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ARTICLE



Model-based simulations of weekday and weekend sleep times self-reported by larks and owls

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ABSTRACT

A model of sleep-wake regulatory process was applied to examine several common beliefs associated with the so-called “social jetlag”, e.g. 1) sleep lost on weekdays due to the scheduled early wakeups might be partly recouped by getting extra sleep on weekends and 2) the weekday sleep loss is greater in evening- than in morning-oriented individuals. Weekday-weekend sleep times reported in 19 previously published papers for 20 samples of morning- and evening-oriented individuals were utilized as an input to the model. The results of statistical analyses and simulations of these times suggested that 1) sleep cannot be caught up on weekends and 2) evening- and morning-oriented individuals are not, in general, dissimilar on the amount of weekday sleep. We concluded that chronobiological mechanisms underlying “social jetlag” require rethinking and that studying mathematical models of sleep-wake regulatory process allow the quantitative predictions about weekday sleep loss in different ages and diurnal types.

ARTICLE HISTORY

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KEYWORDS

Sleep-wake regulation; two-process model; morningness-eveningness; early type; late type; sleep timing; sleep duration; sleep debt; sleep deprivation; simulation

Introduction

Each weekday night people, on average, are losing approximately 1 h of sleep. Can they accumulate sleep debt on weekdays to repay it, at least partly, on weekends? Many people believe that there is a possibility to overcome, at least partly, the consequences of sleep restriction during five work/schooldays by getting extra sleep on two weekend days. There is also another widely held belief: that such a weekday sleep reduction must be larger and such a weekend catch-up sleep must be longer in “owls” than in “larks” (in other terms, morning-oriented or early or M-types vs. evening-oriented or late or E-types).

Such common sense is held by a large number of researchers and can be illustrated by the concept called “social jetlag”. Wittmann et al. (2006) described it as one of the specific forms of misalignment between work hours and preferred sleep times that governed by our body clocks that, in turn, are entrained to the 24 h light-dark cycle rather than to any of social time cues including work hours. They have also noted that, consequently, social jetlag is most pronounced in late chronotypes, “who substantially

have to readjust their temporal habits to social demands (i.e. having to get up early without being able to advance their circadianly controlled sleep-onset)". As a result, "in late chronotypes, the constraints of early work schedules lead to an increasing sleep debt over the week that is compensated for on weekends" (Wittmann et al. 2006).

However, the weekend time in bed does not differ much from the maximal sleep capacity (Klerman and Dijk 2008). What people think is their weekend extra sleep would be exactly what is expected to be just a normal unrestricted sleep. Therefore, it is necessary to prove that, if sleep has been lost due to early weekday wakeups, it might be caught up on weekends.

It has to be also noted that, in the field of human sleep and circadian biology, two rather different ways of distinguishing between "owls" and "larks" were proposed. The traditional approach relies on the self-assessments with a morningness-eveningness (morning-evening preference) scale (e.g. Horne and Östberg 1976) allowing discrimination between "diurnal types" or "chronotypes". A more recently suggested approach differentiates chronotypes into early and late types by using self-reports on current sleep timing on free days (Roenneberg et al. 2003). Since sleep timing is gradually delaying across adolescence until reaching the peak of lateness at age 18–20 years (Roenneberg et al. 2004; Fischer et al. 2017), a dramatic weekday sleep loss occurs due to confrontation between early school times and biological tendency of late adolescents to delay weekend sleep timing (Crowley et al. 2014). However, they lose a large amount of sleep because their organisms already passed through a maturational change in homeostatic sleep regulation, irrespective of their self-assessments on morningness-eveningness scales. One can expect that those who were classified as "larks" with a morningness-eveningness scale might much easier than "owls" shift their weekday morning wakeups on an earlier hour. By contrast, "owls" might manage to sleep more than "larks" on weekdays because they succeed in the attempts to minimize this hardly tolerated shift by all means. Therefore, it is necessary to proof that, irrespective of age, weekday sleep reduction due to early wakeups is profoundly larger in "owls" than "larks".

Consequently, the major aim of this report was to determine whether such proofs might be yielded by applying a quantitative model of sleep-wake regulation for prediction of timing and duration of weekday and weekend sleep. Previously (Putilov and Verevkin 2018) we proposed a methodological framework for simulation of the sequences of weekday and weekend sleep-wake cycles and comparison of discrepancy between simulated and empirically obtained amounts of sleep lost on weekdays due to early risetimes. It was applied for tracing the ontogeny of sleep times on weekdays and weekends (Putilov and Verevkin 2018). Here, we applied the same approach for testing the hypotheses of 1) weekend extra sleep and 2) inequality of "owls" and "larks" on amount of weekday sleep loss.

Methods

Collection of samples with reported sleep times

Sleep times for 20 samples of study participants classified as M- and E-types from 19 previously published reports are listed in Table 1. Mean age of study participants included in these 20 samples varied between 4 and 58 years. The associations between these 20 mean ages and time in bed on weekends are illustrated in Figure 1 separately

Table 1. Rise- and bedtimes reported in 19 studies.

19 reported studies				Weekdays				Weekends			
Reference		Country or (State)	Mean age, years	Bedtime		Risetime		Bedtime		Risetime	
Author(s)	Year			M-	E-	M-	E-	M-	E-	M-	E-
Doi et al.	2016	Japan	4.0	20.65	21.67	6.62	7.28	20.88	22.03	6.87	8.18
Arora & Taheri	2015	UK	12.0	21.23	21.48	6.73	6.88	21.98	23.80	8.58	9.62
Russo et al.	2007	Italy	13.8	22.20	23.35	6.83	7.18	23.68	25.23	8.67	11.37
Mateo et al.	2012	Spain	14.1	22.73	23.52	7.25	7.43	24.08	25.23	9.93	11.33
Arrona-Palacios et al.	2015	Mexico	14.1	22.53	24.37	7.28	8.32	23.02	25.82	9.15	11.50
Diaz-Morales et al.	2007	Spain	14.3	22.83	23.63	7.20	7.40	24.35	25.77	10.00	11.41
Li et al.	2018	Hong Kong	14.5	22.68	23.95	6.65	6.80	23.40	25.13	9.10	11.30
Giannotti et al.	2002	Italy	15.0	22.50	23.08	6.67	7.17	23.67	25.25	8.92	10.92
-,-			17.3	22.50	23.50	6.42	7.17	24.42	26.42	9.17	11.42
Lehto et al.	2016	Finland	17.5	23.38	23.80	6.63	7.42	24.17	25.50	9.68	11.32
Korczak et al.	2008	Brazil	19.6	23.00	24.45	6.67	7.55	23.55	27.05	7.85	11.33
Kabrita et al.	2014	Lebanon	19.9	23.20	24.78	7.07	8.55	24.37	26.62	8.27	11.63
Vitale et al.	2015	Italy	21.3	23.63	24.05	7.17	7.98	25.25	26.22	8.97	10.28
Rosenthal et al.	2001	(MI)	26.0	22.10	25.10	6.15	9.70	22.70	25.72	7.18	10.17
Roepke & Duffy	2010	(MA)	36.0	22.55	25.08	6.28	8.67	23.15	25.53	7.30	10.52
Taillard et al.	1999	France	36.1	22.70	25.08	6.55	7.50	23.40	24.67	8.10	9.88
Paine & Gander	2016	New Zealand	41.1	22.62	23.78	5.93	7.23	23.12	24.23	7.07	8.93
Chan et al.	2014	Hong Kong	50.8	23.07	25.80	5.33	8.40	23.20	25.80	6.93	10.25
Taillard et al.	2004	France	51.3	22.85	23.43	6.20	6.78	23.20	23.90	7.38	8.52
Reutrakul et al.	2013	(IL)	58.4	21.37	24.03	5.22	8.77	21.30	25.22	5.58	9.88

Samples are ordered in accord with reported mean age of study participants; -,-: Giannotti et al. (2002) reported times for two samples of different mean age. Bedtime and Risetime: Times to go to bed and to wake up, respectively, clock hours (decimals). M- and E-: M- and E-types.

for M- and E-types (Figure 1(a,b), respectively). Additional 170 samples were collected from more than 70 published reports to provide comparison of just 20 samples of M- and E-types with the whole set of 190 samples on the pattern of relationships between age and weekend sleep times (Figure 2). Sleep times for most of these samples are listed in Supplementary table to Putilov and Verevkin (2018).

