Sleep timing in industrial and pre-industrial societies syncs to the light/dark cycle

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Did artificial light reshape human sleep/wake cycle? Most likely the answer is yes.
Did artificial light misalign the sleep/wake cycle in industrialized societies relative to the natural cycle of light and dark? For the *average* person —that is, obviating the tail of the distributions— the answer is probably not.
Sleep timing in industrial (data from eight national time use surveys) and pre-industrial, hunter-gatherer/horticulturalist societies (seven data from three previous reports) with and without access to artificial light finds a remarkable accommodation across a wide range of angular distance to Equator (0° to 55°) in trends dominated by the extreme light/dark conditions.
Winter sunrise time —the latest sunrise year round— triggers sleep offset, which delays in the poleward direction. The same trend is observed in bedtimes, dictated by the previous sleep offset, a circadian, homeostatic response. That way two of the most significant human sleep/wake features, the abhorrence for waking before sunrise and the abhorrence for going to bed before sunset, meet in a common natural event. None of them are related to artificial light.

Keywords: sleep/wake cycle; sleep onset; time use survey; circadian rhythm; homeostatic sleep pressure; dst; daylight saving time; summer time

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I. INTRODUCTION

Sleeping and being awake are probably the most basic human activities entrained to Earth's rotation period $T = 24\,\mathrm{h}$ —the definition of hour— and the light/dark (LD) cycle(Roenneberg et al., 2013). Wake is associated to the photoperiod; sleep is associated to the scotoperiod. Yet, they are distributed differently: sleep shares are $2T/3$ (awaken), $T/3$ (sleep); the LD shares are $T/2$ at the Equator.

It is a long understanding that artificial light, industrialization has reshaped the sleep/wake cycle(Ekirch, 2001). To which extend is still a matter of discussion. (Scheer et al., 2009) showed that circadian misalignment induced by artificial light causes pathologies. It is also a wide concern that artificial light may lead to sleep deprivation(Bin et al., 2012).

Collecting data from times when artificial light was not available is a difficult task. Instead, in the past few years some works tried to understand the sleep timing in 21st century, pre-industrial societies with and without access to artificial light: (Moreno et al., 2015) studied communities in Acre (Brazil) and (de la Iglesia et al., 2015) in Formosa (Argentina). Also (Yetish et al., 2015) reported data of "natural sleep" in three pre-industrial, hunter/gatherer societies with no access to electricity.

The LD cycle is also shaped by Earth's obliquity $\varepsilon = 23.5^\circ$ —the angle between Earth's rotation axis and Earth's orbital axis— which gives rise to seasons and seasonality —the adjustment of human activity through seasons. Understanding the role of latitude in human cycles is also an open issue(Leocadio-Miguel et al., 2017; Miguel et al., 2014; Randler and Rahafar, 2017; Roenneberg et al., 2007; White and Terman, 2003). Recently, (Martín-Olalla, 2018a) show that primary activities in laborers aligned to sunrise, thus were influenced by latitude.

This paper will analyze time use surveys in eight industrialized, mid-latitude countries to assess sleep timing in standard population. Industrialized data will be consistently compared with previously reported, pre-industrial, hunter/gatherer, tropical sleep timing. Regular patterns dominated by LD cycle from the Equator to 55° will be revealed.

II. METHODS

II.1. Data sets

Time use surveys try to ascertain when people do activities like sleeping, eating or working within one cycle (day), which is usually sliced in 144 chunks of ten minutes each. The daily rhythm of an activity is the shares of respondents which are doing the activity at a given chunk.

The sleep/wake daily rhythm looks like a rectangular function with most of the respondents awaken at noon and most of them sleeping at midnight and two transitions: one in the morning, one at night (see Figure 1 in (Martín-Olalla, 2018a)). The only exceptions are afternoon protrusions, due to naps, in Italy and Spain.

The timing of human sleep in modern societies can be thoroughly obtained from these transitions: a threshold located at half the range of the daily rhythm helps assessing when the threshold is overshot in the morning (risetime, t_1) and undershot at night (bedtime, t_3). A third timemark can be defined at the moment when the daily rhythm is half consumed and half remains —the cycle starts at 4am—. It will be termed *wakeful noon time* t_2; it slightly differs from the midpoint of bedtime and risetime.

This work will present the sleep timing from eight national time use surveys (NTUS, hereafter) —six in Europe; two in America—. The analysis will cover standard population aged at least 25 year old. Due to the large number of participants daily rhythm and sleep timing averages the myriad of decisions that shape modern societies. Countries and number of participants are listed on Table I. References list the institutions which carried out the surveys.

Previous works by (de la Iglesia et al., 2015), (Moreno et al., 2015) and (Yetish et al., 2015) studied sleep timing in pre-industrial hunter-gatherer/horticulturalist societies. Moreno et al. reported sleep timing (Figure 1) from rubber tappers in the Chico Mendes Amazon Extractive Reserve (Brazil), with and without electric light at home; de la Iglesia et al. did the same (Table 1) for the Toba/Qom people in the province of Formosa, the most equatorial region of Argentina. Yetish et al. reported (Table S2) sleep timing from Hadza people, in the most Equatorial region of Tanzania; the San people in the Kalahari desert; and the Tsimane people in Bolivia. Table I lists geographical data of participating people extracted from original references.

