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Comparison of sleep timing of people with different chronotypes affected by modern lifestyle

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Circadian rhythm is an endogenous rhythmic behavior of organisms which can be entrained by daily light–dark cycles. The timing of human sleep-cycle is regulated by endogenous circadian rhythm and homeostatic processes. Light exposure affects both sleep timing and circadian rhythm. Now humans can extend lighting time by turning on artificial lights and wake up time is usually triggered by alarm clocks to meet social schedules. This modern lifestyle is believed to be related with a temporal mismatch between sleep and circadian rhythmicity (social jet-lag) and insufficient sleep, which lead to ill mental and physical health outcomes. At present, the impacts of self-selection of light exposure and social constrains on sleep timing is far from clear. According to preferred sleep-wake schedule, there are three different chronotypes. In this paper, we apply a mathematical model to get a quantitative comparison of sleep timing of people with different chronotypes with the effects of modern light consumption and social constrains. The results show that the prolonged day light and evening light exposure both delay preferred sleep timing with the sleep duration almost unchanged. People of evening-type or with longer intrinsic periods are most expected to be vulnerable to evening light. Increasing light exposure can offset the effect of evening light to some extent, but it is most difficult for evening-type people. Social constrains cause the largest social jet-lag in people of evening-type, which increases with evening light intensity or intrinsic periods. Morning-type people's sleep symptoms worsens, while that of evening-type people improves with age. This study provides a theoretical reference for preventing and treating sleep disorder and social jet-lag for individuals with different chronotypes.

Keywords: chronotype, self-selected light, sleep, social constraint

PACS: 87.18.Yt, 87.85.Tu, 87.18.Vf **DOI:** 10.1088/1674-1056/acbf1f

1. Introduction

Circadian clocks are the fundamental processes of most organisms to adapt to daily environmental variations. In mammals, the circadian clocks are controlled by a central circadian pacemaker located in the suprachiasmatic nuclei (SCN).[1] Circadian clocks are intrinsic self-sustained oscillators with a period of approximately 24 hours (h), which can be entrained to 24 h by external cues such as daily light–dark cycle.[2] The circadian system ensures normal physiological and behavioral activities of organisms including the timing of sleep and wake.[3]

In order to get entrainment, the circadian oscillator needs to adjust its phase with the light–dark cycle. According to the time when the light is added, it can either accelerate or delay the circadian phase.[4] Generally, the duration of light stimulation, the strength of light and the intrinsic period of the circadian oscillator all affect the efficacy of a light stimulus.[5] Experimental research has shown that light in evening affects sleeping time and circadian rhythm.[6]

The timing of the human sleep-cycle is regulated by both endogenous circadian clock and homeostatic processes.[7] The endogenous circadian clock produces a circadian rhythm in sleep-wake propensity. The sleep homeostat is a relaxation oscillator, which represents homeostatic sleep pressure, namely the physiological need for sleep. Homeostatic sleep pressure disappears during sleep and increases during wakefulness. During the night, circadian sleep propensity increases and thereby facilitates the continuation of sleep; during the day, circadian wake propensity increases and thereby opposes the wake-dependent increase in sleep propensity.[8]

Nowadays, we often sleep late and it is hard to wake up on time. Before industrialized society, the light–dark cycle is determined by sunrise and sunset. But now humans can select the lighting time with artificial lights and choose sleeping time by delaying time for bed. Wakeup time is usually triggered by alarm clocks set to meet social needs, such as work schedules and school start-times. During work days, we have to wake up early and get insufficient sleep. During weekends, we sleep longer to repay the accumulated sleep debt. Thus there is a temporal mismatch between the pattern of weekly sleep and circadian rhythm which is called "social jet lag".[9] The modern lifestyle is believed to be related with the mismatch between our sleep schedules and endogenous circadian rhythm.

The mismatch and insufficient sleep are associated with poor mental and physical health outcomes. The impacts of self-selection light exposure and social constrains on sleep timing is still far from clear. Understanding these phenomena is increasingly important because the artificial light be-

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comes ubiquitous. Mathematical modeling is an effective tool to study the problems related to circadian rhythm.[10–14] Skeldon *et al.* have done a lot of original research on human sleep and rhythm using mathematical models, and have achieved many interesting results.[15–17] In particular, the effects of self-selected lightdark cycles and social constraints on human sleep and circadian timing are studied by Skeldon *et al.* with the help of a modeling approach.[17] However, when it comes to sleep, not all humans are alike. Morning-type individuals go to bed early in the evening and get up early in the morning. Instead, evening-type individuals go to bed late and get up late in the morning. Normal-type individuals are neither evening-type nor morning-type. These phenotypes based on sleep–wake schedule are called chronotypes.[18,19] We wonder how the sleep timing of people with different chronotypes is affected by modern lifestyle. Based on the research methods of Ref. [17], we compared the effects of self-selected light exposure and social constrains on sleep timing of people with different chronotypes, which is a supplement and refinement to the exiting work.[17]