A sample reported by Wolfson et al. (2003) was of special interest for the present simulations because sleep times of each of 302 study participants of their study were determined by three different methods, survey, diary, and actigraphy. Since sleep times for the vast majority of analyzed samples were obtained in the survey, data of Wolfson et al. (2003) provided possibility to compare the differences between subjective (survey) and objective (actigraphy) estimates with discrepancies between simulations and averaged empirical estimates (Figures 3 and 4).

All simulated datasets were collected in accordance with the ethical standards laid down in the Declaration of Helsinki, and their protocols were approved by the ethics committees of the research institutes and universities.

Statistical analysis of reported sleep times

The SPSS statistical software package (IBM, Armonk, NY, USA, version 22.0) was used for calculation of Spearman rank order coefficient of correlation (ρ) to determine which of associations between sleep times and mean age of study participants were significant (Figure 1). Moreover, paired t-test was applied to examine significance of differences

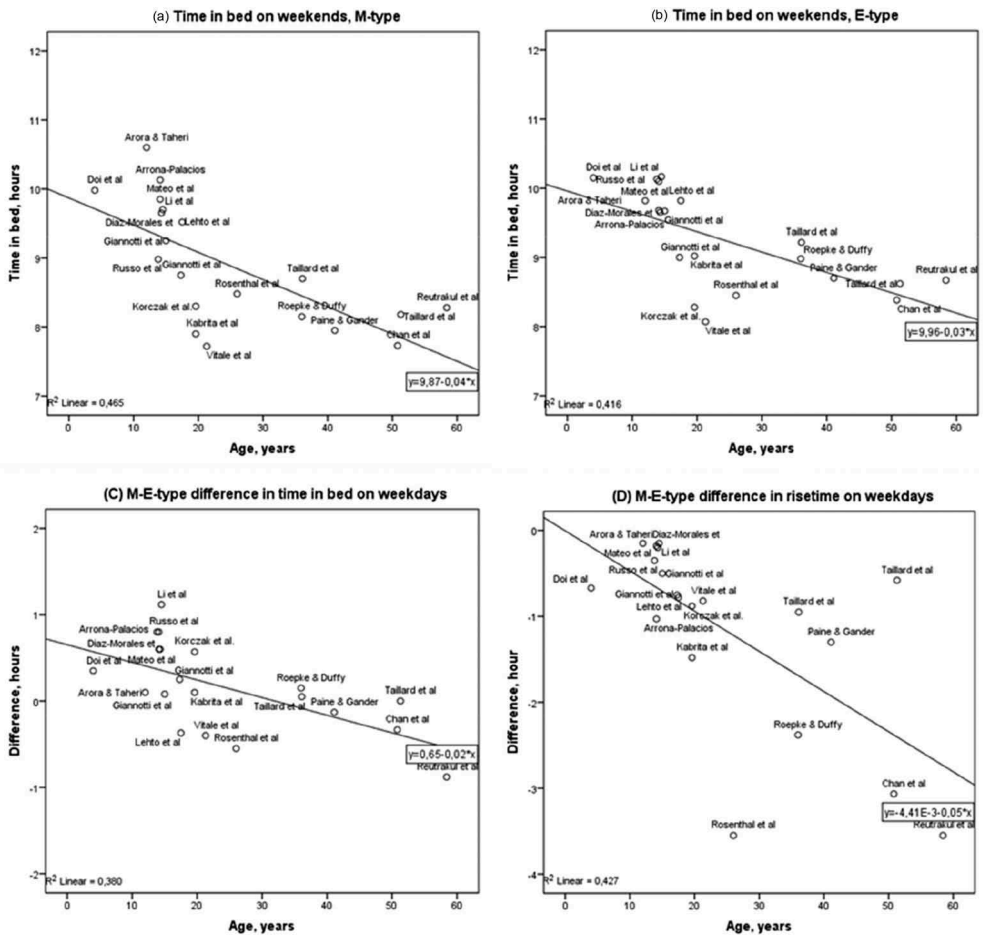


Figure 1. Age by sleep times and by difference between chronotypes in sleep times. Each line illustrates a linear relationship of Age with Time in bed on weekends (a) and (b) and with M-E-type difference in time in bed (c) and risetime on weekdays (d).

between M- and E-types in sleep times. Standard deviations (SD) for mean estimates of sleep times obtained by averaging over samples are illustrated Figures 2–4.

Model

To simulate sleep times, we implemented our version of the two-process model of sleep-wake regulation (Putilov 1995). The model and the way of derivation of its initial parameters (shown in Table 1, left column) are explained in more detail in Putilov (1995, 2014)). It was named “rhythmostat” (Putilov 1995) because it includes a circadian term reflecting the modulating influence of the circadian pacemaker on the parameters of classical homeostatic process (“somnostat” in Daan et al. 1984).

If t_1 and t_2 are the initial times for the buildup and decay phases (rise- and bedtime, respectively), this sleep-wake regulating process can be simulated using the following equations:

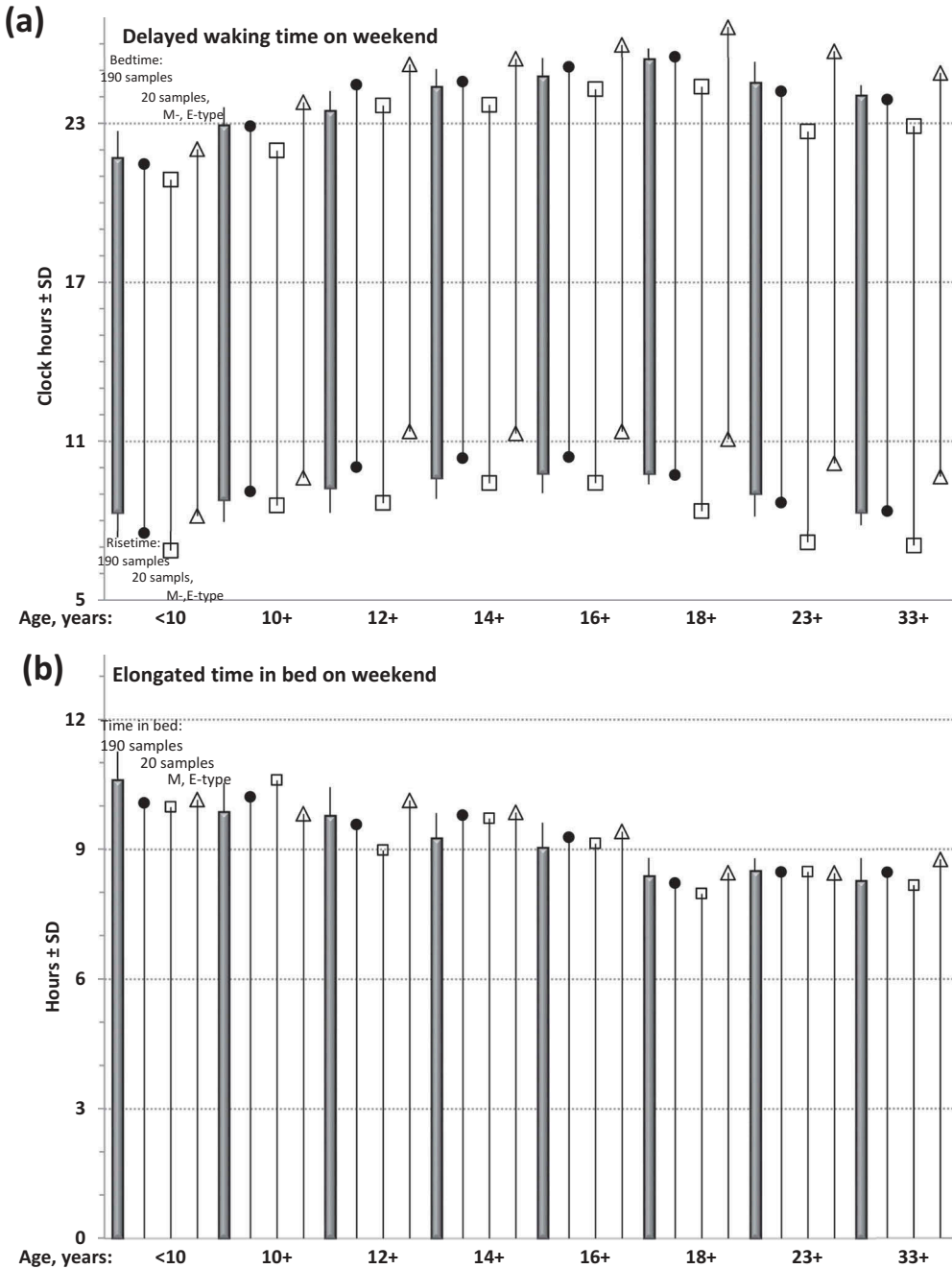


Figure 2. Sleep times for 8 age categories.

The samples included in the whole set ($n = 190$) were grouped into eight age categories (younger than 10, 10+, 12+, 14+, 16+, 18+, 23+, and 33+ with $n = 37, 24, 25, 35, 21, 17, 13,$ and 18, respectively) to compare with the subset of sleep times reported for M- and E-types in 19 studies ($n = 20$; see Table 1). Each age group is represented by one column and three lines. Data on 190 samples are represented by averaged values (column) with + Standard Deviation (+ SD) for bedtime and - SD for risetime (a) or by averaged values (column) with \pm SD (b). Mean values for 20 samples were obtained by averaging over samples of similar mean ages after averaging over M- and E-types and within M- and E- types (closed circles, open squares, and open triangles, respectively).

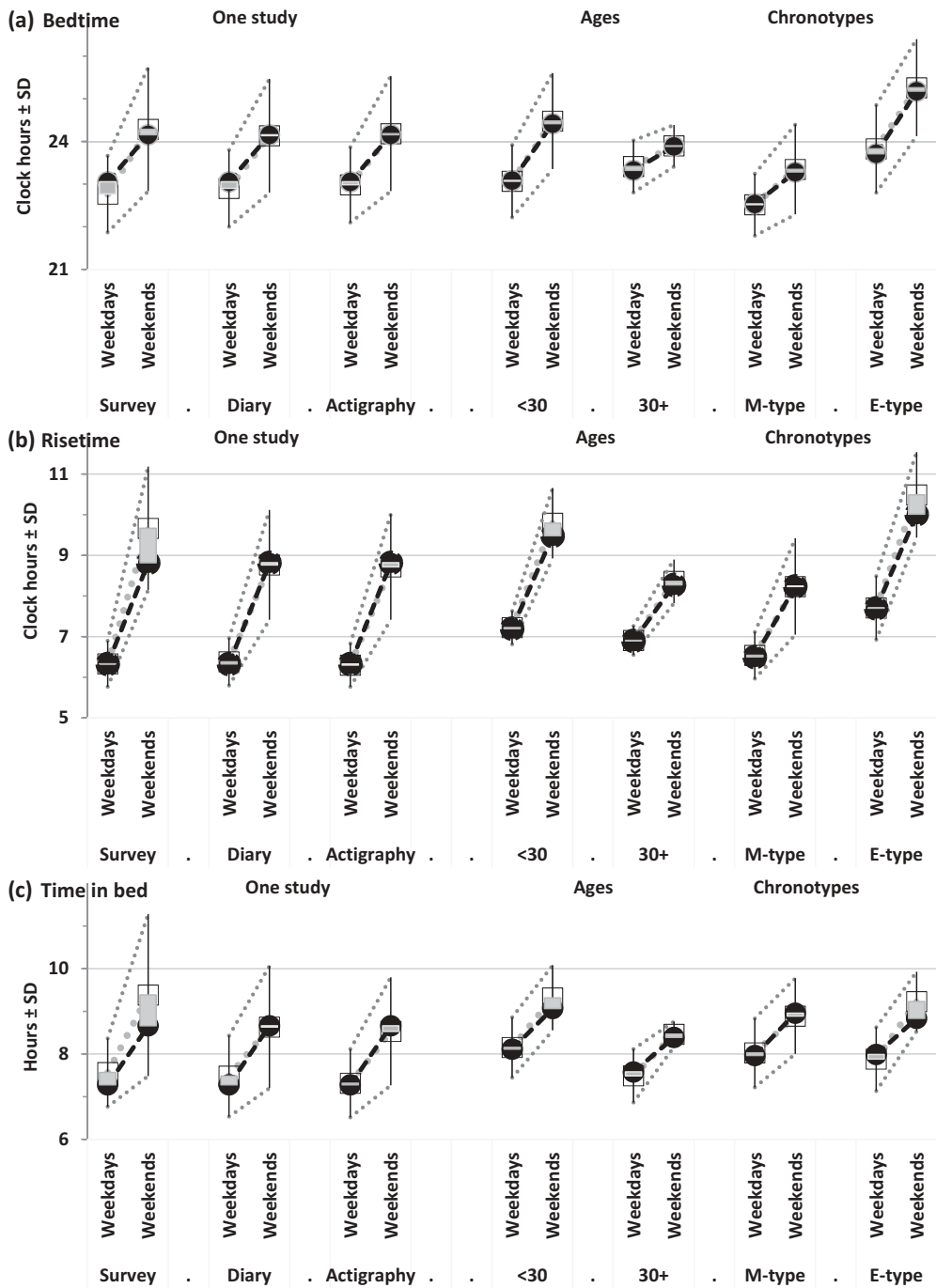
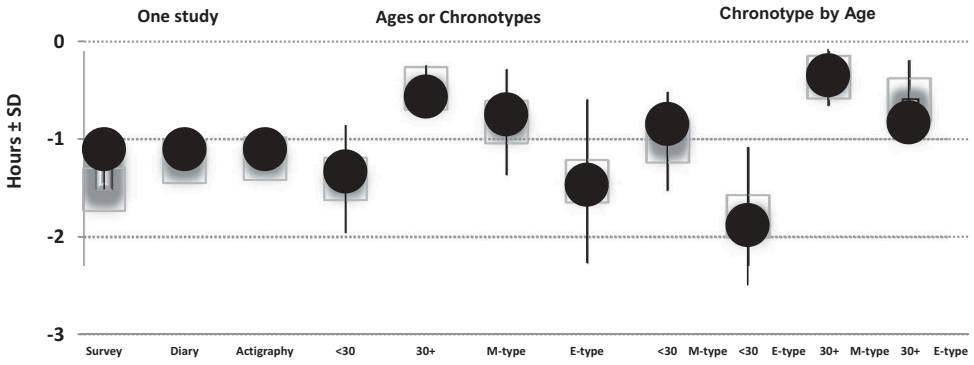


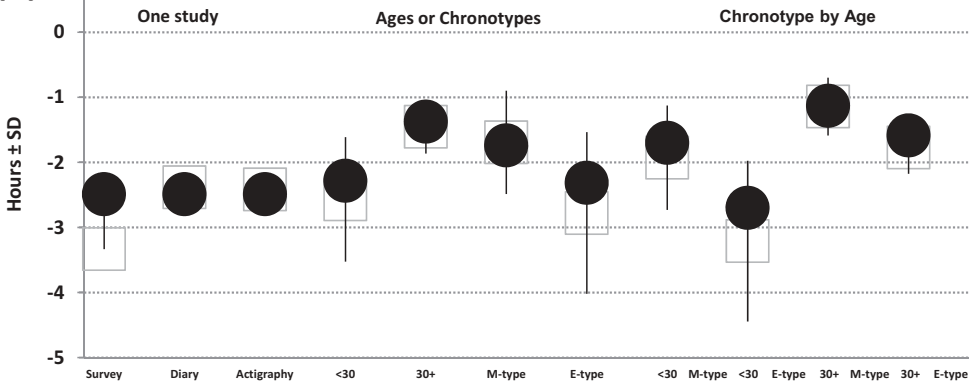
Figure 3. Comparison of simulated sleep times with the range of their empirical variation.