Some differences are evident in comparing time use surveys and studies on pre-industrial societies. NTUS includes a great number of respondents, and are aimed to globally represent a modern society, over a wide geographical region. They are not specifically designed to understand the human sleep/wake cycle; yet, they provide relevant average information of the cycle. In comparison, pre-industrial values refer to a much smaller sample (tens of respondents), they are located in a narrow region and were specifically aimed to understand the sleep/wake cycle of these societies. For instance, de la Iglesia et al. and Yetish et al. employed wrist data-loggers.

Both data sets also differ in how seasonality is assessed. Both (de la Iglesia et al., 2015) and (Yetish et al., 2015) reported summer and winter values of the sleep/wake cycle, whereas (Moreno et al., 2015) collected data in September to November; in this work they will be assigned year round. Hazda people live so close to Equator that seasonal changes are irrelevant. On the contrary sleep timing in NTUS usually covers one year. Yet from spring-summer to autumn-winter sleep timing only differ in one chunk (ten minutes) at most as measured by local time. Sleep timing seasonality in industrialized societies is only induced by daylight saving time (DST), which increases time offset values by one whole hour. Only the province of Saskatchewan in Canada, and the state of Arizona in United States, exhibit permanent time offset.

II.2. Responses and predictors

In the forthcoming analysis sleep timing will be the response to characterize. Surveys provide local time values but they are unuseful for comparing to the light/dark cycle and for comparing within different countries/people. Instead natural gauges like time distance to solar noon, time distance to sunrise/sunset, or, eventually, the solar altitude relative to horizon are the appropriate measures for testing against the LD cycle.

Winter photoperiod D_w —the shortest photoperiod year round— will be the predictor. It is a proxy for absolute latitude $|\phi|$, the angular distance to Equator, to which is related by:

$$D_w(|\phi|) = \frac{2T}{C}\cos^{-1}\left(\frac{\sin z_c + \sin|\phi|\sin\varepsilon}{\cos|\phi|\cos\varepsilon}\right), \tag{1}$$

where $C = 360°$ is one cycle and $z_c = -0.83°$ is a critical solar altitude relative to horizon which defines sunrise and sunset. Notice that $D_w(|\phi|)$ is only defined and non-zero below polar circles.

Photoperiod will not be used in the sense of exposition to light. It is a convenient predictor only because it draws linear relations for the most significant events of the light/dark cycle. Winter sunrise (WSR) and sunset (WSS) can simply be cast as:

$$t_w^{\uparrow\downarrow} = \mp\frac{1}{2}D_w, \tag{2}$$

where time is measured relative to solar noon. Except for minor corrections due to Sun's finite size and atmospheric refraction, shortest photoperiod equals shortest scotoperiod and summer sunrise (SSR) and sunset (SSS) times are also given by $\pm D_w/2$ if time is measured relative to midnight.

The boundaries of the light/dark cycle are then characterized by the gradient $\beta = 1/2 = 30\,\mathrm{min\,h^{-1}}$. It reads thirty minute in advance/delay of winter/summer sunrise/sunset per hour change D_w. Gradient is negative for "late" events —WSR or SSS— and positive for the "early" events —WSS or SSR. Gradient β must be contrasted to the gradient of "mean events" —solar noon, mean sunrise and mean sunset times— which is exactly zero.

Also D_w reads the seasonal range in sunrise/sunset times, which approximately equals to $T/2 - D_w$: the defect of the shortest photoperiod with respect to the semiperiod.

Summarizing, sleep timing —risetimes, bedtimes, wakeful noon times— will be contrasted against D_w to test which light and dark event —late sunrise/sunset ($m = -\beta$), noon/mean ($m = 0$) and early sunrise/sunset ($m = \beta$)— best explains synchronization. A competition between modern mechanical clocks, which are synced to noon, and ancient, pre-industrial clocks, which are related to sunrise and sunset, is implicit in the analysis.

III. RESULTS

Table II lists sleep mean annual timing for modern, industrial societies obtained from NTUS microdata and seasonal timing for pre-industrial hunter-gatherer societies from (de la Iglesia et al., 2015), (Moreno et al., 2015) and (Yetish et al., 2015). Table II also lists univariate descriptive statistics of data sets: average $E(\{y_i\})$, range (distance from maximum value to minimum value), and variability $2s(\{y_i\})$ (twice sample standard deviation, s). Variabilities smaller than $T/24$ —one hour, a standard size of human time variability, linked to time zones and to our preference for whole hours— are highlighted in blue ink.

Table II casts sleep timing in different ways. First, as a distance to solar noon, which only differ from clock readings by the time offset listed in Table I. Second as a distance to WSR, a measure which is alien to modern clocks but will be key in the analysis. Third, winter solar altitude (WSA) at risetimes. Finally, the time distance from bedtimes to the next risetime, a intrinsic reference within the sleep/wake cycle.

NTUS variabilities always undershoot one hour, with bedtimes distance to risetimes hitting only $2s = 26\,\mathrm{min}$. Range scales up to $80\,\mathrm{min}$ at most (bedtimes). Contrastingly, pre-industrial values exhibit a greater dispersion on risetimes; including bedtimes distance to risetimes.