Especially, we take a systematic comparison of the impacts of natural and self-selected light and social constrains on circadian sleep timing, sleep duration, and social jet-lag, which may help us more deeply understand the effects of modern lifestyle on different people. The rest of this article is organized as follows. Section 2 presents the detailed mathematical model. Section 3 shows the numerical simulation and analysis. The conclusion and discussion are presented in Section 4.

2. Description of the mathematical model

The mathematical model used in this paper is a modified version of the Phillips–Chen–Robinson (PCR) model proposed by Skeldon,[17] which is composed of a sleep–wake switch model[20] and a circadian oscillator model.[21]

The sleep–wake cycle of human sleep is regulated by the ascending arousal system (AAS), which includes the wake-promoting monoaminergic nuclei (MA) and the sleep-promoting ventrolateral preoptic area (VLPO).[22] MA and VLPO inhibit each other, forming the sleep–wake switch, where MA is active during wake time and VLPO is active during sleep time.[23]

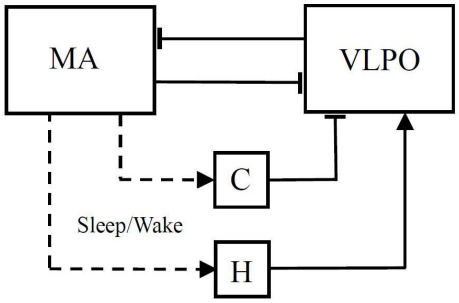


Fig. 1. Schematic diagram for the sleep–wake model, where C and H denote circadian and homeostatic drives, respectively.

The state transitions are determined by the homeostatic sleep drive and the circadian drive from the suprachiasmatic nucleus (SCN) to the VLPO. [22] The circadian rhythm drive is projected via the dorsomedial hypothalamus (DMH) to VLPO (see Fig. 1).[24]

2.1. Sleep-wake switch model

Trigger switch between MA and VLPO groups is simulated by neuronal population modeling method, where the attributes of each group of neurons are averaged, instead of individual neurons being modeled.[25] Mutual inhibition between sleep promoting and wake promoting neurons results in sleep and wake states. Their mean electric potentials are described by V_v and V_m, respectively.

$$\tau_v \frac{\mathrm{d}V_v}{\mathrm{d}t} = -V_v - v_{vm} Q_m + D_v, \tag{1}$$

$$\tau_m \frac{\mathrm{d}V_m}{\mathrm{d}t} = -V_m - v_{mv} Q_v + D_m, \tag{2}$$

where τ_v and τ_m are the time delays caused by charging of VLPO and MA; v_{jk} $(j = v, m)$ are coupling strengths of the connections to population j from k; Q_v and Q_m are the mean firing rates of the neuronal populations, which have sigmoidal relationship with their mean membrane potentials

$$Q_{v,m} = \frac{Q_{\max}}{1 + \exp\left[-\left(V_{v,m} - \theta\right)/\sigma\right]}, \tag{3}$$

where $Q_{\max}$ is a maximum mean firing rate; θ and σ are constants.

The D_m is the drive to the wake promoting neurons, which is fixed. D_v is the drive to the sleep promoting neurons, which is composed of the homeostatic sleep pressure $(H(t))$ and circadian rhythm of the SCN $(C(t))$ as follows:

$$D_v = A_v - v_{vc} C(t) + v_{vh} H(t), \tag{4}$$

where A_v, v_{vc}, and v_{vh} are constants describing inhibitory input to the sleep promoting neurons, the amplitude of the circadian wake propensity rhythm and the ability of H to promote sleep, respectively. It is assumed that the homeostatic drive H accumulates during wakefulness and dissipates during sleep as follows:

$$\chi \frac{\mathrm{d}H}{\mathrm{d}t} = -H + \mu Q_m, \tag{5}$$

where χ and μ are the homeostatic time constants.