Empirical data are represented by averaged values (open squares) with \pm Standard Deviation (\pm SD). Mean values and SD were obtained by averaging over individuals (Survey, Diary, and Actigraphy) or samples ($n = 14$ and 6 for ages, and $n = 20$ for any of chronotypes). Shaded areas denote deviations of these mean values from simulated values (closed circles) reported in Table 3.

(a) Shift in bedtime



(b) Shift in risetime



(c) Shift in time in bed

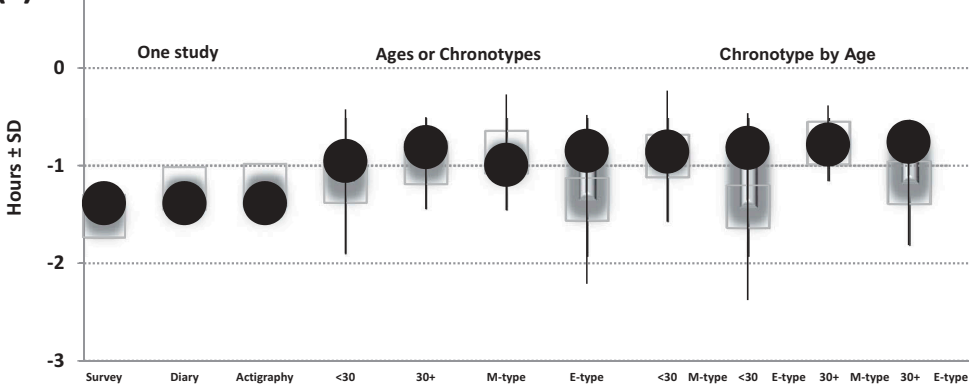


Figure 4. Comparison of simulated shifts in sleep times with their range of empirical variation. Empirical data are represented by averaged values (open squares) with \pm Standard Deviation (\pm SD). Shadowed areas denote deviations of these mean values from simulated values (closed circles; see also Table 3). Data on the right side illustrate the results for sleep times obtained by further subdivision of 20 samples into younger and older M- and E-types (<30 and >30, $n = 14$ and 6 , respectively).

$$X(t) = [X_u + C(t)] - \{[X_u + C(t)] - X_b\} * e^{-(t-t1)/[Tb-k*C(t)]} \quad (1a)$$

$$X(t) = [X_l + C(t)] - \{X_d - [X_l + C(t)]\} * e^{-(t-t2)/[Td-k*C(t)]} \quad (1b)$$

where

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

is a periodic function with a period τ assigned to 24 hours (Putilov 1995).

Initial parameters of the model

The parameters of this model (Table 2, left column) were initially derived from the experimentally obtained durations of recovery sleep after six gradually increasing intervals of extended wakefulness (Åkerstedt and Gillberg 1981) and the levels of Slow-Wave Activity (SWA) obtained for 10 naps (Dijk et al. 1987) and two recovery sleep episodes (Dijk et al. 1990, 1991; see Putilov 1995, for more details). X was expressed in relative SWA units (Putilov 1995, 2014). The present simulations were performed by utilizing slightly modified initial parameters of this sleep-wake regulating process (Putilov 1995).

Table 2. Parameters of the model utilized for simulating sleep times.

Simulated data Parameters			Averaged		M-type	E-type
	Initial	One study	14 < 30	6 30+	20	20
Times for buildup and decay phases:						
$t2-t1$ (wake duration), hours	16.00	14.95	14.70	15.50	14.90	14.90
$t2$ (bedtime), clock hours	23.00	24.20	24.50	23.90	23.30	25.30
$t1$ (risetime), clock hours	7.00	8.85	9.80	8.40	8.40*	10.40*
Risetime on weekdays, clock hours		6.33	7.20	6.90	6.50	7.70
Exponential buildup and decay phases:						
T_b (buildup phase constant), hours	27.04	25.22	22.62	24.55	26.63	22.52
T_d (decay phase constant), hours	1.95	2.29	2.56	1.98	2.75	2.08
SWA _l (lower asymptote), relative SWA	0.70	0.70	0.70	0.70	0.70	0.70
SWA _b (lowest decay), relative SWA	0.75	0.75	0.765	0.75	0.76	0.76
SWA _d (highest buildup), relative SWA	2.50	2.50	3.25	2.50	3.00	3.00
SWA _u (upper asymptote), relative SWA	4.50	4.50	5.75	4.50	5.50	5.50
Sine wave-form circadian modulation:						
A (circadian amplitude), relative SWA	0.50	0.50	0.50	0.50	0.50	0.50
φ_0 (initial circadian phase), radians	4.13	3.66	3.66	3.66	4.19	3.14
φ_{max} (circadian peak), clock hours	15.00	16.00	16.00	16.00	14.00	18.00
Phase angle between $t2$ and φ_{max} , hours	-8.00	-8.00	-8.00	-8.00	-9.00	-7.00
τ (entrained circadian period), hours	24.00	24.00	24.00	24.00	24.00	24.00
k (2-fold increase of the circadian term)	2.00	2.00	2.00	2.00	2.00	2.00

Parameters of the model (1) used to simulate sleep times illustrated in Figures 2–5. Initial: Initial parameters were derived in Putilov (1995) by using data on sleep duration after extended wakefulness and on SWA in naps and extended sleep episodes (mean SWA = 1 in baseline night episode). One study: Slight modification of these parameters (1-h shift of the circadian phase) was necessary to account for sleep times reported in the study of Wolfson et al. (2003). Averaged: Simulation of sleep times obtained by averaging over M- and E-types for the subsamples of younger and older ages (<30 and 30+, $n = 14$ and 6 , respectively). Further slight modification of these parameters (increase of SWA levels) was necessary to account for difference between ages (Table 1). To account for the differences between M- and E-types, earlier and later sleep times and circadian phase ((2- and 4-h difference, respectively) were proposed; *: Averaged risetimes for M- and E-types reported for 20 samples were slightly different (8.2 and 10.5, respectively) from those used for this simulation for proposing identical time in bed on weekend to chontypes. In all other simulations, the reported bed- and risetimes were rounded off and utilized as initial times.

Modification of parameters of the model: initial times

Because times in bed on weekends in the analyzed samples (8.89 h and 9.23 h in M- and E-types, respectively) were similar to the experimentally determined maximal sleep capacity (8.9 ± 0.4 h) in participants of similar ages in Klerman and Dijk (2008) study, we utilized data on weekend bed- and risetimes (t_1 and t_2) and on weekday risetime (t_2 from Monday to Friday) as an input to the model. For the sake of simplicity and clarity, we rounded off all sleep times and most of other model's parameters (Table 2). Thus, the initial values (t_1 and t_2) for the vast majority of simulations were those reported for the whole set of 20 samples, for the subsets of younger and older ages (< 30 and > 30 years, $n = 14$ and 6, respectively), and for the sample of Wolfson et al. (2003).