Descriptive statistics for the full set of data ($N = 15$) display huge variability for sleep times distance to noon $2s \sim 120\,\mathrm{min}$: there is not a unique sleep timing relative to noon. First $N = 15$ entries in Table II are sorted in increasing values of shortest photoperiod (see Table I); a trend is apparent: sleep timing decreases (advances) with decreasing $|\phi|$.

Variability is halved and lies below one hour if sleep times are referred to WSR. No trend is apparent for sleep timing relative to WSR. A unique sleep timing does exits: people rise $\sim 0.7\,\mathrm{h}$ before WSR; wakeful noon occurs $\sim 7.2\,\mathrm{h}$ after WSR and bedtimes are $\sim 9.2\,\mathrm{h}$ before next WSR; in every circumstance, within a variability smaller than one hour. This is a quite remarkable observation.

Figure 1 helps visualizing this issue. Lines and background colors in Figure 1 highlight the LD cycle: lighter background is the photoperiod, darker background is the scotoperiod; dotted lines display winter altitude starting at $-12°$ (outer most) in steps of $6°$; vertical lines highlight distance to noon ($m = 0$); slanted, dash-dot lines, distance to late events (WSR and SSS, $m = -\beta$); dash-dot-dotted lines, distance to early events (WSS and SSR, $m = +\beta$). Within this natural scenario, data points show human sleep timing. Adjacent straight lines are all separated by one whole hour and helps visualizing the variability of sleep timing.

Noon synchronization is only perceived in winter by narrowing the latitudinal range. As an example NTUS sleep timing can be placed on one-hour vertical boxes as observed in Figure 1 and Table II. The key factor is the range and variability of the winter sunrise in this subset: it is only one hour (see Table I).

In summer (bottom panel), subsolar point has moved poleward, locates now in an intermediate position between Tropical, pre-industrial people and mid-latitude, industrial countries. Therefore, solar altitude —which computes angular distance to subsolar point— is increasingly similar in the range of observations as noted by dotted lines. Larger LD seasonality induces larger sleep timing seasonality in industrial values, which generally moves industrial data relative to pre-industrial data decreasing the gap relative to noon. As a result, sleep timing can not be placed within one-hour width strips.

These arguments consistently describe the placement of sleep timing within the LD cycle. Quantitative values can be obtained from multiple linear regression in which D_w is the predictor x and the response is any of the entries in Table II. Notice, however, that in figure 1 the predictor is displayed on the vertical axis, and some of the responses (distance to noon), on the horizontal axis.

Regression results are listed in Table III. Probabilistic values smaller than the standard level are highlighted in blue ink. The full set of winter industrial and pre-industrial data hit slopes close to $-\beta = -30\,\mathrm{min\,h^{-1}}$ when timing is referred to noon. Confidence intervals always include $m = -\beta$ as well as they exclude $m = 0$ (noon) and $m = +\beta$ (summer sunrise). Therefore, if sleep timing is referred to WSR, p-values are larger than the standard level and the null hypothesis "t_i distance to WSR do not depend on the photoperiod" sustains for every timemark. Bedtimes

