in risetimes (fwRT) and weekday times in bed (wTiB) were dichotomized to calculate amount of survey participants with fwRT >3.0 h and wTiB < 6.0. These cut-off values were regarded as the indicators of weekday circadian misalignment and weekday sleep insufficiency, respectively. The percentages of weekday circadian misalignment and sleep insufficiency were compared in the subsamples (Tables S10 and S11).

See also Supplementary Materials for statistical analysis of sleep times and sleep- and wakeabilities.

Simulation Study

Phase of the circadian clocks is expected to advance after early weekday wakeups both on weekdays and the following weekends. The results of *in silico* study suggested a way of measurement of the difference in such advance between later and earlier weekday rises during weekends. However, this difference can be measured using weekend sleep times. It cannot be measured on weekdays because it is impossible to determine what is a cause of earlier weekday sleep timing, either earlier wake-ups or circadian phase advance (Figures S1 and S2). Therefore, a possibility of advancing phase shift of the circadian clocks on both weekdays and weekends was examined by means of model-based simulations of sleep times calculated for each of the subdivisions (two ages x three chonotypes x three wRT). The phase of circadian modulation of the parameters of sleep-wake regulating process was included in the list of those parameters of the model that were allowed to vary to account for the differences in sleep times of survey participants of two ages, three chronotypes and three wRT (see Supplementary Materials for more details). These simulations were performed using the least-squares method. The process of fitting parameters of the model was stopped after reaching the maximally allowed difference in ±0.2 h between any of 9 empirically obtained and simulated sleep times (Tables S12-S14).

Results

Results of the In Silico *Study in Brief*

The results of *in silico* study included the suggestion about a possibility to calculate (1) an additional sleep loss and (2) an additional advance of sleep timing after the shifts of weekday risetimes on an earlier hour. Such measures as (1) additional sleep loss on weekdays and (2) further advance of the sleep phase were proposed to be the two consequences of the shifts from later to earlier risetimes on weekdays. Table 1 lists these two measures and their abbreviations as well as the sleep times and their derivations used for calculations of these two measures. The results of the *in silico* study are describes in details in Supplementary Materials. To sum up these results, the model was used to demonstrate that the phase-shifting effect of wRT cannot be directly measured (i.e. in absolute terms) in the absence of reports on vRT and vBT, i.e. sleep times on vacation with *ad lib* sleep on every day of the week. However, the reports on bed- and risetimes on weekdays and weekends (wBT, wRT, fBT, and fRT) for earlier and later wRT allow the following indirect measurement of the phase-shifting effect. (1) The difference between earlier and later risers in fBT or fRT provides a relative measure of this phase-shifting effect, i.e. an additional phase-shifting effect of earlier wRT on weekends due to such an advance of wRT. (2) The difference between earlier and later risers in fwRT provides a relative measure of sleep loss on weekdays, i.e. an additional loss of sleep due to this advance of wRT. Consequently, the difference between the earlier and later wRT (e.g. 3.0 h in Figures S1C, S1D and S2) can be calculated as the sum of two values: (1) the relative advance of sleep on weekends measured as the difference between earlier and later risers in fBT/fRT (e.g. 1.0 h in Figures S1C and S1D) and 2) the relative sleep loss measured as the difference between them in fwRT (e.g. 2.0 h in Figures S1C, S1D and S2). In other words, the difference between the earlier and later risers in advance of their circadian phases can be estimated as the difference between their wRT minus the difference in their sleep loss (fwRT).

Results of the Survey: Subdivisions into Chronotypes and Weekday Risers

Data of the survey were used to demonstrate the way of obtaining these estimations for subdivisions of survey participants representing different wRT, age, and chronotype.

Three chronotypes were distinguished on the results of analysis of chronotype self-assessments. Factor analysis of the results of three self-assessments of chronotype (see section 2.4 of Methods) yielded the first principal component (PC1) with eigenvalue > 1 (1.905) that accounted for 63.5% of total variance. The loadings of these three assessments on this component varied between 0.5 and 0.6. In accord with the distribution of scores on PC1, the whole sample of students and lecturers was subdivided into morning, other, and evening subsamples of approximately equal size, PC1 score ≤ −0.40 for morning type subsample, PC1 score > −0.40 but ≤ 0.40 for other type subsample, and PC1 score > 0.40 for evening type subsample (Tables S3-S5). After additional subdivision of these three subsamples in accord with three weekday risetime (wRT <6.5 h, ≥6.5 h but ≤7.0 h, and >7.0 h, respectively), sleep times were subjected to three-way ANOVAs (Table 2). The results provided the estimates of sleep times for each of 18 subdivisions, i.e. two ages (students and lecturers) x three chronotypes (morning, other, and evening) x three wRT (earliest, early and late). The obtained subsample-averaged sleep times are illustrated in Figure S3 (left graphs) and included in Tables S3-S5.