Modification of parameters of the model: SWA levels

It is well-known that the amount of SWA dramatically reduces from childhood to old adulthood (Gradisar et al. 2011; Campbell et al. 2012), that duration of sleep is also reduces in the same direction (Ohayon et al. 2004; Moraes et al. 2014), and that sleep timing is reaching its maximal delay at age 18–20 years (Roenneberg et al. 2004; Fischer et al. 2017). Given that the initial parameters of the rhythmostat have been derived using data on duration of sleep following extension of wakefulness in six subjects aged between 29 and 45 years (Åkerstedt and Gillberg 1981), we additionally changed some of other model's parameters, namely, SWA levels, to account for age difference between these subjects and samples analyzed here (Table 2, central columns). Although we allowed age-associated variation in the parameters of the homeostatic buildup and decay of SWA (1), we did not propose such an age-associated variation in the circadian term (2) because this would contradict to the majority of reports indicating the absence of any age-associated difference in free-running circadian period (e.g. Czeisler et al. 1999; Kendall et al. 2001; Crowley and Eastman 2018).

Modification of parameters of the model: circadian phase

To account for the delay of sleep times in E-types relative to those of M-types we suggested 2-h difference between chronotypes in sleep timing (Table 2) but allowed the identical time in bed. Since it was shown that phase angle between sleep and circadian phase is wider in M- than E-types (Baehr et al. 2000; Duffy et al. 2001; Mongrain et al. 2004; Emens et al. 2009), we assigned 4-hour difference between chronotypes in entrained circadian phase. This gave, respectively, 9- and 7-hour advance (phase angle) of the peak of the circadian modulation relative to the bedtime (Table 2, right columns). We also performed separate simulations for younger and older M- and E-types (< 30 and > 30 years) utilizing their reported weekend sleep times (Figure 4, right). For any simulation, weekday risetime was taken by rounding off the empirical weekday risetime.

Table 3. Discrepancies between empirical and simulated sleep times.

Simulated data		One study				Averaged		M-type	E-type
		Survey	Diary	Actigraphy	Difference	14 < 30	6 30+	20	20
Bedtime	Weekdays	-0.29	-0.15	-0.07	-0.22	-0.02	-0.01	-0.02	0.12
	Weekends	0.13	-0.02	0.03	0.10	0.06	0.05	0.06	0.08
Risetime	Weekdays	0.00	0.05	-0.03	0.03	0.02	0.03	0.04	0.01
	Weekends	0.85	-0.05	-0.10	0.95	0.31	0.21	0.00	0.47
Time in bed	Weekdays	0.29	0.21	0.04	0.25	0.04	0.03	0.06	-0.11
	Weekends	0.72	-0.03	-0.13	0.85	0.25	0.15	-0.07	0.39
Bedtime	Shift	-0.41	-0.13	-0.10	-0.32	-0.08	-0.06	-0.08	0.03
Risetime	Shift	-0.84	0.11	0.07	-0.92	-0.29	-0.18	0.05	-0.46
Time in bed	Shift	-0.43	0.23	0.17	-0.60	-0.21	-0.12	0.13	-0.50

Discrepancies were calculated by subtracting simulated sleep times from empirically obtained sleep times. One study: Sleep times reported by Wolfson et al. (2003) for three methods of data collection (Survey, Diary, and Actigraphy); Averaged: Simulation of sleep times calculated by averaging over M- and E-types; 14 < 30 and 6 30+: The subsamples with ages younger and older than 30 ($n = 14$ and 6 , respectively); Difference: Objective sleep times (Actigraphy) were subtracted from subjective sleep times (Survey); Time in bed: Difference between rise- and bedtimes. Shift: Weekday-Weekend difference in sleep times. See also Figures 3 and 4 allowing the comparison of these discrepancies with variation in empirical estimates.

Results

Chronotype- and age-associated differences in reported sleep times

The only non-significant difference between M- and E-types on sleep times averaged over 20 samples (Table 1) was found for the time in bed on weekdays (paired t-test: $t_{19} = 1.29$, $p = 0.212$). Despite this, the time in bed on weekends was significantly longer in E-types ($t_{19} = -3.24$, $p = 0.004$), and, consequently, the weekday-weekend shift in time in bed was larger in these types ($t_{19} = 3.24$, $p = 0.004$). However, this difference between the two chronotypes (-0.48 h), was smaller than the same directional difference obtained in Wolfson et al. (2003) study by the methods of survey and actigraphy (-0.60 h; see Table 3).

Averaged over 20 samples mean age (Table 1) was 24.8 years ($SD = 15.3$ years). The time in bed on weekends was closely associated with age in both M- and E-types ($\rho_{18} = -0.821$ and -0.781 , respectively, $p < 0.001$ for both; see also Figure 1(a,b)). For weekdays the association was found to be significant only for M-types ($\rho_{18} = -0.830$, $p < 0.001$, and -0.414 , $p = 0.069$, respectively). The association was not significant in E-types due to age-associated change in difference between chronotypes in time in bed on weekdays ($\rho_{18} = -0.717$, $p < 0.001$; see Figure 1(c)). Due to similar weekday risetimes determined by early school times ($\rho_{18} = -0.699$, $p = 0.001$; see Figure 1(d)), younger E-types spent less time in bed than M-types, but, since the difference between chronotypes in weekday risetimes increased with age (Figure 1(d)), older E-types spent more time in bed than M-types (Figure 1(c)). Such relationships resulted in mentioned about similarity of chronotypes on the weekday time in bed obtained by averaging over 20 samples.

Figure 2 illustrates that weekend sleep timing would not be of much help for distinguishing between M- and E-types in 20 analyzed samples. E-types from middle-age adults (33+ years) went to bed approximately at the same clock hour as M-types from young adults (18+ years), whereas M-types from the same middle-age adults (33+ years) went to bed approximately at the same clock hour as E-types among study participants of early school age (<10 years). Similarly, E-types from middle-age adults (33

+ years) or from early adolescents (10+ years) had weekend wakeups at the same clock time as had M-types from late adolescents (16+ years).

In contrast, participants of M- and E-types (Figure 2) remained stable across ages in terms of the difference in weekend sleep timing between these types (on average, the differences in bed- and risetimes were -1.92 h and -2.25 h, respectively).

Simulations of sequences of weekday and weekend sleep-wake cycles

Using three sleep times (weekend bed- and risetimes and weekday risetime) as an input to our model of sleep-wake regulatory process (1) we simulated the sequences of weekday and weekend sleep-wake cycles (Figure 5). The simulations predicted weekday bedtime and time in bed (Figures 3 and 4) and these predictions were found to be similar to the empirically obtained estimates (Table 3).

Discrepancies between simulated and empirically obtained sleep times

In the study of Wolfson et al. (2003), rather similar estimates were obtained for weekend bedtime by applying different methods of sleep time estimation (Figure 2(a)), whereas the difference between survey and actigraphy was found to be the largest for weekend risetime (Figure 2(b)) that seemed to be significantly overestimated in the survey ($p < 0.001$). Consequently, time in bed on weekends (Figure 2(c)) was significantly longer ($p < 0.001$) in the survey (Wolfson et al. 2003). Simulation of averaged over three methods sleep times provided much larger discrepancies between simulated and empirical sleep times for survey data as compared to actigraphic data (Figures 3 and 4, left). The discrepancies for any other simulation were smaller than the differences between sleep times obtained by the methods of survey and actigraphy (Table 3). Moreover, these discrepancies and these differences were, as a rule, the same directional (Table 3 and Figures 3 and 4).

