Seasonal synchronization of sleep timing in industrial and pre-industrial societies

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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 across a wide range of angular distance to the Equator (0° to 55°) finds a remarkable accommodation in trends dominated by the light/dark cycle.

Daylight saving time (DST) in modern societies helps swinging synchronization through seasons. During standard time, winter sunrise synchronizes sleep timing in the observed range of angular distance to the Equator. That means sleep timing delays with increasing distance to the Equator. DST mitigates this delay and makes summer sleep timing is less influenced by distance to the Equator.

Keywords: sleep/wake cycle; sleep onset; time use survey; circadian rhythm; homeostatic sleep pressure; dst; daylight saving time; summer time; latitude; light/dark cycle; sunrise; sunset; photoperiod; scotoperiod

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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[1]. Wakefulness is associated to the photoperiod (light); sleep is associated to the scotoperiod (dark). Yet, they are distributed differently: sleep/wake shares are $2T/3$ (awaken), $T/3$ (sleeping); the LD shares are $T/2$ at the Equator.

It is a long understanding that artificial light and industrialization has reshaped human sleep/wake cycle[2]. To which extend is still a matter of discussion. Scheer *et al.*[3] showed that circadian misalignment induced by artificial light causes pathologies. It is also a wide concern that artificial light may have lead to sleep deprivation[4].

Collecting data from times when artificial light was not available is a difficult task. Instead, in the past few years three studies tried to understand the sleep timing in 21st century, pre-industrial societies with and without access to artificial light: Moreno *et al.*[5] studied communities in Acre (Brazil) and de la Iglesia *et al.*[6] in Formosa (Argentina). Also Yetish *et al.*[7] reported data of "natural sleep" in three pre-industrial, hunter/gatherer societies with no access to electricity located in Tanzania, Bolivia and the Kalahari Desert.

The LD cycle is also shaped by Earth's obliquity $\varepsilon = 23.5°$ —the angle between Earth's rotation axis and Earth's orbital axis— which gives rise to seasons, seasonal variations and make the absolute latitude (the angular distance to the Equator) play a role in the LD cycle. Understanding the role of latitude in human cycles is then an open issue[8–12]. Recently, Martín-Olalla[13] showed that primary activities in laborers aligned to winter sunrise and sunset, thus they were influenced by latitude.

This paper will analyze time use surveys in eight industrialized, mid-latitude countries to assess sleep timing in population aged 25 or more. Industrialized, mid-latitude 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 basic activities like sleeping, eating or working in a standard day. They are a fundamental tool for understanding social behaviour. A survey usually slices a day in ten minute ($T/144$) time-slots. For each time-slot all respondents are asked to indicate their main activity.

The daily rhythm of an activity is the number of respondents which reported doing the activity at a given time-slot scaled by the whole number of respondents (see Ref. [13] for a detailed description). Therefore a daily rhythm averages the myriad of individual decisions that shapes a society.

The daily rhythm of the sleep/wake activity looks like a smoothed rectangular function with the vast majority of respondents awaken at noon and sleeping by midnight. Two transitions —one in the morning, one at night (see Figure 1 in Ref. [13])— from the sleep to wake state and viceversa are observed.

A threshold located at half the range of the daily rhythm —which is close to 50 %— helps defining two timemarks which will characterize sleep timing in a modern society: (1) risetime or sleep offset t_1, the moment when the daily rhythm overshoots the threshold in the morning; and (2) bedtime or sleep onset t_3, the moment when the daily rhythm undershoots the threshold at night. Since t_1 and t_3 are extracted from the daily rhythm they can be viewed as an average of individual risetimes and bedtimes.

The quadrature of the daily rhythm computes the share of the activity in one day. A third timemark can be measured at the moment when half the quadrature has been consumed and half remains, for that purpose a day starts at 4am, when most of the individuals sleep. This timemark will be termed *wakeful noon time* t_2; it slightly differs from the midpoint of bedtime and risetime because the daily rhythm is slightly non-symmetrical.

This work will present the sleep timing from eight national time use surveys (NTUS, hereafter) —six in Europe[14–19]; two in America[20,21]—. Countries and number of respondents are listed on Table I.