Results of the Survey: Non-Significant Effects of ANOVAs

Non-significant main effects and non-significant interactions of ANOVAs are highlighted in Table 2 Their importance for interpretation of obtained results included the following conclusions.

(1) One of such non-significant results suggested that neither chronotype nor wRT affected time in bed on weekends (fTiB). This result supported one of the results of the *in silico* study predicting that time in bed is similar after earlier and later wRT. This similarity indicated that the return to the endogenously determined sleep timing and duration occurs after just one night of *ad lib* sleep (i.e. the night between Friday and Saturday) irrespective of how large was the advance of risetime on weekdays. Such a response to earlier weekday wake-ups occurs due to the modulation of the parameters of the sleep-wake homeostatic process by the circadian clocks. The similarity of fTiB after different shifts of wRT in subdivisions provided a possibility of applying the methodology of estimation of relative advances of sleep

Table 2. F-ratios for main effects of three independent factors and their interactions.

Main effect or interaction				Main effect			"Age"		"Score"	
Independent factor				"Age"	"Score"	"wRT"	"Score"	"wRT"	"wRT"	Triple
Assessment (abbreviation)				$F_{1/4922}$	$F_{2/4922}$	$F_{2/4922}$	$F_{2/4922}$	$F_{2/4922}$	$F_{4/4922}$	$F_{4/4922}$
Sleep time	Bedtime	weekday	(wBT)	64.53***	106.05***	33.44***	1.51	3.75*	6.31***	3.70**
		weekend	(fBT)	39.85***	128.53***	23.58***	*0.15*	*1.17*	*2.04*	*1.73*
	Risetime	weekday	(wRT)	**3.15**	18.75***	1470.2***	4.98**	**1.03**	12.83***	3.40**
		weekend	(fRT)	121.99***	167.13***	37.39***	*0.77*	*0.94*	*1.92*	*0.44*
	Time in bed	weekday	(wTiB)	73.13***	64.63***	133.86***	4.91**	4.77**	3.35**	2.04
		weekend	(fTiB)	12.69***	***2.09***	***0.69***	***0.40***	***0.03***	***0.59***	***1.29***
	Weekend-weekday gap	time in bed	(fwTiB)	88.10***	42.06***	63.85***	2.76	2.15	2.28	0.63
		bedtime	(fwBT)	***0.58***	5.41**	***0.88***	***0.48***	***1.00***	***0.76***	***0.43***
		risetime	(fwRT)	133.59***	116.88***	115.61***	2.47	1.92	4.11**	0.82
Scale	Sleepability	Nighttime	(NS)	40.96***	18.18***	5.99**	0.44	0.09	0.45	0.37
		Daytime	(DS)	9.52**	19.46***	3.93*	1.68	1.05	2.18	1.48
	Wakeability	Daytime	(DW)	3.16	32.42***	8.50***	5.87**	0.62	2.76*	0.61

F-ratios yielded by three-way ANOVAs for main effects of independent factors and interactions between them. Scale: Scores on the scales Nighttime Sleepability, Daytime Sleepability, and Daytime Wakeability of the SWAT. Independent factors were "Age" (younger survey participants, 4346 university students, and older survey participants, 594 lecturers), "Score" (three ranges of PC1 score for morning types, PC1 score ≤ −0.4, other types, PC1 score > −0.4 but PC1 score ≤ 0.4, and evening types, PC1 score > 0.4), and "wRT" (three ranges of wRT for the earliest weekday risers, wRT <6.5 h, early weekday risers, wRT ≥6.5 h but wRT ≤7.0 h, and late weekday risers, wRT >7.0 h). Highlighted non-significant main effects and interactions: in bold ("Age" and its interaction with "wRT"), in *bold italic* (either "Score" and "wRT" or "Age" and "wRT" as well as the interactions between them), and in *italic underlined* (all interactions). See other notes to Table 1.

phase by simple comparison of weekend sleep timing in subdivisions with the earliest and later wRT. As it was shown by the results of the *in silico* study, the advance shift of sleep phase after early wRT can be measured by comparing weekend sleep times in the subsamples of earlier and later weekday risers. As demonstrated in Figures S1B, S1D, S2A and S2D, a relative phase advancing effects of two different wRT (wRT = 5.2 h and 8.2 h) is equal to 1.0 h, while the remaining 2.0-h difference in wRT = 3.0 h is explained by the difference between earlier and later weekday risers in weekend-weekday gap in risetime (fwRT). Table 3 summarizes and Figure S5 illustrates the results presented in Tables S6-S8 on the differences in sleep times reported by the survey participants from six subdivisions of the whole sample. In students and lecturers of three chronotypes (2 × 3), the difference in wRT between the subdivisions of the earliest and late weekday risers (wRT <6.5 h and >7.0 h, respectively) varied between 2.0 h and 2.8 h. Such a difference is the sum of the differences in fRT and fwRT that varied from 0.5 h to 1.3 h and from 1.0 h to 2.0 h, respectively (Tables 3 and S6-S8). On average, the 1.0-h advance shift of wRT led to only 0.6-h of additional loss of sleep on each of 5 weekdays due to the compensating 0.4-h advance of sleep at the following weekend (Table 3, last column). Thus, the advance shift in weekday wakeups always resulted in (1) an advance of sleep phase on weekends and (2) an additional loss of sleep on weekdays. As a rule, the later was somewhat larger than the former (Table 3).