Simulated weekday-weekend shifts in sleep times

The simulations predicted that there was no extra buildup of the levels of SWA during weekday wakefulness, and, on weekends, there was no possibility to sleep the extra time simply due to the absence of this extra buildup of the levels of SWA (Figure 5). The sleep-wake regulatory mechanism prevented such an extra buildup of SWA by sending study participants to sleep at the appropriate clock time after achieving a normal final daily level of SWA (Figure 5(a,b)). Due to the advanced risetime on weekdays, this appropriate bedtime was somewhat earlier than the weekend bedtime. Therefore, the following sleep on the Friday–Saturday night became longer (Figure 5(b)).

Notably, the model predicts that, due to the circadian influence, people cannot sleep longer after delay of bedtime beyond the limits determined by the sleep-wake regulating mechanism. If sleep is initiated later in the evening, sleep is terminated later in the morning, but the morning delay is somewhat shorter than the evening delay, and, hence, sleep duration is shorter (Figure 5(b,c)).

Moreover, it has to be noted that modeling results question the definition of social jetlag as the weekday-weekend shift of the sleep-wake cycle relative to the circadian

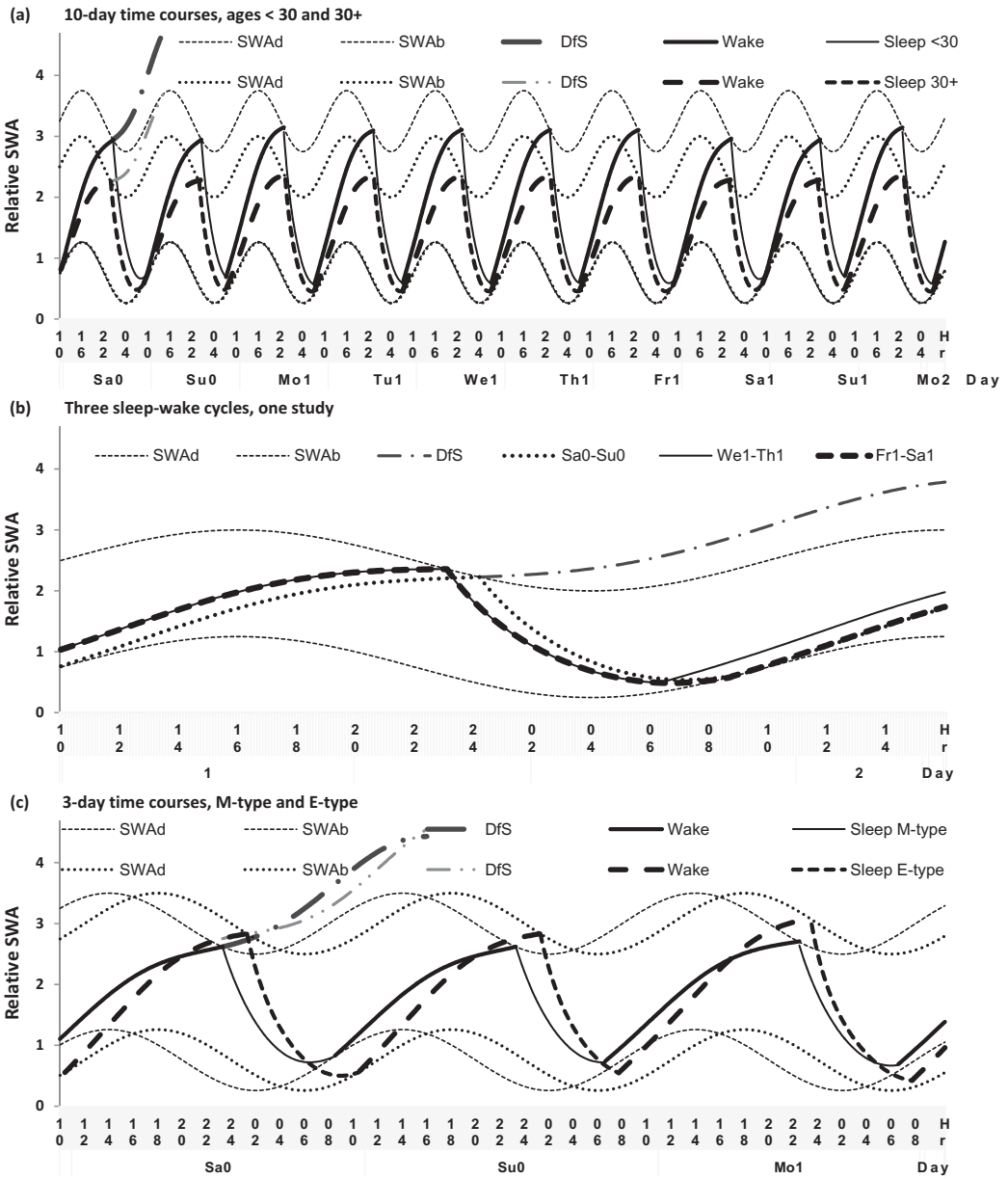


Figure 5. Simulation of the sleep-wake cycles.

(a) Ten consecutive sleep-wake cycles including two last free (e.g. vacation) days and the following workdays and weekends. The example of sleep cycles simulated for two ages, <30 and 30+ years. (b) The sleep-wake cycles for free (e.g. vacation) days (Sa0-Su0), weekday (We1-Th1) and weekend nights (Fr1-Sa1). The example of sleep times reported by Wolfson et al. (2003). (c) Three consecutive sleep-wake cycles represent two last free (e.g. vacation) days and the following workday (Monday). The example of sleep cycles of M- and E-types. SWAd and SWAb: Highest buildup and lowest decay of relative SWA, respectively; DfS: Further buildup of SWA expected due to Deprivation from Sleep; Wake and Sleep: Phases of the sleep-wake regulating process simulated as alternations between exponential buildups and decays of SWA with the parameters of exponential functions modulated by sine-form function with 24 h period (circadian term). The parameters of the model (1) for each simulation are listed in Table 2.

pacemaker entrained by the external light-dark cycle during the week. As can be seen in [Figure 5\(b\)](#), there is, at least, one time point during the 24-h period when a phase of the sleep-wake cycle is predicted to remain identical for any day of the week. Namely, right before the time of socially imposed early morning awakening on weekdays SWA was found to reach similar levels on nights from one weekday to another weekday, from Friday to Saturday, and from Saturday to Sunday ([Figure 5\(b\)](#)).

Sleep times simulated for younger and older ages

As we expected, any change in the levels of SWA was not required for simulating data of older ages (> 30) due to similarity of these ages to the ages of the participants of the experimental studies which data were utilized for derivation of the initial parameters of our model ([Table 2](#)). Again, in accord with our expectations, levels of SWA were found to be higher in simulations of sleep times of samples with study participants of younger ages ([Table 2](#) and [Figure 1\(a\)](#)). Although the weekday-weekend shift of sleep timing was larger in younger ages than in older ages, the shifts of their time in bed were roughly similar ([Figure 3](#)). The discrepancies between empirical and simulated times were larger for younger ages and they were the same directional with the differences between sleep times obtained with survey and actigraphy ([Table 2](#) and [Figures 3](#) and [4](#)).

Simulated sleep times for M- and E-types

Simulated sleep-wake cycles for averaged over 20 samples M- and E-types are illustrated in [Figure 5\(c\)](#). The discrepancies between simulated and empirical sleep times were the largest for E-types and they were the same directional with the differences between sleep times obtained by the methods of survey and actigraphy ([Table 3](#) and [Figures 3](#) and [4](#)). Survey data and averaged empirical data (20 samples) gave later than predicted weekend risetime and longer time in bed ([Figures 3](#) and [4](#)). The empirical weekend time in bed was found to be longer than predicted in E-types, and it was closed to the predicted time in M-types (see above). In contrast, practically identical values were predicted for these chronotypes in the simulations postulating the exact 2-h difference in sleep phase and fully identical time in bed for M- and E-types ([Table 2](#) and [Figures 3\(c\)](#) and [4\(c\)](#)). Utilizing the actually reported weekend sleep times in separate simulations of younger and older M- and E-types provided a very similar result ([Figure 4\(c\)](#), right). Again, the prediction was that the weekend time in bed must be identical, but empirically obtained values were longer in E-types irrespective of age ([Figure 4\(c\)](#), right).