Previous works by de la Iglesia *et al.*[6], Moreno *et al.*[5] and Yetish *et al.*[7] studied sleep timing in pre-industrial hunter-gatherer/horticulturalist societies. Moreno *et al.* reported sleep timing (Figure 1 in the reference) 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 in the reference) for the Toba/Qom people in the province of Formosa, the most equatorial region of Argentina. Yetish *et al.* reported (Table S2 in the reference) 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 the original references.

Time use surveys and studies on pre-industrial societies differ on some relevant issues. NTUS are large studies 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. On the other hand, pre-industrial studies refer to a 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.

Both data sets also differ in how seasonal variations are assessed. Yetish *et al.* and de la Iglesia *et al.* reported summer and winter sleep timing, whereas Moreno *et al.*[5] collected data in September to November; which in this work will be assigned year round. Time use surveys usually cover one year. Yet sleep timing only differ from spring-summer to autumn-winter in one time-slot at most, as measured by clock time. Seasonal variations of the sleep timing in industrialized societies are only induced by daylight saving time (DST)[22], 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.

The most challenging factor however is which subset of respondents of a national time use survey best fit to the reduced sample of hunter/gatherers. Differences between employees and non-employees are evident in modern societies. Also week days are notably different from week ends. In the following analysis time use surveys will be represented by weekly averaged values for population aged at least 25. Weekly average will sample weekday (Monday to Friday) and weekend (Saturday and Sunday) sleep timing with weights 5 and 2, respectively. However figures will show error lines ranging from laborers in a week day values —lower bound— to standard population in a week-end values —higher bound—.

II.2. Responses and predictors

In the forthcoming analysis sleep timing will be the response to characterize. Standard local time values can not be contrasted to the light/dark cycle. Instead natural gauges like time distance to solar noon, time distance to sunrise/sunset, or, eventually, the solar altitude relative to horizon are appropriate measures for testing against the LD cycle.

Winter photoperiod D_w —the shortest photoperiod of the year— 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 the 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) times are given by:

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

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

The boundaries of the LD 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 in 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, equinoctial sunrise and sunset times— which is exactly zero.

Also D_w reads the seasonal variation of 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 mean annual weekly averages of sleep timing in standard population of modern, industrial societies obtained from NTUS sleep/wake daily rhythms and winter sleep timing for pre-industrial hunter-gatherer societies[5–7]. Table III lists summer values: NTUS/Industrial values have been advanced by one hour following DST regulations; pre-industrial data are those of summer when available.

Both of these tables list countries/people in increasing values of D_w or decreasing values of $|\phi|$, following Table I. Also they show 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.

Sleep timing is presented in different ways through different columns. First, as a distance to solar noon, which only differs 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) or summer solar altitude (SSA) at risetimes. Finally, the time distance from bedtimes to the next risetime, a measure which is intrinsic to the sleep/wake cycle.

NTUS/Industrial sample variabilities always undershoot one hour, with bedtimes distance to risetimes hitting $2s = 23\,\mathrm{min}$; range amounts to $69\,\mathrm{min}$ at most (bedtimes). Contrastingly, pre-industrial variabilities generally exhibit a greater dispersion.

In winter (table II) descriptive statistics for the full set of data ($N = 15$) show huge variability for sleep times distance to noon $2s \sim 120\,\mathrm{min}$: there is not a unique sleep timing relative to noon. A trend is apparent: sleep timing advances (decreases) with decreasing $|\phi|$ or increasing D_w.

Such trend is not observed in the next column, which computes times as a distance to WSR. A unique sleep timing does exist for the full data set: risetimes occur $\sim 0.8\,\mathrm{h}$ before WSR; wakeful noon times occur $\sim 7.1\,\mathrm{h}$ after WSR and bedtimes occur $\sim 9.2\,\mathrm{h}$ before next WSR; within a variability smaller than one hour. This is a quite remarkable observation. In summer (table III) these results flip over: variabilities of sleep timing distance to noon are slightly smaller than those of sleep timing distance to WSR.

Figure 1 shows human sleep timing and the LD cycle. Top panel refers to winter, bottom panel to summer. All lines and background colors just highlight the LD cycle: lighter background is the photoperiod, darker background is the scotoperiod; dotted lines display winter altitude starting at $-18°$ (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, $m = +\beta$). Adjacent straight lines are all separated by one whole hour.