(2) Another non-significant result (Table 2) suggested that students and lecturers did not differ in wRT. Therefore, the changes in the pattern of exposure to the 24-h light-dark cycle are

Table 3. Summary of the difference in sleep times between late and earliest risers.

		Age	Students			Lecturers			Mean				
Sleep time		Score	≤-0.4	>-0.4, ≤0.4	>0.4	≤-0.4	>-0.4, ≤0.4	>0.4	≤-0.4	>0.4	Students	Lecturers	Mean
Bedtime	weekday	(wBT)	0.43	0.39	0.61	0.80	0.07	2.10	0.53	0.70	0.65	1.23	0.74
	weekend	(fBT)	0.56	0.59	0.60	0.90	0.11	1.65	0.66	0.66	0.78	1.26	0.86
Risetime	weekday	(wRT)	2.29	2.41	2.56	1.97	2.12	2.83	2.22	2.59	2.45	2.32	2.43
	weekend	(fRT)	0.99	0.45	0.79	1.02	0.61	1.30	1.04	0.81	0.93	1.36	1.01
Time in bed	weekday	(wTiB)	**1.85**	**2.01**	**1.92**	**1.16**	**2.05**	**0.72**	**1.69**	**1.86**	**1.79**	**1.09**	**1.68**
	weekend	(fTiB)	***0.43***	***−0.14***	***0.15***	***0.12***	***0.51***	***−0.35***	***0.38***	***0.11***	***0.14***	***0.10***	***0.14***
Weekend-weekday gap	time in bed	(fwTiB)	**−1.43**	**−2.15**	**−1.76**	**−1.04**	**−1.56**	**−1.07**	**−1.31**	**−1.75**	**−1.65**	**−0.99**	**−1.54**
	bedtime	(fwBT)	***0.13***	***0.20***	***0.00***	***0.10***	***0.05***	***−0.46***	***0.13***	***−0.03***	***0.13***	***0.03***	***0.12***
	risetime	(fwRT)	**−1.30**	**−1.96**	**−1.77**	**−0.95**	**−1.51**	**−1.53**	**−1.18**	**−1.78**	**−1.52**	**−0.96**	**−1.42**

Difference between sleep times of late and earliest risers, wRT < 6.5 and > 7.0, respectively. Printed in *bold italic*: On average, the following differences are close to zero, fTiB or fwBT = fwRT − fwTiB. Therefore, the difference in fwTiB = fwRT ~ wTiB (printed in bold). See Tables S3-S5 for sleep times for these subsamples with different wRT, see Tables S6-S9 and Figure S4 for the differences in sleep times between wRT < 6.5 and > 7.0.

expected to be similar in people of two different ages (Figure S3).

(3) The next non-significant result indicated that neither age nor wRT can influence the gap between weekends and weekdays in bedtime (fwBT). This result provides evidence for a close similarity of this gap in lecturers and students with the earliest and late wRT (Figure 1), i.e., people of two ages gained similar amount of sleep on weekday, fwBT, irrespective of amount of weekday sleep loss, fwRT, that was much larger in students and earliest weekday risers.

(4) Finally, all interactions were non-significant for sleep times on weekends, including the interactions with wRT. These non-significant results, in particular, indicated that the difference between the earliest and late weekday rises in fBT or fRT were very similar in participants with different chronotype and age (Table 2). In other words, the amount of advance of weekend sleep timing due to the shifts of the 24-h pattern of exposure to light was independent from age and chronotype of the survey participants (Figure 1).

Results of the Survey: Weekday Sleep Insufficiency and Circadian Misalignment

The survey results suggested similarity of responses of lecturers and students to the shift of weekday risetime from late to earliest (wRT from >7.0 h to <6.5 h, respectively). However, when they are waking up at the same hour on weekday, does not matter whether this is wRT from >7.0 h or <6.5 h, sleep loss is expected to be always much larger in students due to their preference for late weekend wakeups. Consequently, Table S10 reveals the drastic difference between students and lecturers in percentage of survey participants with weekday circadian misalignment and sleep insufficiency determined as fwRT >3.0 h and wTiB < 6.0, respectively. Weekday sleep insufficiency was diagnosed in almost a third of students (32%) but in only 8% of all lecturers. Among these survey participants with weekday sleep insufficiency, weekday circadian misalignment was also found to be much larger in students than lecturers (22% and 4%, respectively; Table S10).