Discussion

Most people believe that there exists a real way of overcoming the consequences of sleep restriction during five work/schooldays. Namely, they might, at least partly, recoup sleep lost due to the scheduled early wakeups by getting extra sleep on two weekend days. Another common belief is that there exists a remarkable difference between “owls” and “larks” in the amount of sleep lost on weekdays that is manifested in a longer catch-up sleep and a later risetime on weekends in “owls”. The results of our simulations questioned both believes by showing that 1) sleep might not be caught up on

weekends and 2) “owls” and “larks” might not be profoundly dissimilar on weekday sleep loss. In other words, the results indicated that tacking on an extra hour or two of sleep a night on weekends is nothing but receiving a normal dose of sleep and, in general, two distinct chronotypes appear to be identical on the amount of weekday sleep loss. Possibly, they also identical on the duration of undisturbed weekend sleep. Additionally, there is also a similarity between people younger and older than 30 years on the amount of weekday sleep loss that contrasts with the dramatic difference between them in the duration of undisturbed weekend sleep.

Analysis of sleep times reported for 20 samples indicated that the impression that E-types profoundly differ from M-types on the amount of sleep lost on weekdays might be explained by the age bias toward younger mean age of participants of the vast majority of published studies. E-types in the age of adolescence sleep less than M-types of this age due to the identical school times. However, it seems that people of later ages manage to adjust their weekday risetime to their morning-evening preference. Even more, because M-types are expected to better tolerate than E-types early morning wakeups, they are more vulnerable to the weekday sleep loss. Therefore, if there is a real aversive health effect of losing sleep on weekdays, “owls” might be more than the same age “larks” vulnerable to this effect only when weekday risetime is identical for both chronotypes.

The question arises why then the averaged weekend time in bed was found to be significantly longer in E- than M-types despite similarity of their averaged weekday sleep loss and identity of their simulated times in bed on weekends? The simplest explanation is the overestimation of weekend risetime by those individuals who tend to wake up late, e.g. E-types and late adolescents and young adults. This explanation is supported by results indicating that the weekend risetime was characterized by the largest discrepancies between simulated and empirical sleep times along with the largest and same directional difference between survey and actigraphy data.

Another explanation might be a phase delay of their circadian phase due to exposure to artificial evening light in the beginning of Saturday night. Such an exposure is expected to delay the risetime on Sunday morning (Akacem et al. 2016). The following advance shift of bedtime might happen during the week due to exposure to morning light after several early wakeups. This shift might lead to full or partial compensation of the weekend delay of sleep timing. Surprisingly, we did not find journal publications examining such possibility (a typical rather than “social” jetlag in “owls”). However, such shift was reported in dissertation by Zerbini (2017): the weekend onset of melatonin excretion was found to be delayed both in summer and winter in study participants reported late weekend bedtime, but this onset remained unchanged in participants with early and intermediate weekend bedtimes.

The modern literature on the rhythms-markers of the circadian pacemakers indicates that the circadian phase (Crowley et al. 2014) and period (Crowley and Eastman 2018) did not change across transition from early adolescence to early adulthood and that the circadian period remains unchanged in later ages (Czeisler et al. 1999; Kendall et al. 2001). Our present and previous simulations (Putilov and Verevkin 2018) also suggested that it is not necessary to propose any changes in the position of circadian phase for explaining age-associated delays and advances of sleep times.

Thus, it seems that chronobiological mechanisms underlying “social jetlag” require rethinking because 1) sleep debt cannot be not accumulated due to early morning awakenings on weekdays, 2) sleep lost on weekdays due to scheduled early wakeups cannot be repaid, 3) in general, clock times for weekend sleep cannot be solely used to distinguish between “larks” and “owls”, 4) in general, “social jetlag” cannot be more prominent in “owls” than “larks”, 5) the circadian phase cannot delay in adolescents following the delay of sleep times, 6) and it cannot advance back despite advancing sleep times in middle-aged adults, 7) a sleep phase determined by SWA level in the morning hours can remain rather stable throughout the week, 8) instead, the circadian phase in evening-oriented individuals can shift back-and-forth relative to natural light regimen throughout the week, etc.

The present results might have a practical implication in sleep medicine by providing quantitative predictions for people of different age and chronotype of the amount of sleep needed on weekdays/vacations and lost on weekdays depending upon their risetime of weekdays. Interestingly, the results also point at a possibility to estimate the levels of SWA in these people depending upon amount of weekday-weekend shift in their bedtime (the higher the SWA level, the larger the shift).

To summarize, the studying simple mathematical models of sleep-wake regulatory process allow us to make predictions about amount of sleep lost on weekdays by people of different diurnal types and ages. The model-based simulations of sleep times indicate that sleep debt cannot be accumulated due to early weekday risetimes. Therefore, there is nothing to be repaid, even partly, during the following weekends/vacations. The empirical data and their simulations also provide evidence for general similarity of M- and E-types on the amount of weekday sleep loss and indicate that E-types do not sleep longer than M-types on weekdays. Moreover, they, probably, also need not sleep longer on weekends/vacations, at least, when their circadian phase remains in a stable phase relationship with the 24-h light-dark cycle during the whole week.

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References

- Akacem LD, Wright KP Jr, LeBourgeois MK. 2016. Bedtime and evening light exposure influence circadian timing in preschool-age children: a field study. *Neurobiol Sleep Circadian Rhythms*. 1(2):27–31.
- Åkerstedt T, Gillberg M. 1981. The circadian variation of experimentally displaced sleep. *Sleep*. 4:159–169.
- Arora T, Taheri S. 2015. Associations among late chronotype, body mass index and dietary behaviors in young adolescents. *Int J Obes (Lond)*. 39(1):39–44.
- Arrona-Palacios A, García A, Valdez P. 2015. Sleep-wake habits and circadian preference in Mexican secondary school. *Sleep Med*. 16(10):1259–1264.
- Baehr EK, Revelle W, Eastman CI. 2000. Individual differences in the phase and amplitude of the human circadian temperature rhythm: with an emphasis on morningness-eveningness. *J Sleep Res*. 9:117–127.
- Campbell IG, Grimm KJ, de Bie E, Feinberg I. 2012. Sex, puberty, and the timing of sleep EEG measured adolescent brain maturation. *Proc Natl Acad Sci USA*. 109(15):5740–5743.
- Chan JW, Lam SP, Li SX, Yu MW, Chan NY, Zhang J, Wing YK. 2014. Eveningness and insomnia: independent risk factors of nonremission in major depressive disorder. *Sleep*. 37(5):911–917.
- Collado Mateo MJ, Díaz-Morales JF, Escribano Barreno C, Delgado Prieto P, Randler C. 2012. Morningness-eveningness and sleep habits among adolescents: age and gender differences. *Psicothema*. 24(3):410–415.
- Crowley SJ, Eastman CI. 2018. Free-running circadian period in adolescents and adults. *J Sleep Res*. 27:e12678.
- Crowley SJ, Van Reen E, LeBourgeois MK, Acebo C, Tarokh L, Seifer R, Barker DH, Carskadon MA. 2014. A longitudinal assessment of sleep timing, circadian phase, and phase angle of entrainment across human adolescence. *PLoS One*. 9(11):e112199.
- Czeisler CA, Duffy JF, Shanahan TL, Brown NE, Mitchell JF, Rimmer DW, Ronda JM, Silva EJ, Allan JS, Emens JS, et al. 1999. Stability, precision, and near-24-hour period of the human circadian pacemaker. *Science*. 284:2177–2181.
- Daan S, Beersma DGM, Borbély AA. 1984. Timing of human sleep: recovery process gated by a circadian pacemaker. *Am J Physiol Regulatory Integrative Comp Physiol*. 246:R161–R178.
- Díaz-Morales JF, de León MC, Sorroche MG. 2007. Validity of the morningness-eveningness scale for children among Spanish adolescents. *Chronobiol Int*. 24(3):435–447.
- Dijk D-J, Beersma DGM, Daan S. 1987. EEG power density during nap sleep: reflection of an hourglass measuring the duration of prior wakefulness. *J Biol Rhythms*. 2:207–220.
- Dijk D-J, Brunner DP, Borbély AA. 1990. Time course of EEG power density during long sleep in humans. *Am J Physiol Regulatory Integrative Comp Physiol*. 258:R650–R661.
- Dijk D-J, Brunner DP, Borbély AA. 1991. EEG power density during recovery sleep in the morning. *Electroencephalogr Clin Neurophysiol*. 78:203–214.
- Doi Y, Ishihara K, Uchiyama M. 2016. Epidemiological study on chronotype among preschool children in Japan: Prevalence, sleep-wake patterns, and associated factors. *Chronobiol Int*. 33(10):1340–1350.
- Duffy JF, Rimmer DW, Czeisler CA. 2001. Association of intrinsic circadian period with morningness-eveningness, usual wake time, and circadian phase. *Behav Neurosci*. 115:895–899.
- Emens JS, Yuhas K, Rough J, Kochar N, Peters D, Lewy AJ. 2009. Phase angle of entrainment in morning- and evening-types under naturalistic conditions. *Chronobiol Int*. 26:474–493.
- Fischer D, Lombardi DA, Marucci-Wellman H, Roenneberg T. 2017. Chronotypes in the US – influence of age and sex. *PLoS One*. 12:1–17.