2.2. Circadian rhythm model

The circadian rhythm $C(t)$ is modeled based on a forced van der Pol oscillator, where the light signal from photoreceptors in the eye is the forcing.[17]

$$\kappa \frac{\mathrm{d}x}{\mathrm{d}t} = \gamma \left(x - \frac{4x^3}{3} \right) - y \left(\left(\frac{24}{f \tau_c} \right)^2 + kB \right), \tag{6}$$

$$\kappa \frac{\mathrm{d}y}{\mathrm{d}t} = x + B, \tag{7}$$

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \lambda\left(\alpha(1-n) - \beta n\right), \tag{8}$$

$$B = (1-bx)(1-by)\hat{B}, \tag{9}$$

$$\hat{B} = G\alpha(1-n). \tag{10}$$

In the above model, x and y are the variables of the van der Pol oscillator and n is the fraction of activated photoreceptors. κ is a constant that adjusts the van der Pol oscillator to have a period of 24 h. The term B denotes the light forcing with intensity I on photoreceptors. τ_{c} is the intrinsic period, f is included to fix the period at τ_{c}, γ is the stiffness of the oscillator, λ, k, b, and G are constants.

The resultant photic drive B to the pacemaker is then modeled as proportional to the rate $\alpha(1-n)$ at which photoreceptors are activated, giving

$$\alpha = \alpha_0\left(\tilde{I}/I_0\right)^p, \tag{11}$$

$$\tilde{I} = \theta\left(Q_m - Q_{\mathrm{th}}\right)I(t), \tag{12}$$

where $\theta(Q_m - Q_{\mathrm{th}})$ is a step function, and $Q_{\mathrm{th}} = 1\ \mathrm{s}^{-1}$, p is a constant. When Q_m is greater than the threshold value Q_{th}, the sleep state is defined as wake; otherwise, the state is defined as sleep.

$$I(t) = l_2 + \frac{(l_1 - l_2)}{2}\left(\tanh\left(c\left(t - s_1\right)\right) - \tanh\left(c\left(t - s_2\right)\right)\right), \tag{13}$$

which represents light–dark cycles. l_1 and l_2 represent light intensities during core day light hours and at other times, respectively. According to the properties of $\tanh(\cdot)$ function, when t crosses s_1 from left to right, light intensity switches from l_2 to l_1, and when t crosses s_2 from left to right, light intensity switched from l_1 to l_2. The constant c determines the switch speed.[17]

Table 1. Nominal parameter values for the model.

$Q_{\max}$	$100\ \mathrm{s}^{-1}$	V_{mv}	1.8 mV·s
V_{vm}	2.1 mV·s	A_m	1.3 mV
V_{vh}	$1\ \mathrm{mV{\cdot}nM^{-1}}$	τ_v	10 s
τ_m	10 s	Q_{th}	$1\ \mathrm{s}^{-1}$
μ	4.2 nM·s	σ	3 mV
θ	10 mV	v_{vc}	5.8 mV
A_v	−10.2 mV	χ	25, 30, 45 h
κ	$12/\pi$ h	τ_{c}	24.2 h
I_0	9500 lux	p	0.6
γ	0.23	k	0.55
β	0.013	f	0.99669
α_0	0.16	b	0.4
c	1/3000	s_1	6
s_2	18	G	19.9
λ	$60\ \mathrm{h}^{-1}$	–	–

The circadian rhythm of the SCN, $C(t)$, is given by[17]

$$C(t) = \frac{1}{2}(1 + 0.80y - 0.47x). \tag{14}$$

The parameter values in the model are given in Table 1 as below. In the PCR model, adjusting the value of χ can realize different chronotypes.[20] In this paper, we use $\chi = 25$, 30, 45 to simulate morning-type, normal-type, and evening-type chronotypes, respectively.

3. Results

3.1. Comparison of sleep timing of people with different chronotypes affected by different light cycles

In modern society, most people live and work in the environment with artificial light rather than natural light. People can select the lighting time freely.

3.1.1. Impacts of prolonged day light exposure

Here we consider two types of light, which are the natural light whose lighting time is based on sunrise and sunset, and the prolonged light which represents the self-selected prolonged light.[17] In both conditions, the described light input is gated by the sleep–wake cycle, *i.e.*, light input occurs only during awakening but not during sleep. The diagram of lighting and its effects are shown in Figs. 2(a) and 2(b).

The clock time of the minimum circadian wake propensity (or the maximum of circadian sleep propensity) is noted by $C_{\min}$, which is also the time when sleep is the heaviest. Figure 2(a) gives the mathematically simulated light–dark cycles. Figure 2(b) shows the simulated sleep duration and $C_{\min}$, indicated by gray circles, from which we can see that with the prolongation of the light time, the time of falling asleep and $C_{\min}$ are both correspondingly delayed, but the sleep duration does not change significantly. The effects on the three different chronotypes are similar. Under the same light condition, the time interval between natural awakening and $C_{\min}$ of morning-type people is the shortest, and that of evening-type people is the longest. This means that people of morning-type are most sleepy when they are close to waking up.