Figure 2 illustrates that the percentage of weekday circadian misalignment and sleep insufficiency was higher in the earliest weekday risers and evening types. Being a student was associated with weekday circadian misalignment in 49% of the earliest weekday risers and in 43% of evening types. Weekday sleep insufficiency was diagnosed in 50% of the students classified as the earliest weekday risers and in 42% of the students classified as evening type (Table S11 and Figure 2).

See also Supplementary Materials for the results of statistical analysis of sleep times and sleep- and wake-abilities and for results of simulations.

Results of Simulations in Brief

The shifts of phase of the circadian clocks cannot be directly measured from sleep times self-reported for weekdays, but a simulation of sleep times with the model of sleep-wake regulations can provide evidence for such shifts. The results of the present simulations (see Supplementary Materials) indicated that, not only on weekends, but also on weekdays, the circadian phase of the sleep-wake cycle is expected to be shifted ahead in response to early weekday wakeups (Figure S7C and S7D). The extent of this shift was shown to be larger in people with later than earlier weekend sleep timing (Figure S7 and Tables S12-S14).

Discussion

The biasing the work/study culture towards the circadian clocks of people with early *ad lib* sleep timing causes the conflict between social and biological clocks of many people preferring late timing of their *ad lib* sleep. The circadian clocks seem to be responsible for the opposing one another effects of advancing weekday wakeups: (1) weekday sleep loss and (2) its partial compensation by advancing shift of the circadian sleep phase. Here, we proposed the methodology for measurement of these effects from weekday and weekend sleep times, i.e. in the absence of information about the circadian phase and the light-dark cycle. In the present *in silico* study, we showed that the phase-shifting effect of weekday risetime cannot be directly measured because information about sleep times on vacation with *ad lib* sleep at any day of the week is also missing. However, weekday and weekend sleep times can be used to measure this effect in relative terms, as further increase of weekday sleep loss and further advance of weekend sleep timing after further advancing shift of weekday wakeups. The results of our *in silico* study indicated (1) that this advance of weekend sleep timing can be estimated as the difference between weekend bed-/risetimes observed after an earlier and later risetimes and (2) that this advance is equal to the difference between the earlier and later risetimes minus the difference in sleep loss measured as the difference in weekend-weekday gap in risetime.

The present results suggested that, despite the drastic difference between the survey participants of different age and chronotype in sleep loss, the age- and chronotype-associated differences in responses to the shift of