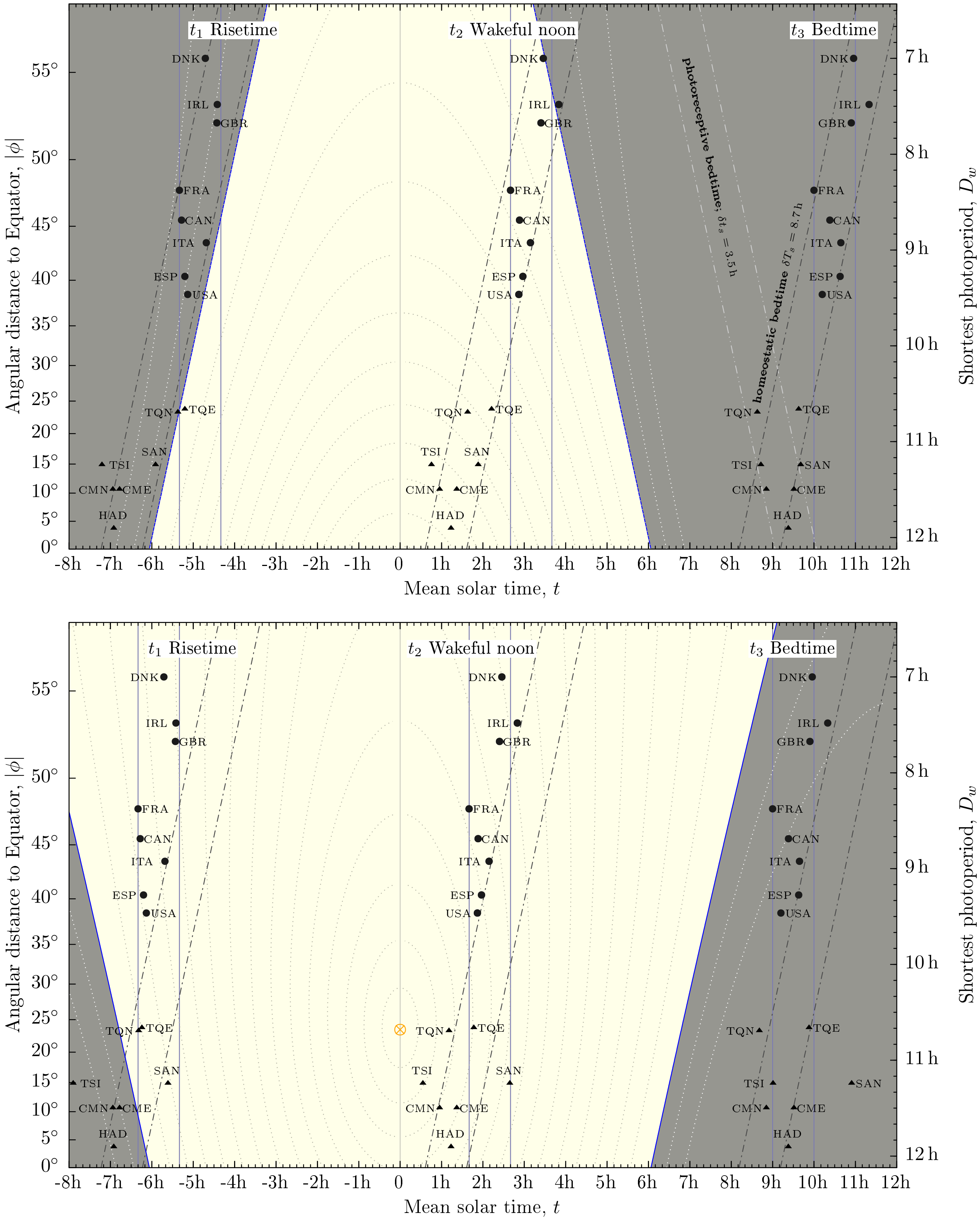

Figure 1 Sleep timing against shortest photoperiod in industrial and pre-industrial societies. Horizontal axis displays mean solar time (distance to solar noon), vertical axes display shortest photoperiod (right) and latitude (left). Top panel displays winter day; bottom panel, summer day. Lighter background is the photoperiod; darker background is the scotoperiod. Dotted line display solar altitude starting at $z = -12°$ (outer most) in steps of 6°. The subsolar point ($z = 90°$) is noted by a crossed circle. Solid, vertical lines highlight distance to noon; slanted, dash-dotted lines, distance to late events; slanted dash-dot-dotted lines, distance to early events. Human sleep timing is noted in circles (NTUS/Industrial) and triangles (pre-industrial/hunter-gatherer), which come from (Yetish et al., 2015) (Hazda, San and Tsimane people), (de la Iglesia et al., 2015) (Toba/Qom people) and (Moreno et al., 2015) (Chico Mendes). Dash-dotted lines keep still in top and bottom panels to visualize the seasonality of NTUS/Industrial data, which moves one hour to the left induced by DST. Geographical values are listed in Table I; sleep timing is listed in Table II; regression analyses are summarized in Table III

distance to risetimes hit a slope $\beta/10$ with $p = 0.63$. This describe how similar risetime and bedtime distributions are: their difference offsets trends.

Regression results for winter solar altitudes WSA at risetimes is worthy to mention. They hit a slope equal to $-1.4(22)\,^\circ\,\mathrm{h}^{-1}$ with $p = 0.2$. Therefore WSA at risetimes sustains the null hypothesis at the standard level. It is the only occurrence in solar altitudes related to sleep timing.

NTUS/Industrial only values hit slopes close to $-\beta/2$ and the confidence interval includes both the late synchronizer $m = -\beta$ and the noon synchronizer $m = 0$ due to the small range of WSR for this subset.

Table III also lists regression analysis results in summer. The advance of NTUS/Industrial values leads to a decrease in slope values. Risetimes and wakeful noon times hit slopes $\sim \beta/2$ and confidence intervals excludes $m = -\beta$ and $m = 0$. However bedtimes hit as slope $\sim \beta/5$ and the confidence interval includes $m = 0$. Therefore the null hypothesis "summer bedtimes do not depend on shortest photoperiod" sustains at the standard level. Likewise bedtimes distance to risetimes hit p-values smaller than the standard level so that this quantity has a statistical dependence on D_w with slope $\sim \beta/3$. Risetime and bedtime summer distributions are less similar than they were in winter. It is due to the fact that industrial values of $t_3 - t_1$ do not change seasonally whereas pre-industrial values tend to shrink from winter to summer.

IV. DISCUSSION

Sleep timing is modulated by three simple ideas: people abhor waking before sunrise, people abhor going to bed before sunset, and daily sleep time amounts to $\sim T/3$.

The first idea aligns sleep/wake cycle to sunrise —the ancient time reference— instead of noon —the modern time reference. This makes wakefulness meet the scotoperiod mostly after sunset. At the Equator this amounts roughly to $2T/3 - T/2 = T/6$ or four hours.

As people moved poleward in a tilted planet, the abhorrence for too early sleep offset was dominated by WSR and its gradient $-\beta$. Within a gently range of latitudes, this constrain efficiently works. It is only above $D_s \sim 6\,\mathrm{h}$, where the photoperiod is exceedingly short, that people must awake significantly before sunrise in winter. See (Martín-Olalla, 2018a,b) for evidence based in the "sleep and other personal care" cycle.