3.1.2. Impacts of evening light exposure

Here we compare the impacts of the self-selected evening light on sleep timing of people with different chronotypes. The simulation results are shown in Figs. 2(c), 2(d) and 3. Here the intrinsic circadian period is 24.2 h for all the people with different chronotypes.

Figure 2(c) gives the mathematically simulated light–dark cycles. Figure 2(d) shows the sleep duration and $C_{\min}$, from which we can see that the presence of evening light delays the time of falling asleep and $C_{\min}$. The sleep duration is almost unchanged. Comparing with different chronotypes, we find that evening light has the smallest impact on morning-type people and the largest impact on evening-type people. For morning-type people, they originally fall asleep at around 21:00, but with 40 lux evening light, they fall asleep around 21:45. For evening-type people, they originally fall asleep at around 23:15, but with 40 lux evening light, they fall asleep around 01:15.

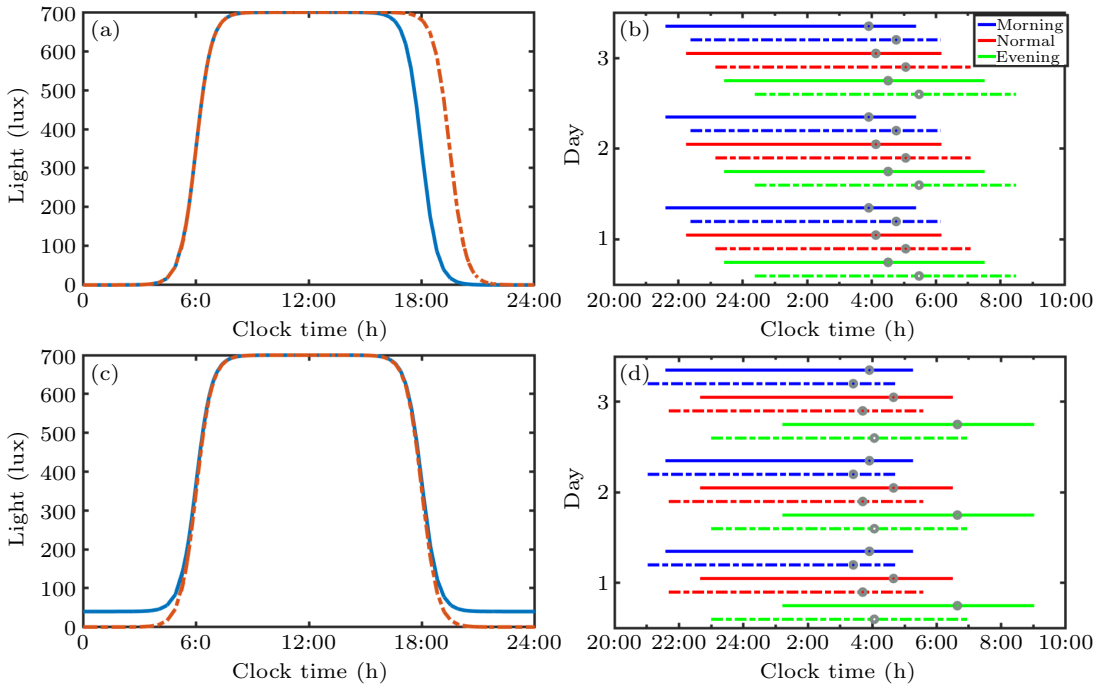


Fig. 2. Effects of different light exposures on sleep timing of people with different chronotypes. (a) The blue solid curve represents the natural light cycle with light interval 06:00–18:00; the red dotted line represents the prolonged light cycle with light interval 06:00–19:30. (b) The solid lines and dotted lines express the sleep timing under natural light cycle and prolonged light cycle of panel (a), respectively. (c) The blue solid line represents the light cycle with evening light exposure whose intensity is 40 lux; the red dotted line means the light cycle without evening light exposure. (d) The solid lines and dotted lines express the sleep time under the light cycle with evening light and the light cycle without evening light of panel (c), respectively. In panels (b) and (d), blue, red, and green lines represent morning-type, normal-type, and evening-type, respectively.