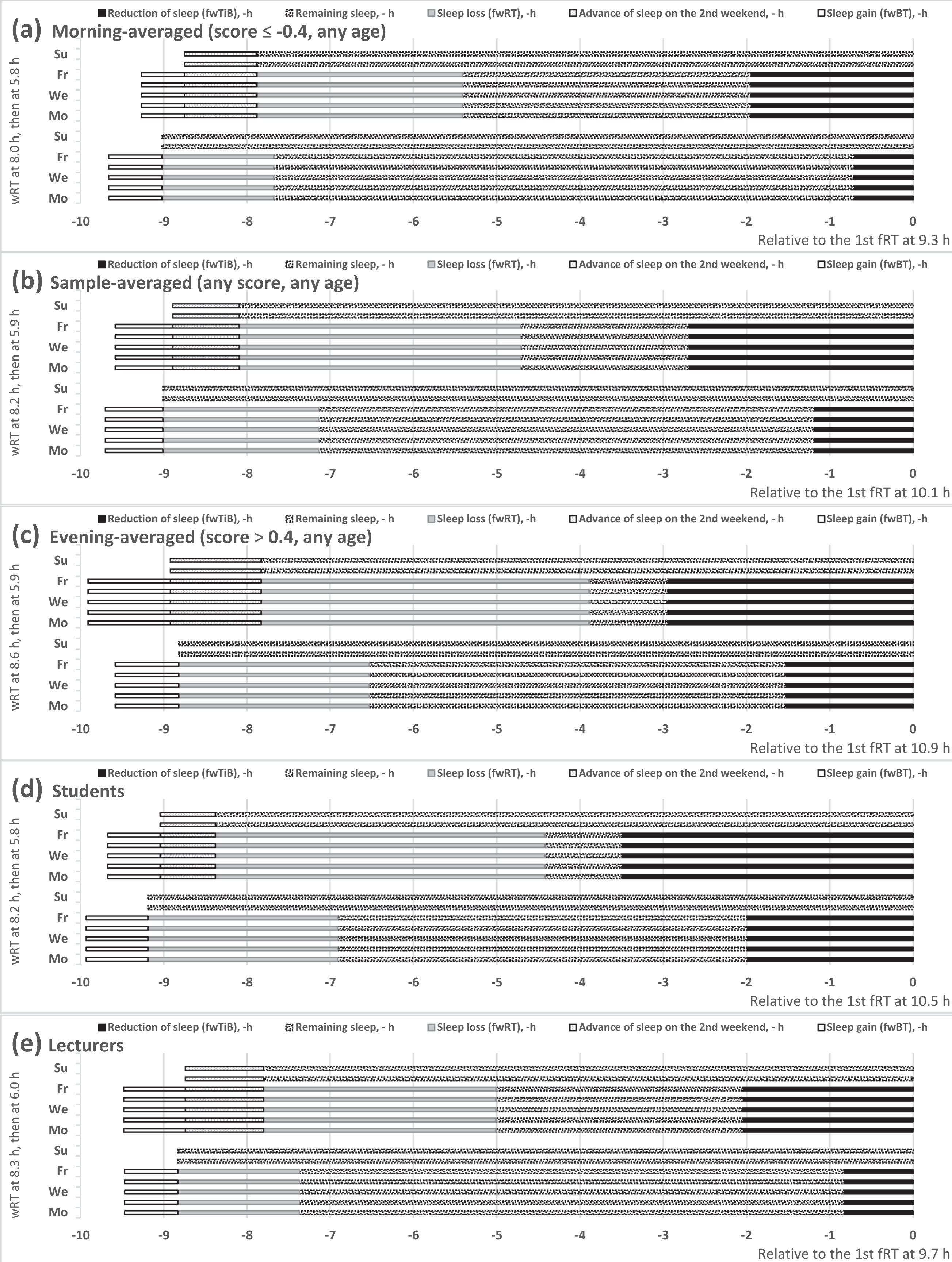

Figure 1. Fractions of sleep in the whole sample, two ages, and three chronotypes. These subdivisions of time in bed on several time intervals provided a comparison of subsamples on these fractions plus on weekday sleep reduction (fwTiB) caused by five early weekday risetimes. (a-e) For any subdivision, this reduction is equal to the difference between fwRT and fwBT (i.e. weekday sleep loss and weekday sleep gain). Given that the analysis of data of the survey (see Table 2) suggested the zero difference in fwBT between two weeks, the difference between these two weeks in fwRT is close to the difference in fwTiB (fwTiB = fwRT – fwBT ~ fwRT). See also the estimates for this figure in Tables 3 and S6-S8.

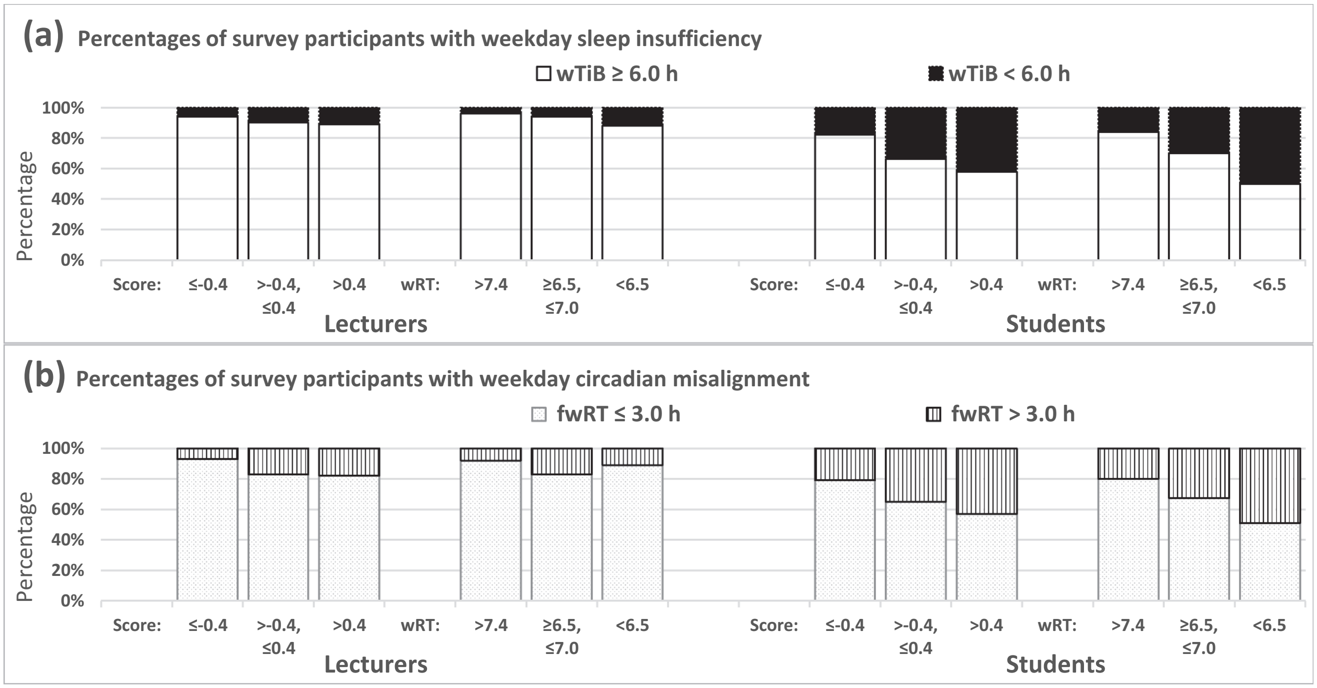

Figure 2. Circadian misalignment and sleep insufficiency. (a) Weekday times in bed (wTiB) and (b) weekend-weekday gap in risetimes (fwRT) were dichotomized, and wTiB < 6.0 and fwRT >3.0 h were determined as the indicators of weekday sleep insufficiency and circadian misalignment, respectively. See the percentages of survey participants with such weekday circadian misalignment and sleep insufficiency in Tables S10 and S11.