WSR synchronization also propagates throughout one cycle, which suggests it is regulated by a circadian mechanism like the homeostatic sleep pressure(Borbély et al., 2016). Earlier sleep offset leads to earlier sleep onset as a result of tiredness or as a way of forecasting earlier risetimes, preventing sleep deprivation. Other human activities, like laboring, exhibit a degree of overturning in modern societies: labor start times are synced to WSR and labor end times tend to be dictated by winter sunset WSS(Martín-Olalla, 2018a).

The lack of synchronization overturning increases the gap between human sleep timing and LD events. Wakeful noon times, delayed from solar noon by $T/12$ at the Equator, increase deviation as D_w decreases; their gradient is β: half an hour in delay per hour of decrease in D_w. Later, bedtimes lag from WSS by $T/6$ at the Equator and increasingly deviate as D_w decreases. The gradient is now 2β: one hour of delay per hour of decrease in D_w. Here "delay" is not intended to mean circadian misalignment. It highlights that wakeful scotoperiod increases with decreasing D_w if sleep timing keep homeostaticly tied to WSR.

Pre-industrial, tropical bedtimes can be placed in a one-hour slanted box centered $\delta t_s = 3.5\,\mathrm{h}$ after WSS, see dash-dot-dotted lines in Figure 1 (winter). The strip an plausible guess for a bedtime linked to a photoreceptive mechanism, like melatonin onset, and more prominent in the absence of artificial light. Within the range of pre-industrial latitudes this strip overlaps with an homeostatic bedtime centered 8.7 h before risetimes and tied to WSR. It is worthy to mention, though probably incidental, that Toba/Qom people with no access to electricity (TQN) lie in the photoreceptive strip whereas access to electricity (TQE) delays bedtimes by one hour (see Table II) and find accommodation in the homeostatic strip. It should also be mentioned that European countries meet dinner time some three hours after WSS(Martín-Olalla, 2018a) from 60° to 40°, within the photoreceptive strip.

The centers of the homeostatic strip and the photoreceptive strip match to each other at $D_w \sim 11.25\,\mathrm{h}$. Their difference increases with decreasing D_w at a rate 2β. At the latitude of Spain and United States that makes 2 h advance; at France's it makes 3 h and at Great Britain's almost 4 h.

Ancient bedtimes in Europe may have been located anywhere between this two mechanisms. The lack of efficient, cheap artificial light and intense physical labor at that time would have favored the photoreceptive mechanism; however, still then, its closeness to risetime would have played against, if the homeostatic sleep pressure is natural mechanism as suggested by pre-industrial sleep timing. Very understandably, earlier bedtimes —somehow tied to WSS— would have led to interrupted or segmented sleep(Ekirch, 2005, 2016).

Summer day, that with the shortest scotoperiod, is the worst case scenario for natural sleeping. Evidence in Figure 1 (bottom panel) suggests people abhor going to bed before sunset and do not abhor sleeping after sunrise when the photoperiod is long enough.

Summer premises are only relevant in the mid-latitude range. At higher latitudes, Sun can be permanently above $z_s = -6°$, the civil twilight. In the Tropical range SSR never advances too much and SSS never delays too much. In the mid-latitudes the modern preference for year round social timing, plus the abhorrance for rising before sunrise and the abhorrance for going to bed before sunset accommodates to late events —WSR and SSS—, dominated by the gradient $-\beta$.

Seasonality is the adjustment of human activity to the seasonal changes in sunrise times. At high enough latitudes, the LD cycle oscillates between quasi-permanent photoperiod and quasi-permanent dark. Human sleep/wake cycle can not truly track LD seasonality. Below $D_w = 11\,\mathrm{h}$, where most of pre-industrial data lie, LD seasonality is smaller than one hour, thus their effects should be negligible.

The only pre-industrial people that experience some noticeable degree of LD seasonality is the Toba/Qom people, living just over the Tropic of Capricorn. Sunrise times sweep $\sim 1.5\,\mathrm{h}$ from winter to summer. Correspondingly, (de la Iglesia et al., 2015) reported Toba/Qom summer risetimes advance one hour relative to winter values. Yet, summer bedtimes delay by 20 min (TQE) or do not change (TQN).

Interestingly enough NTUS/Industrialized risetimes exhibit the same degree of seasonality as in the Toba/Qom community: one hour, induced by DST. Yet European sunrise times sweep 3 h to 5 h, depending on latitude. Contrastingly DST also advances NTUS summer bedtimes by one hour so that summer sleep deprivation, if any, is less significant than in the Toba/Qom community.

It is a question to understand if seasonality was larger than one hour in ancient times. However it may have never been the case that risetimes have swung from WSR to SSR above some circle of latitude: tying risetimes too close to SSR would have led to sleep onset earlier than sunset around $D_w = 8\,\mathrm{h}$ unless the sleep/wake cycle were segmented.

In any case one-hour seasonality in Europe was not an oddity when social timing started being tied to clocks. As early as 1810, the Rules of the Spanish Congress mandated (Rule 2) that “the Speaker shall convene the Daily Sessions at 10am (October to March) and 9am (April to September)”[1]. The same regulation remains nowadays silent, only induced by DST. Both requires the unpleasant transitions which are linked to our preference for nonseasonal clocks and whole hours.