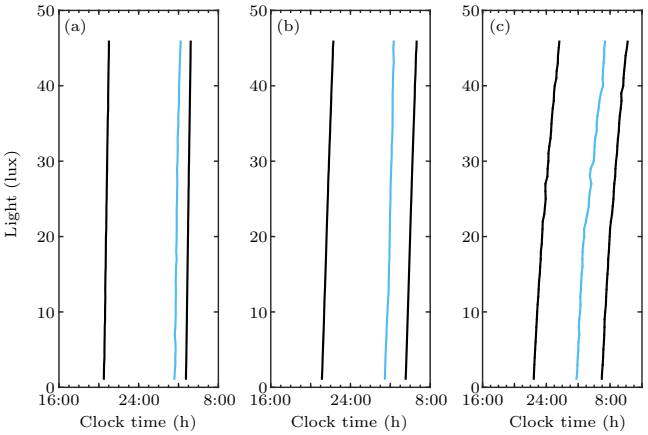


Fig. 3. Effects of different evening light intensities on sleep timing of people with different chronotypes. The fixed day time interval is around 6:00–18:00 with a day light intensity of 700 lux. In each subfigure, left and right lines represent start and end time of sleep respectively, and the time between them represents sleep duration, and middle line shows the timing of $C_{\min}$. Panels (a), (b), and (c) show the sleep of morning-type people, normal-type people, and evening-type people with variable evening light intensity, respectively.

As shown in Fig. 3, with the increase of evening light intensity, the time of falling asleep is getting later. However, the duration of sleep remains almost the same. The phase-relationship between $C_{\min}$ and wake-time is almost unaffected. It can be seen from the slope of the left and right lines that the same evening light intensity has the greatest impact on the evening-type people and the smallest impact on the morning-type people. This result is reasonable, which is mainly attributable to the time of falling asleep. As we know, morning-type people fall asleep at the earliest time, so the time of receiving evening light is the shortest. On the contrary, evening-type people fall asleep the last, so they receive evening light for the longest time.

It was found that healthy adults have different intrinsic periods of the circadian timing system, which is near-24-hour and about 80% of people have an intrinsic period longer than 24 h.[26] We wonder how people of different chronotypes with different intrinsic circadian periods are affected by evening light exposure. Here we set the simulated range of intrinsic periods is from 23.5 h to 24.7 h, which covers approximately 99% of the intrinsic periods.[26] $C_{\min}$ as a function of evening light for different intrinsic periods is shown in Fig. 4, from which we can see that the influence of evening light on spontaneous sleep time strongly depends on the intrinsic circadian period, which is consistent with Ref. [17]. The impacts of evening light vary greatly between individuals with different intrinsic circadian periods. Specifically, when the intrinsic period is less than 24, the dependency is weak, but when the intrinsic period is greater than 24, the dependency is strong. That is to say the people with longer intrinsic periods are expected to be vulnerable to evening light. As for the three different chronotypes, the influence of evening light on evening-type people depends on the intrinsic period of the individual to the greatest extent, while the influence of morning-type people is least dependent. In other words, the intrinsic period has the

greatest impact on the sleep of evening-type people, and has the smallest impact on the sleep of morning-type people.

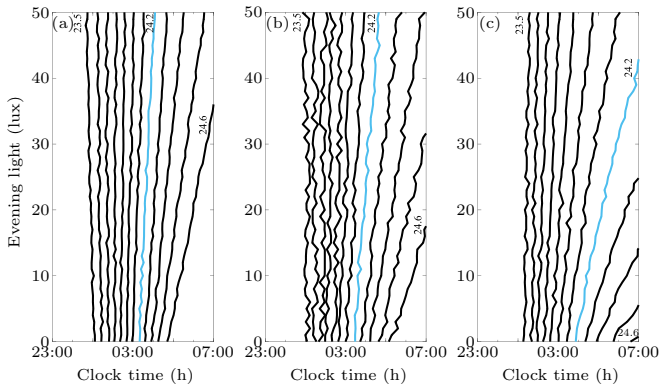


Fig. 4. Timing of the minimum of circadian wake propensity ($C_{\min}$) as a function of evening light for different intrinsic circadian periods. The intrinsic period range is 23.5 h to 24.6 h with a step of 0.1 h from left to right. Panels (a), (b), and (c) represent the morning-type, normal-type, and evening-type, respectively.

3.1.3. Impacts of increasing day light intensity

To some degree, the increasing day light exposure can offset the effect of evening light on spontaneous sleep timing (Fig. 5). However, the relationship is highly nonlinear. From the vertical distance between the lines for different evening light intensities, we can see offsetting the effect of a small increase in evening light intensity needs a large increase in day light intensity, as indicated in Ref. [17]. Comparing the subfigures of Fig. 5, we find it is most difficult for increasing the day light to offset the effect of evening light for the evening-type people, and it is easiest for the morning-type people. This result is consistent with the previous statement that evening light has the greatest impact on sleep timing of evening-type people.