weekday wakeups from late to the earliest risetimes were non-significant. Depending upon a subsample, the advances of weekday risetime on 2.0–2.8 hours led to only 1.0–2.0 hours of additional sleep loss on weekdays because the advances of sleep phase compensated 0.5–1.3 hours of sleep. On average, the shift of weekday risetime on one hour led to 0.6-h increase of weekday sleep loss and 0.4-h compensating advance of weekend sleep timing. These estimates were in full agreement with the estimates obtained in the previous comparison of sleep times in two halves of a set of 1048 samples with 1.0-h difference in weekday risetime between these halves (6.5 h vs. 7.5 h). It was found that this 1.0-h difference in weekday risetime was equal to the sum of 0.6 h of additional weekday sleep loss and 0.4 h of weekend sleep advance (Putilov 2023).

Information on sleep times for weekdays and weekends is not sufficient for direct estimation of the advance of the circadian sleep timing caused by the shifts of weekday risetimes relative to the risetimes on weekends leading to the shift of exposure of the circadian clocks to the external 24-h dark-like cycle. Therefore, mathematical modeling can help to explain the clock mechanisms behind the responses of the sleep-wake cycle to early weekday risetimes. The results of the present simulation study indicated that, in addition to the difference in timing of the sleep-wake cycle, the difference in phase of the circadian clocks can underlie the difference in sleep times between later and earlier weekday risers and between evening and morning types. Therefore, the results of such simulations provided support for the assumption that the phase of the sleep-wake cycle can shift ahead in response to early weekday wakeups not only during weekends but also during weekdays.

Overall, the proposed approach suggested a way of measurement of partial compensation of irrecoverable loss of sleep on weekdays due to an advance of the pattern of exposure to light that, in turn, leads to an advance of the circadian sleep timing.

Similarity of the advancing effects of early weekday risetimes in people of different ages and chronotypes can be expected from the earlier published findings pointing at a close similarity of the phase response curves in people with earlier and later timing of the sleep-wake cycle (Kripke et al. 2007). In agreement with this finding, we found that the advancing shifts of the weekend sleep timing after the shifts of weekday risetime from later to earlier hours were not significantly different in the survey participants from different age- and chronotype subdivisions. Notably, the total amount of weekday sleep loss demonstrated, in contrast to the advancing effect, the drastic difference between these subdivisions.

A larger shift of weekday wakeups relative to weekend wakeups is expected to lead to an earlier self-exposure to light on weekdays. As it was stressed by Skeldon and Dijk (2021), the sun's position in the sky remains unaffected during such natural experiments on human sleep timing. Therefore, the difference in weekday shift of the circadian phase and sleep times cannot be explained by the change in exposure to natural light sources. At least in winter season, people are active both in the early morning hours and in the late evening hours, i.e., during scotoperiod. Artificial lighting is inevitable during these hours. Therefore, the advance of exposure to artificial light sources seems to be the major contributor to the shift of phase of the circadian clocks leading to the shift of phase of circadian modulation of the parameters of sleep-wake regulating process. The results of the present simulations suggesting a possibility of the advance of phase of the circadian clocks in response to early weekday wakeups collaborate the previously published evidence for the substantial influence the wake time, likely via the associated morning light exposure, on the timing of the human circadian clocks (Burgess and Eastman 2006; Crowley and Carskadon 2010; Hasler et al. 2025; Zerbini et al. 2021, 2022).

Notably, even when empirical results fail to support the existence of such shifts of the circadian phase in response to earlier wakeups, this does not imply that these shifts do not occur. For instance, Esquivel-Mendoza et al. (2023) compared the time of dim light melatonin onset in 11 study participants before and during lockdown. They reported significant 22-min delay of sleep end time during lockdown, but the 25-min delay of dim light melatonin onset was non-significant (Esquivel-Mendoza et al. 2023). However, the previous simulations of weekend sleep times reported before and during lockdown (mean for 74 samples) suggested that such a delay of the circadian phase and risetime are expected to be, on average, even a bit smaller than 25 min, 0.35 h = 21 min (Putilov 2023). Therefore, the non-significant effect reported by Esquivel-Mendoza et al. (2023) might be expected to become significant in a sample of larger size.