Upon this natural scenario, human sleep timing is displayed. Data points shows weekly averaged values (NTUS/Industrial, solid circles) and pre-industrial values (solid triangles). Error lines in NTUS/Industrial data range from laborers' sleep timing in a week day to standard population sleep timing in a week end. There is a significant variability in risetimes across different subset of population whereas bedtimes are quite more stable. It should also be noted that weekly averaged values (solid circles) depends on the shares of laborers in the subset of standard population. For week

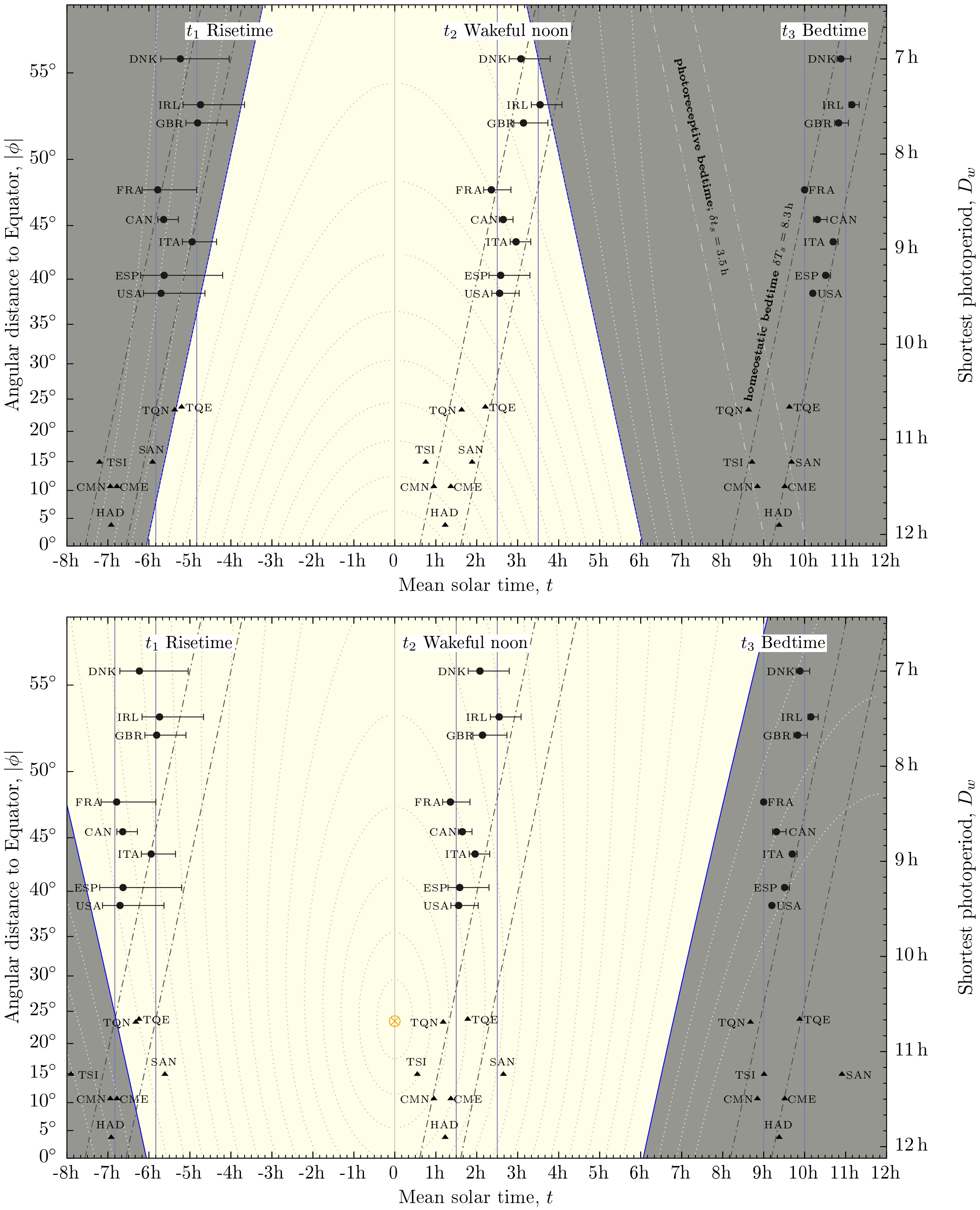

Figure 1. Sleep timing against shortest photoperiod in industrial and pre-industrial societies. Horizontal axis displays mean solar time (distance to solar noon), vertical axes display shortest photoperiod (right) and latitude (left). Top panel displays winter day; bottom panel, summer day. Lighter background is the photoperiod; darker background is the scotoperiod. Dotted line display solar altitude starting at $z = -18^\circ$ (outer most) in steps of 6°. The subsolar point ($z = 90^\circ$) 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, weekly averages for population aged at least 25) and triangles (pre-industrial/hunter-gatherer), which come from Moreno *et al.*[5] (Chico Mendes), de la Iglesia *et al.*[6] (Toba/Qom people) and Yetish *et al.*[7] (Hazda, San and Tsimane people). Horizontal error lines display sleep timing for laborers in a week day (low bound) to standard population in week-end (high bound). 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 (top) and Table III (bottom); regression analyses are summarized in Table IV.

days this share ranges from 40 % (Spain and Canada) to 66 % (Denmark) with average 49 % and standard deviation 8 %.

In winter (top panel) all timemarks fit into slanted boxes of one hour width which are synchronized to WSR. Risetimes are placed in the vicinity of WSR along a range 55°.

In summer (bottom panel) DST regulation pulls industrial values one hour to the left, which decreases the delay in human activity induced by the delay in WSR as D_w decreases. Toba/Qom people also exhibit this behaviour albeit without DST regulation. As a result risetimes and wakeful noon times can not be placed in one-hour width slanted boxes. On the contrary they fit to vertical boxes, specially bedtimes which are mostly located from 9pm to 10pm irrespective of the distance to Equator.

The preceeding arguments mostly describe the univariate properties of sleep timing and its placement across the LD cycle. The next step is computing bivariate correlations in which D_w is the predictor —notice however it is displayed on the vertical axis in Figure 1— and weekly averaged sleep timing is the response. Table IV shows the results for multiple linear regression analyses. It should be stressed that no regression results are displayed on Figure 1 which, for the sake of simplicity, only shows natural lines.