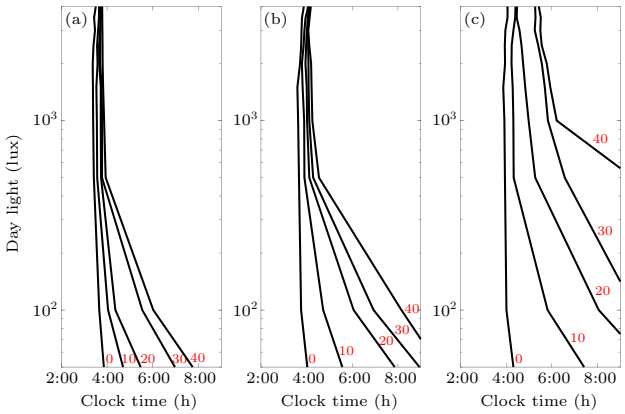


Fig. 5. Timing of the minimum of circadian wake propensity ($C_{\min}$) as a function of day light for different evening light intensities. The evening light intensity range is 0 lux to 40 lux with a step of 10 lux from left to right. Panels (a), (b), and (c) represent the morning-type, normal-type, and evening-type, respectively.

3.2. Comparison of sleep timing of people with different chronotypes under the condition of social constraints

In modern society, people are often woken up by alarm clocks for work or study, which are called social constraints. In order to simulate the impacts of social constraints, we refer to the wake-up method of the shift workers in Ref. [27]. When the alarm clock rings, the values of V_v and V_m are forcibly changed to those of waking time in the model.

Figure 6 shows the sleep timing and $C_{\min}$ of a week with an alarm clock of 4:30 from Monday to Friday. Due to the forced awakening during work days, people sleep longer on weekends to make up for the sleep debt accumulated within a week. Without social constrains, $C_{\min}$ occurs two to three hours before wake. However with the inclusion of social constraints, $C_{\min}$ still occurs two to three hours before wake time at weekends, but occurs much closer to wake time on work days. During work days, the sleep duration of morning-type people is the longest, and that of evening-type people is the shortest. The main reason is that these three chronotypes of people are woken up at the same time, but they fall asleep at different times. Specifically, the morning-type people fall asleep early, and the evening-type people fall asleep late. Therefore, the sleep duration of morning-type people is less affected, and that of evening-type people is more affected.

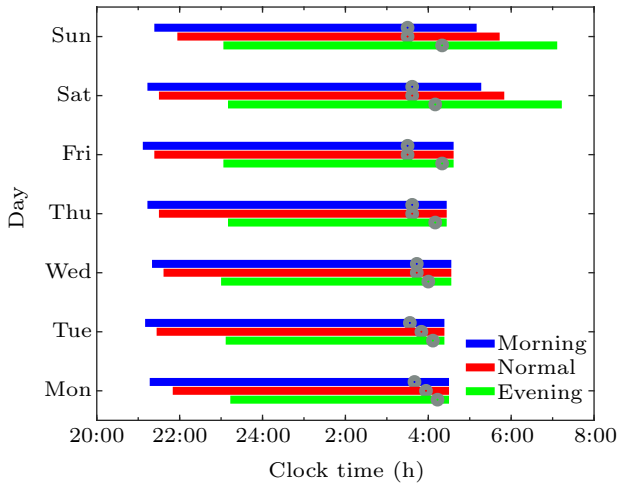


Fig. 6. The sleep timing with an alarm clock of 4:30 weekdays for different chronotypes. For every day, the light exposure interval is 6:00–18:00 with day light intensity 700 lux/evening light intensity 0 lux. The blue, red, and green lines represent morning-type, normal-type, and evening-type, respectively. The gray circles denote $C_{\min}$.

Social jet-lag refers to the difference between the wake-time on weekdays when there is an alarm clock and the natural wake-time on Saturday. Based on the method of Ref. [17], the comparison of effects of evening light intensity and intrinsic periods on social jet-lag of three chronotypes is shown in Fig. 7. It can be seen from the comparison of Figs. 7(a)–7(c) that for the same intrinsic period and night light intensity, the social jet-lag of evening-type people is the largest and that of morning-type people is the smallest. This suggests that evening-type people need more sleep on weekends to compensate for sleep debt they owe during weekdays.