It is well established that the questionnaires for self-assessment of morning-evening preference (e.g. Horne and Östberg 1976) have significant heritability (reviewed by Leocadio-Miguel et al. 2021). For instance, heritability estimates reported in eight twin studies, four family studies, and four genome-wide association studies varied between 0.40 and 0.54, 0.21 and 0.48, and 0.12 and 0.21, respectively. In one of the family studies (Leocadio-Miguel et al. 2021), the heritability estimate obtained for such a preference questionnaire (0.37) was found to be somewhat higher than the estimate for the questionnaire designed to self-assess morningness-eveningness in accord with current weekend sleep timing (0.32). This difference is not surprising because the differences in preferred and current (or actual) sleep times represent two different, trait-like and state-like, respectively, aspects of individual variation in the sleep-wake pattern (Putilov 2017). The current rather than preferred sleep-wake patterns seem to be more profoundly modified by various external factors, such as social obligations, work schedules, lifestyle choices, eating habits, drug and alcohol consumption, geo-graphic location, etc. (e.g. Coutrot et al. 2022; Devine et al. 2021; Fischer and Lombardi 2022; Sharma et al. 2022). The drastic impact of social obligations on such a self-assessment can be, in the present study, exemplified by variation in timing of weekday wakeups. When the survey participants are classified into morning and evening types using the questionnaire tools designed to self-assess trait-like or ability-like variation in chronotype, they have practically identical sleep times on weekend in the case of scheduling their weekday risetime earlier than 6:30 and later than 7:00, respectively. Further simulation studies are required to quantitatively evaluate the sleep-shifting effects influenced by such external factors as lifestyle choices, eating habits and diet, consumption of alcohol and medications, light pollution, location within time zone, latitude and longitude, and so on.

Sleep researchers are concerning about the epidemic of sleep deprivation among adolescents characterized by insufficient and ill-timed sleep caused by their typical rest-learning schedules maintained during the school year (Åkerstedt et al. 2023; Carskadon 2011; Davidson et al. 2022; Gradisar et al. 2011; Meltzer et al. 2022; Owens 2014). The present paper has practical implications for quantitative estimation of the severity of such sleep deprivation in people with distinct chronotypes, ages, and risetimes. It seems that actual weekday sleep loss is underestimated when it is calculated as the weekend-weekday gap in sleep duration. The results of the *in silico* study suggested that actual sleep loss is equal to the sum of this gap in sleep duration and the week-end-weekday gap in bedtime. In other words, sleep loss is equal to the sum of the reduction of weekday sleep compared to weekend sleep plus weekday sleep gain. Particularly, the applying of the model-driven approach to the estimation of sleep loss revealed the dramatic weekday sleep curtailment in students and evening types. This loss averaged for three categories of risetimes, exceeds one-third of the total weekday time in bed expected in the case of spontaneous rather than forced termination of sleep on weekdays. Negative health impacts of such dramatically reduced, insufficient sleep were well-documented (e.g. Buxton et al. 2012; Cappuccio et al. 2010; Grandner et al. 2010; Itani et al. 2017; von Ruesten et al. 2012).

Results of present simulation can help to navigate among the potential intervention strategies aimed on mitigation of adverse health impacts of weekday sleep insufficiency and circadian misalignment. The postulations of neither dysregulation of the sleep-wake cycle nor shifts of the sleep-wake phases relative to the phase of the circadian central clocks were necessary in the present simulations. Instead, these simulations and earlier published experimental results (Åkerstedt et al. 2009; Hennecke et al. 2019) pointed at the ability of our body to return to previous (endogenously determined) sleep timing and duration after just one night of *ad lib* sleep, e.g. during the first day of each two-day weekend. Therefore, the adverse health effects of early weekday wakeups due to the misalignment of the sleep-wake cycle in relation to the biological night can be mostly linked to the negative impacts of sleep restriction and irrecoverable partial loss of sleep on weekdays.

The following disturbance of the clock- and sleep-regulating mechanisms can be hypothesized for explaining the cause of such negative health effects. The expression of circadian clock genes in the neurons of suprachiasmatic nuclei (SCN) is under control of the external lark-dark cycle and, therefore, the work of the central circadian clocks cannot be affected by sleep – wake perturbations associated with earlier weekday wake-ups. In other words, the work of central circadian clocks remained unaffected and they are permanently entrained to the external 24-h sleep-wake cycle. In contrast, the expression of many of these genes in other brain cells is fully or partially driven by the sleep-wake cycle (Jan et al. 2024) and, therefore, the extension of wake phase on early morning hours affects the expression of circadian genes peripheral to the SCN. Most importantly, the changes in this rhythmic genes' expression in response to sleep loss are surprisingly long, i.e., they were documented for, at least, three days (Archer et al. 2014; Hor et al. 2019; Möller-Levet et al. 2013) that is much longer than one night of *ad lib* sleep required for restoration of the sleep-wake cycle. Consequently, such a long-lasting disturbance of normal functioning of the peripheral clocks can be a reasonable explanation of the negative health impact of early weekday wakeups. Several days with early wakeups disturb the circadian clocks peripheral to the SCN for a much longer time period compared to just one night of *ad lib* sleep required for restoring the endogenously determined sleep timing under the undisturbed circadian governance of the sleep-wake cycle. As a result, normal functioning of the whole human organism is also disturbed for such a longer than weekend period due to the disturbance of the peripheral clock mechanisms rather than due to disturbance of the central circadian clocks and the mechanisms of sleep regulation. As it was stressed by Hor et al. (2019), the metabolic perturbations caused by multiple nights of restricted sleep can serve an example of this long-lasting disturbance because, as it was demonstrated by Depner et al. (2019) and Ness et al. (2019), even two nights of recovery sleep were insufficient to completely reverse such metabolic perturbations.