Mid-latitude sleep timing seasonality close the gap with tropical values relative to noon. (Kantermann et al., 2007) argued that DST is a geographical translocation which moves industrialized timing “equatorward”. However it must be noted that it is the subsolar point that moves poleward, closing the gap with mid-latitude countries. As a consequence, and across the range of latitudes, solar altitude lines are more alike in summer than in winter. Not surprisingly sleep timing is also more alike, relative to noon. As a point to observe, in summer, moving from Hadza’s wakeful noon time to Danish wakeful noon time barely crosses three altitude lines for a change $\Delta z_s \sim 18°$; in winter, it is ten lines for a change $\Delta z_w \sim 60°$.

V. CONCLUSIONS

Sleep timing in pre-industrial, hunter/gatherer-horticulturalist and industrial societies remarkably accommodates to the cycle of light and dark across a wide range of angular distance to Equator (0° to 55°) and social development.

Sleep timing is dominated by late LD events: the latest sunrise (winter) and the latest sunset (summer). They accommodate the golden rules: a day —as perceived by the average person— shall not start before sunrise and shall not end before sunset. These premises are not broken in the observed range of latitudes and social development.

Artificial light notably impacted human activity increasing, for instance, night shifts and rising concerns on the impact of circadian misalignment in human health. Also more than certainly artificial light has impacted the way the average person handles her wake during the scotoperiod. Yet it has not broken the golden rules. The average person does not rise before sunrise aiming to harvest artificial light or goes to be before sunset. Also the sleep/wake daily rhythm of modern societies still looks like a rectangular function which oscillates from the sleep state to the wake state and back to sleep state, in a window $2T/3$. Sleep/wake daily rhythm in a modern society is far from being 1/3 of the population sleeping (and 2/3 awaken) at any time of the day, with sleep to wake and wake to sleep transitions evenly distributed at any time of the day. That would be a 24/7 society where artificial light would play the role of natural light during the period formerly known as “scotoperiod”.

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[1] See `http://www.congreso.es/docu/blog/reglamento_cortes_1810.pdf` (in Spanish)

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Time use survey microdata were parsed with a `language C` code compiled by `gcc 5.4` and read in `octave 4.0`. This software was used to compute sleep timing. Its function `regress` was used for multiple linear regression analysis. All tabular material and figures were automatically produced from the same input files containing sleep timing. Manuscript was originally written in $\LaTeX\,2_\varepsilon$, typed in `GNU Emacs 24.5` assisted by `AucTeX 12.1`. Graphs were produced by `gnuplot 5.1 cairolatex` terminal. `Mendeley-Desktop 1.9` helped handling bibliography. All this on three different computers each running a `Xubuntu 16.04 LTS Xenial Xerus` distro and synced by `ownCloud`. `Mendeley` and `ownCloud` services were locally provided by author's institution Universidad de Sevilla.

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Appendix A: Tabular material

Geographical data and ephemerides

Country/People	*Label*	*Participants*	*Distance to Equator* $\lvert\phi\rvert$	*Shortest photoperiod* D_w	*WSR/WSS distance to noon* $t_w^{\uparrow\downarrow} = \mp D_w/2$	*Time offset* $\Delta - \lambda T/C$
Industrial/NTUS						
Denmark	DNK	5833	55.7°	7.00 h	∓3.50 h	13 min
Ireland	IRL	1834	53.3°	7.48 h	∓3.74 h	25 min
United Kingdom	GBR	15 409	52.3°	7.67 h	∓3.84 h	6 min
France	FRA	25 617	47.8°	8.38 h	∓4.19 h	50 min
Canada	CAN	17 107	45.5°	8.69 h	∓4.34 h	17 min
Italy	ITA	32 068	43.6°	8.92 h	∓4.46 h	11 min
Spain	ESP	16 571	40.4°	9.28 h	∓4.64 h	72 min
United States	USA	131 914	38.5°	9.46 h	∓4.73 h	8 min
Average		$E(\{x_i\})$	47.1°	8.36 h	∓4.18 h	25 min
Range		$\Delta\{x_i\}_{\text{min}}^{\text{max}}$	17.2°	148 min	74 min	66 min
Variability		$2s(\{x_i\})$	12.5°	107 min	54 min	47 min
Pre-industrial						
*Toba/Qom	TQE	10	23.8°	10.66 h	∓5.33 h	67 min
*Toba/Qom	TQN	10	23.3°	10.69 h	∓5.35 h	67 min
†San	SAN	10	14.9°	11.24 h	∓5.62 h	
†Tsimane	TSI	10	14.9°	11.24 h	∓5.62 h	
‡Chico Mendes	CME	300	10.7°	11.50 h	∓5.75 h	−26 min
†Hadza	HAD	10	3.7°	11.90 h	∓5.95 h	
Average		$E(\{x_i\})$	15.2°	11.21 h	∓5.60 h	18 min
Range		$\Delta\{x_i\}_{\text{min}}^{\text{max}}$	20.1°	75 min	37 min	93 min
Variability		$2s(\{x_i\})$	15.3°	57 min	29 min	79 min
Both combined						
Average		$E(\{x_i\})$	33.5°	9.58 h	∓4.79 h	26 min
Range		$\Delta\{x_i\}_{\text{min}}^{\text{max}}$	51.9°	294 min	147 min	72 min
Variability		$2s(\{x_i\})$	35.4°	195 min	98 min	54 min