Specific to each chronotype, those with more light exposure in the evening or longer intrinsic circadian periods are expected to experience more social jet-lag. This is consistent with the dependence of spontaneous sleep timing on evening

light and intrinsic period of Figs. 3 and 4, where with the increase of evening light intensity and intrinsic period, the sleep time is delayed (see Fig. 3). Note that those with longer intrinsic periods have spontaneous wake times after the alarm time which results in social jet-lag even in the absence of evening light.

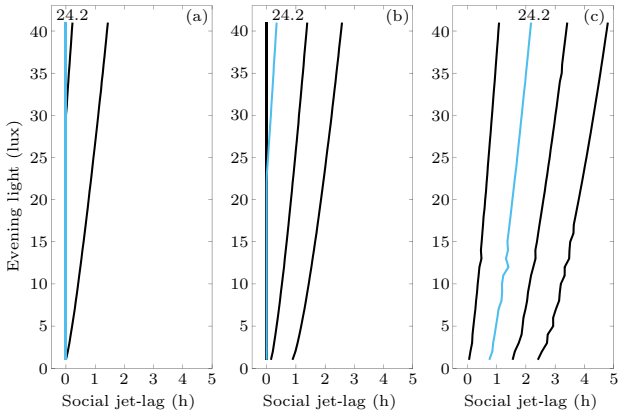


Fig. 7. Social jet-lag as a function of evening light for differnt intrinsic periods. The intrinsic period range is 24.0 h to 24.6 h with a step of 0.2 h from left to right in each subfigure. In particular, the lines with periods 24 h and 24.2 h coincide in panel (a). Panels (a), (b), and (c) represent the morning-type, normal-type and evening-type, respectively.

3.3. Comparison of sleep timing of people with different chronotypes with age

There is sufficient evidence that the preferred sleep time changes throughout the lifespan.[28] For older people the homeostatic sleep pressure during wake increases at a slower rate than that of younger people, and the amplitude of the circadian rhythm is reduced. Previous studies have shown that monotonically reducing circadian amplitude and the rate of homeostatic rise during wake reproduces age-related changes in sleep timing.[29] In the mathematical model of Eqs. (1)–(14), reducing parameters μ and V_{vc} can achieve these two changes.[15] Now we use the model to simulate the changes of sleep timing of people with different chronotypes throughout the lifespan. Here we do not consider social constraints. With the help of Origin software, we extract the μ and V_{vc} values corresponding to different ages in Fig. 4 of Ref. [29].

The sleep timing, measured by the midpoint of sleep (mid-sleep),[17] across the lifespan is shown in Fig. 8. In Figs. 8(a)–8(c), there is not evening light; in Figs. 8(d)–8(f), the evening light intensity is 40 lux. From Fig. 8, we can see that the mid-sleep time and wake time both become earlier and sleep duration shortens with age. Figures 8(a) and 8(d) show that before the age of 20, sleep time is delayed with age, but after the age of 20, sleep time is advanced with age. These results are in accordance with empirical observations. Comparing Figs. 8(a)–8(c) with Figs. 8(d)–8(f), we know that without evening light, the predicted differences in sleep timing with age are relatively modest. In general, the simulations show that the serious delay observed in teenagers in the modern industrialized society is largely due to the ability to select the patterns of light exposure. By analyzing the slopes of the lines representing three chronotypes, we find that morning-type people's sleep timing changes most and that of evening-type people changes least with age. With the growth of age, the symptoms of morning-type people become more and more serious, and the sleep of evening-type people gradually becomes better and even normal.