- Giannotti F, Cortesi F, Sebastiani T, Ottaviano S. 2002. Circadian preference, sleep and daytime behaviour in adolescence. *J Sleep Res.* 11(3):191–199.
- Gradisar M, Gardner G, Dohnt H. 2011. Recent worldwide sleep patterns and problems during adolescence: a review and meta-analysis of age, region, and sleep. *Sleep Med.* 12:110–118.
- Horne JA, Östberg O. 1976. A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *Int J Chronobiol.* 4:97–110.
- Kabrita CS, Hajjar-Muça TA, Duffy JF. 2014. Predictors of poor sleep quality among Lebanese university students: association between evening typology, lifestyle behaviors, and sleep habits. *Nat Sci Sleep.* 6:11–18.
- Kendall AR, Lewy AJ, Sacks RL. 2001. Effects of aging on the intrinsic circadian period of totally blind humans. *J Biol Rhythms.* 16:87–95.
- Klerman EB, Dijk D-J. 2008. Age-related reduction in the maximal capacity for sleep—implications for insomnia. *Curr Biol.* 18:1118–1123.
- Korczak AL, Martynhak BJ, Pedrazzoli M, Brito AF, Louzada FM. 2008. Influence of chronotype and social zeitgebers on sleep/wake patterns. *Braz J Med Biol Res.* 41(10):914–919.
- Lehto JE, Aho O, Eklund M, Heinaro M, Kettunen S, Peltomäki A, Ylä-Kotola K, Öst K, Partonen T. 2016. Circadian preferences and sleep in 15- to 20-year old Finnish students. *Sleep Sci.* 9 (2):78–83.
- Li SX, Chan NY, Man Yu MW, Lam SP, Zhang J, Yan Chan JW, Li AM, Wing YK. 2018. Eveningness chronotype, insomnia symptoms, and emotional and behavioural problems in adolescents. *Sleep Med.* 47:93–99.
- Mongrain V, Lavoie S, Selmaoui B, Paquet J, Dumont M. 2004. Phase relationship between sleep–wake cycle and underlying rhythms in morningness–eveningness. *J Biol Rhythms.* 19:248–257.
- Moraes W, Piovezan R, Poyares D, Bittencourt LR, Santos-Silva R, Tufik S. 2014. Effects of aging on sleep structure throughout adulthood: a population-based study. *Sleep Med.* 15(4):401–409.
- Ohayon MM, Carskadon MA, Guilleminault C, Vitiello MV. 2004. Meta-analysis of quantitative sleep parameters from childhood to old age in healthy individuals: developing normative sleep values across the human lifespan. *Sleep.* 27:1255–1273.
- Paine SJ, Gander PH. 2016. Differences in circadian phase and weekday/weekend sleep patterns in a sample of middle-aged morning types and eveningtypes. *Chronobiol Int.* 33(8):1009–1017.
- Putilov AA. 1995. The timing of sleep modelling: circadian modulation of the homeostatic process. *Biol Rhythm Res.* 26:1–19.
- Putilov AA. 2014. Simulation of an ultradian sleep homeostasis through fitting time courses of its EEG indicators obtained during baseline recordings of night sleep. *Biol Rhythm Res.* 45:759–787.
- Putilov AA, Verevkin EG. 2018. Simulation of the ontogeny of social jet lag: a shift in just one of the parameters of a model of sleep–wake regulating process accounts for the delay of sleep phase across adolescence. *Front Physiol.* 9:1529:1–11.
- Reutrakul S, Hood MM, Crowley SJ, Morgan MK, Teodori M, Knutson KL, Van Cauter E. 2013. Chronotype is independently associated with glycemic control in type 2 diabetes. *Diabetes Care.* 36(9):2523–2529.
- Roenneberg T, Kuehnlé T, Pramstaller PP, Ricken J, Havel M, Guth A, Mewes M. 2004. A marker for the end of adolescence. *Curr Biol.* 14:R1038–R1039.
- Roenneberg T, Wirz-Justice A, Mewes M. 2003. Life between clocks: daily temporal patterns of human chronotypes. *J Biol Rhythms.* 18:80–90.
- Roepke SE, Duffy JF. 2010. Differential impact of chronotype on weekday and weekend sleep timing and duration. *Nat Sci Sleep.* 2010(2):213–220.
- Rosenthal L, Day R, Gerhardstein R, Meixner R, Roth T, Guido P, Fortier J. 2001. Sleepiness/alertness among healthy evening and morning type individuals. *Sleep Med.* 2(3):243–248.
- Russo PM, Bruni O, Lucidi F, Ferri R, Violani C. 2007. Sleep habits and circadian preference in Italian children and adolescents. *J Sleep Res.* 16:163–169.
- Taillard J, Philip P, Bioulac B. 1999. Morningness/eveningness and the need for sleep. *J Sleep Res.* 8 (4):291–295.

- Taillard J, Philip P, Chastang JF, Bioulac B. 2004. Validation of Horne and Ostberg morningness-eveningness questionnaire in a middle-aged population of French workers. *J Biol Rhythms*. 19(1):76–86.
- Vitale JA, Roveda E, Montaruli A, Galasso L, Weydahl A, Caumo A, Carandente F. 2015. Chronotype influences activity circadian rhythm and sleep: differences in sleep quality between weekdays and weekend. *Chronobiol Int*. 32(3):405–415.
- Wittmann M, Dinich J, Merrow M, Roenneberg T. 2006. Social jetlag: misalignment of biological and social time. *Chronobiol Int*. 23:497–509.
- Wolfson AR, Carskadon MA, Acebo C, Seifer R, Fallone G, Lubyak SE, Martin JL. 2003. Evidence for the validity of a sleep habits survey for adolescents. *Sleep*. 26(2):213–216.
- Zerbini G. 2017. Conflicted clocks: social jetlag, entrainment and the role of chronotype: from physiology to academic performance; from students to working adults. Groningen: University of Groningen. (Dissertation chapter 8. Melatonin expression: winter and summer, week in and week out. G.Zerbini, T.Roenneberg, and M. Merrow).