Table I Overview of geographical data (latitude and time-offset) and ephemerides. Geographical data in industrial countries are population-weighted median values extracted from the database of cities with a population larger than 1000 inhabitants at `http://www.geonames.org`; labels are ISO 3166-1 alpha-3 codes. Those for pre-industrial societies were taken from (de la Iglesia et al., 2015) (starred), (Yetish et al., 2015) (dagger) and (Moreno et al., 2015) (double dagger). Shortest photoperiod is a function of $|\phi|$ and Earth's obliquity (see Equation (1)). Winter sunrises WSR and winter sunsets WSS are given as a distance to solar noon in decimal hours. Time offset is the difference between solar noon and local time midday (rounded to one minute) related to time zone offset Δ and longitude λ; C is the arc of a circumference 360°. Time offset and a factor $T/2 = 12\,\text{h}$ must be added to $t_w^{\uparrow\downarrow}$ to get WSR/WSS local times. For each subset sample average value, sample range and the variability expressed as twice sample standard deviation are listed; variability smaller than one hour are highlighted in blue ink. Shortest photoperiod and distance to Equator values appear in Figures 1. Shortest photoperiod is the predictor in Table III.

Sleep timing in industrial and pre-industrial societies

Country/People	Label	*Risetime*			*Wakeful noon*		*Bedtime*		
		to noon t_1	*to WSR* $t_1 - \beta D_w$	*WSA* z_w	*to noon* t_2	*to WSR* $t_2 - \beta D_w$	*to noon* t_3	*to WSR* $t_3 - \beta D_w - T$	*to risetime* $t_3 - t_1 - T$
NTUS/Industrial. Sample size, $N = 8$									
Denmark	DNK	−4.7 h	−1.2 h	−9°	3.5 h	7.0 h	11.0 h	−9.5 h	−8.3 h
Ireland	IRL	−4.4 h	−0.7 h	−6°	3.8 h	7.6 h	11.3 h	−8.9 h	−8.2 h
United Kingdom	GBR	−4.4 h	−0.6 h	−5°	3.4 h	7.2 h	10.9 h	−9.3 h	−8.7 h
France	FRA	−5.3 h	−1.1 h	−11°	2.7 h	6.9 h	10.0 h	−9.8 h	−8.7 h
Canada	CAN	−5.3 h	−0.9 h	−9°	2.9 h	7.2 h	10.4 h	−9.3 h	−8.3 h
Italy	ITA	−4.7 h	−0.2 h	−3°	3.1 h	7.6 h	10.6 h	−8.9 h	−8.7 h
Spain	ESP	−5.2 h	−0.6 h	−7°	3.0 h	7.6 h	10.6 h	−8.7 h	−8.2 h
United States	USA	−5.1 h	−0.4 h	−5°	2.9 h	7.6 h	10.2 h	−9.1 h	−8.7 h
Average	$E(\{y_i\})$	−4.9 h	−0.7 h	−7°	3.2 h	7.3 h	10.6 h	−9.2 h	−8.5 h
Range	$\Delta\{y_i\}_{\min}^{\max}$	55 min	59 min	8°	70 min	45 min	80 min	65 min	30 min
Variability	$2s(\{y_i\})$	46 min	42 min	5°	46 min	37 min	52 min	43 min	26 min
Pre-industrial/Hunter-gatherer (winter). Sample size, $N = 7$									
*Toba/Qom	TQE	−5.2 h	+0.1 h	1°	2.2 h	7.5 h	9.6 h	−9.0 h	−9.2 h
*Toba/Qom	TQN	−5.4 h	−0.0 h	−1°	1.6 h	7.0 h	8.6 h	−10.0 h	−10.0 h
†San	SAN	−5.9 h	−0.3 h	−5°	1.9 h	7.5 h	9.7 h	−8.7 h	−8.4 h
†Tsimane	TSI	−7.2 h	−1.6 h	−22°	0.8 h	6.4 h	8.7 h	−9.7 h	−8.1 h
†Chico Mendes	CMN	−6.9 h	−1.2 h	−17°	1.0 h	6.7 h	8.8 h	−9.4 h	−8.2 h
‡Chico Mendes	CME	−6.8 h	−1.0 h	−15°	1.4 h	7.1 h	9.5 h	−8.7 h	−7.7 h
†Hadza	HAD	−6.9 h	−1.0 h	−14°	1.2 h	7.2 h	9.4 h	−8.7 h	−7.7 h
Average	$E(\{y_i\})$	−6.3 h	−0.7 h	−10°	1.4 h	7.1 h	9.2 h	−9.2 h	−8.5 h
Range	$\Delta\{y_i\}_{\min}^{\max}$	120 min	103 min	23°	87 min	70 min	63 min	81 min	138 min
Variability	$2s(\{y_i\})$	99 min	78 min	18°	62 min	50 min	54 min	64 min	101 min
NTUS/Industrial and Pre-industrial (winter). Sample size, $N = 15$									
Average	$E(\{y_i\})$	−5.6 h	−0.7 h	−9°	2.4 h	7.2 h	10.0 h	−9.2 h	−8.5 h
Range	$\Delta\{y_i\}_{\min}^{\max}$	167 min	103 min	23°	185 min	74 min	162 min	81 min	138 min
Variability	$2s(\{y_i\})$	115 min	59 min	13°	119 min	45 min	102 min	52 min	69 min
Pre-industrial/Hunter-gatherer (summer, when different). Sample size, $N = 4$									
*Toba/Qom	TQE	−6.2 h			1.8 h		9.9 h		−7.9 h
*Toba/Qom	TQN	−6.3 h			1.2 h		8.7 h		−9.0 h
†San	SAN	−5.6 h			2.7 h		10.9 h		−7.5 h
†Tsimane	TSI	−7.9 h			0.6 h		9.0 h		−7.1 h
Average	$E(\{y_i\})$	−6.5 h			1.5 h		9.6 h		−7.9 h
Range	$\Delta\{y_i\}_{\min}^{\max}$	137 min			126 min		134 min		115 min
Variability	$2s(\{y_i\})$	117 min			107 min		120 min		99 min