Consequently, the best way to equalize morning and evening types on the amount of irrecoverable weekday sleep loss and circadian misalignment would be to directly change weekday sleep timing by permitting a >2 h difference between these types in weekday risetime (Putilov et al. 2022). The present study results pointed on a small negative effect of such permission. Sleep quality in evening types seems to decrease relative to that in morning types due to the extension of their time in bed on weekdays as indicated by their lowered nighttime sleepability score after later weekday risetimes. However, daytime wakeability showed a beneficial response to this extension. Light interventions (e.g. Misiunaite et al., 2020; Smith and Eastman 2012) can be also recommended to change the ratio between two terms of the equation of advancing shift of weekday risetime (i.e. this advancing shift of weekday risetime = advancing shift of circadian and sleep phases + increase in weekday sleep loss). An appropriately timed exposure to artificial bright light can help to increase the contribution of advancing shift of circadian and sleep phases at the expense of the contribution of weekday sleep loss.

There are several limitations to the analyzed dataset. The major of these limitations is in cross-sectional design of the survey. Therefore, an earliest riser and a late weekday riser are not the same person. Moreover, the self-reports of their sleep times may not be accurate and the profound change in sleep-wake pattern across ages does not allow the generalization of the results to the whole lifespan, i.e. on children and the middle aged. Consequently, the present results require confirmation in studies measuring the objective markers of circadian phase and sleep timing. Finally, the present simulations are based on self-reports of just four sleep times and, therefore, they cannot account for the profound day-to-day variation in sleep timing and duration expected in the vast majority of survey participants (see, for instance, Fjell and Walhovd 2024). Consequently, further studies can address the question of applicability of the model to the simulation of individual longitudinal data on sleep times reported or objectively measured for each day of one or more weeks. There are also limitations to the analysis of the dataset. Its subdivision was made using the fully artificial criteria. Therefore, such subdivision ignores sex and individual differences in sleep times, as well as the contribution of such factors as body mass index, meal timing, drug and alcohol consumption, and so on.

Conclusions

We proposed a model-driven approach to the estimation of an additional advance of sleep phase on weekends and an additional loss of sleep on weekdays in response to an additional advance of weekday wakeups. In the present *in silico* study, a model of sleep-wake regulation was applied to show that (1) the difference between later and earlier weekday risers in weekday risetime is equal to the sum of differences between them in sleep loss and sleep phase advance that (2) these differences can be measured as the difference in weekend-weekday gap in risetime and the difference in weekend bed- or risetimes, respectively. We also demonstrated the applicability of such approach by estimating the differences in sleep loss and advance of sleep phase using bed- and risetimes reported for weekdays and weekends by 4940 survey participants. On average, these estimates were found to be practically identical to the estimates previously obtained by comparison of sleep times in two halves of a set of 1048 samples with earlier and later risetimes collected from the literature (Putilov 2023). The model-based simulations of sleep times confirmed the assumption of advancing phase shifts of the circadian clocks on weekdays after early weekday wakeups.

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Author Contributions

Conceptualization, A.A.P.; methodology, A.A.P., E.V., O.D., and D.S.; software, A.A.P. and E.V.; validation, A.A.P. and E.V.; formal analysis, A.A.P.; investigation, A.A.P., D.S., Z. B., E.Y., O.M., V.T., E.T., M.L., Z.L., R.B., E.B., M.D., O.D., A.N.P., and V.D.; resources, A.A.P., V.D., and D.S.; data curation, A.A.P., E.V., O.D., and D.S.; writing – original draft preparation, A.A.P., D.S., Z. B., E. Y., O. M., V. T., E. T., M. L., Z. L., R. B., E. B., M. D., O.D., A.N.P., and V.D.; writing – review and editing, A.A.P.; visualization, A.A.P.; supervision, A.A.P., V.D., and D.S.; project administration, A.A.P., V.D., O.D., and D.S.; funding acquisition, A.A.P., V. D., and D.S.

Data Availability Statement

Data of the survey and simulation results are available from the first author on reasonable request.

Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the Institute of Higher Nervous Activity and Neurophysiology in June 2019 (Approval#12402-02-7112).

Informed Consent Statement

The study participants were informed in detail about the survey procedure, and informed consent was obtained from each participant in the form of the answer “Agree” to the following statement: “I give informed consent to anonymously and voluntarily participate in this online survey of sleep-wake behavior and habits.”

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