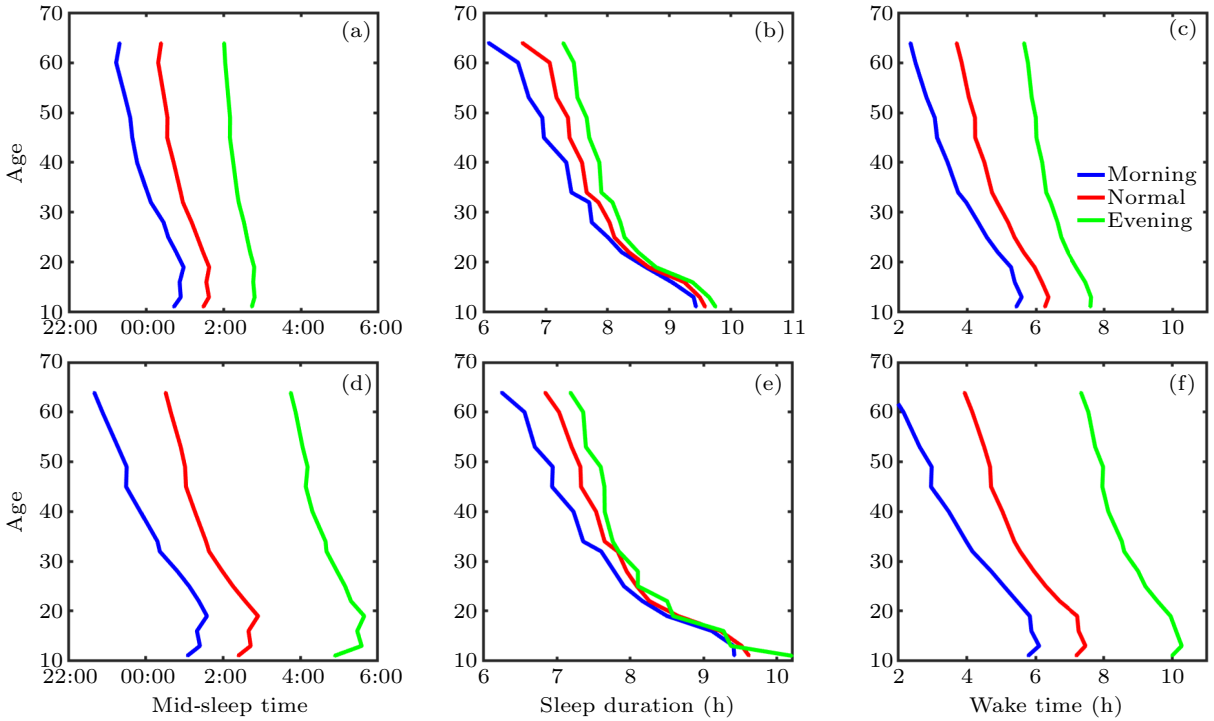


Fig. 8. Impacts of age on sleep timing. (a) and (d) Sleep timing as measured by mid-sleep on days with no social constraints, (b) and (e) sleep duration, and (c) and (f) wake time. The evening light intensities are 0 lux and 40 lux in panels (a)–(c) and (d)–(e), respectively.

4. Discussion and conclusion

In modern society, people can select the lighting time with artificial lights and choose sleeping time by putting off time for bed. Wake up time is usually triggered by alarm clocks to meet social needs, such as work schedules and school start-times. This causes insufficient sleep or mismatch between sleep and circadian rhythm, leading to mental or physical ill health. As a supplement and refinement to existing work,[17] in this paper, we aim to make clear the effects of selfselected light and social constraints on sleep of different chronotypes, so that individuals can reasonably arrange their work or study accordingly. By systematic research we get some interesting results.

(i) The prolonged light exposure and evening light both delay the time of falling asleep and the time when the minimum value of the circadian wake propensity $C_{\min}$ appears, but the sleep duration almost unchanged. People of morning-type are most sleepy when they are close to waking up. Evening light has the smallest impact on morning-type people and the largest impact on evening-type people. The people with longer intrinsic periods are expected to be vulnerable to evening light.

(ii) Increasing day light exposure can offset the effect of evening light on spontaneous sleep timing to a certain degree. However offsetting the effect of a small increase in evening light intensity needs a large increase in day light intensity. For evening-type people, it is the most difficult to offset the effect of night light by increasing daytime light, while for early sleepers, it is the easiest.

(iii) With social constrains, people of evening-type has the largest social jet-lag, which increases with evening light intensity or intrinsic periods. With the growth of age, the sleep of morning-type people worsens, and that of evening-type people improves.

These simulations are consistent with recent field studies. Evening light suppresses and delays melatonin, delaying sleep timing.[29] The circadian phase is much earlier when people go camping and discard artificial light.[2] Social jet-lag that is the mismatch between the starting time of school or work and the preferred sleep timing, is more serious in individuals with longer intrinsic periods and later chronotype.[30,31]

These findings show the quantitative impacts of modern lifestyle on sleep timing in people of different chronotypes from mathematical view, which provide a theoretical reference for preventing or treating sleep disorder and social jet-lag for individuals with different chronotypes. The results suggest that increasing day light exposure and decreasing night light exposure can help to sleep healthily for all the people. However, for morning-type people, it is more effective to improve day light exposure, and for evening-type people or individuals with long intrinsic period, it is more effective to reduce night light exposure.

In addition to light and social constraints, there are other factors, such as gender and lifestyle, which also have an impact on sleep timing. In the near future, we will try to use mathematical models to study the impacts of other factors on sleep timing so as to provide some theoretical support for human healthy sleep.

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