Table II Sleep timing in NTUS/Industrial and in pre-industrial societies from (de la Iglesia et al., 2015) (starred), (Moreno et al., 2015) (double dagger) and (Yetish et al., 2015) (dagger). Pre-industrial labels ending in "E" (TQE and CME) stands for subgroups with access to electricity. Hadza people values are valid year round. Chico Mendes were collected in September to November. Wakeful noon times of pre-industrial people are the midpoints $(t_1 + t_3)/2$. Times are expressed in decimal hours as a distance to solar noon t_i or a distance to winter sunrise (WSR) $t_i - \beta D_w$. Risetimes also list winter solar altitude WSA. Bedtimes also list distance to next risetime. NTUS data are valid during winter time; one hour must be subtracted during summer time. For each subset sample average value, sample range and the variability expressed as twice sample standard deviation are listed; variability smaller than one hour are highlighted in blue ink. Values are displayed in Figure 1. Listed values are the response in regression analysis results shown in Table III.

Regression analysis for sleep timing in industrial and pre-industrial societies

Response	*Slope* m_s $\mathrm{min\,h^{-1}}$	*Confidence interval* CI β	*Pearson's coefficient* R^2	*Probabilistic value* p	*Possible outliers*
NTUS/Industrial and pre-industrial hunter/gatherer (winter), $N = 15$ $\lvert\phi\rvert$ *ranges from* 4° *to* 56°*;* D_w *ranges from* $12\,\mathrm{h}$ *to* $7\,\mathrm{h}$					
Risetimes to noon	$-30(11)$	$[-1.35, -0.64]$	0.74	$< 10^{-4}$	none
to WSR			$< 10^{-4}$	0.97	none
WSA	$-1.4(22)^\star$	$[-3.51, +0.80]^\star$	0.12	0.2	TSI
Wakeful noon times to noon	$-33.5(80)$	$[-1.38, -0.85]$	0.86	$< 10^{-6}$	TSI
to WSR			0.063	0.37	TSI
Bedtimes to noon	$-27.0(93)$	$[-1.21, -0.59]$	0.75	$< 10^{-4}$	TQN
to WSR			0.036	0.5	TQN
to risetimes	$3(12)$	$[-0.32, +0.51]$	0.019	0.63	TQN
NTUS/Industrial and pre-industrial hunter/gatherer (summer), $N = 15$ $\lvert\phi\rvert$ *ranges from* 4° *to* 56°*;* D_w *ranges from* $12\,\mathrm{h}$ *to* $7\,\mathrm{h}$					
Risetimes to noon	$-17(11)$	$[-0.92, -0.20]$	0.47	$< 10^{-2}$	SAN TSI
Wakeful noon times to noon	$-16(10)$	$[-0.89, -0.20]$	0.48	$< 10^{-2}$	SAN
Bedtimes to noon	$-6(12)$	$[-0.61, +0.22]$	0.072	0.33	SAN
to risetimes	$11.0(95)$	$[+0.05, +0.68]$	0.33	0.026	TQN TSI
NTUS/Industrial only, $N = 8$ $\lvert\phi\rvert$ *ranges from* 39° *to* 56°*;* D_w *ranges from* $9\,\mathrm{h}$ *to* $7\,\mathrm{h}$					
Risetimes to noon	$-17(19)$	$[-1.20, +0.09]$	0.42	0.08	none
to WSR			0.32	0.14	none
WSA	$0.8(29)^\star$	$[-2.09, +3.74]^\star$	0.074	0.51	none
Wakeful noon times to noon	$-19(18)$	$[-1.22, -0.05]$	0.54	0.038	FRA
to WSR			0.28	0.18	FRA
Bedtimes to noon	$-19(22)$	$[-1.37, +0.08]$	0.44	0.072	FRA
to WSR			0.19	0.28	FRA
to risetimes	$-3(14)$	$[-0.57, +0.39]$	0.035	0.66	none

Table III Multiple linear regression analysis for sleep timing. Predictor is always shortest photoperiod D_w. Parentheses display a symmetric confidence semi-interval at the standard level. Starred values (WSA) display units of degrees per hour. Slopes and confidence intervals for distance to WSR are obtained subtracting 30 and 1, respectively, to values listed for distance to noon. Probabilistic values smaller than the standard level $\alpha = 5\,\%$ are highlighted in blue ink. Possible outliers are data whose confidence interval of residual excluded zero at the standard level. Predictor is listed in Table I; responses are listed in Table II; both are on display in Figure 1.