For responses relative to noon Table IV shows slope m_s (first column) and confidence intervals CI (second column). The numerical values are given in units of minutes per hour (m_s) and in units of $\beta = 30\,\mathrm{min\,h^{-1}}$ (CI). Slopes and confidence intervals for timemarks relative to WSR can be obtained by subtracting $30\,\mathrm{min\,h^{-1}}$ and 1 to the numerical values listed for the corresponding timemark relative to noon, but they do not appear on the table.

If CI contains $m = -1$, $m = 0$ or $m = +1$ then WSR, noon or WSS is a likely synchronizer for the response. In that case, the p-value (third column) will exceed the standard level —and that is highlighted in blue ink in Table IV— and the null hypothesis "response does not depend on the predictor" will sustain at the standard level. The fourth column displays Pearson's coefficient, which essentially behaves in the opposite way to p-values. The last column shows possible outliers at the standard level: data whose confidence interval of residual for the full model excludes zero at the standard level.

For the full data set ($N = 15$) and in winter time, sleep timing relative to noon does not sustain the null hypotheses at the standard level. All p-values are smaller than 0.05 and the confidence interval excludes $m = 0$. Slopes hit values close to $-26\,\mathrm{min\,h^{-1}} \sim -5\beta/6$. On the contrary, timemarks relative to WSR and WSA at risetimes sustain their null hypotheses at the standard level, thus they are stationary with latitude as observed in Figure 1 (top). Finally bedtimes distance to risetimes also sustain the null hypothesis, meaning that the distribution of risetimes and bedtimes are statistically similar to each other.

Seasonal variations tend to make the distribution of sleep timings more alike in summer. Therefore in this season slopes decrease (in absolute value) to $-\beta/2$ when the response is risetimes ($m_s = -13(11)\,\mathrm{min\,h^{-1}}$) and wakeful noon times ($m_s = -14(10)\,\mathrm{min\,h^{-1}}$).

The advance of industrial bedtimes and the delay of some pre-industrial bedtimes makes them get a slope $m_s = -5(12)\,\mathrm{min\,h^{-1}} \sim -\beta/6$ so that the confidence interval contains $m = 0$. Therefore the null hypothesis for summer bedtimes distance to noon sustains at the standard level: they are stationary with distance to the Equator. Finally bedtimes distance to risetimes also sustain the null hypothesis.

NTUS/Industrial only data ($N = 8$) also get slopes close to $-\beta/2$. The confidence interval usually contains both the late synchronizer $m = -1$ and the noon synchronizer $m = 0$. Therefore the null hypothesis sustains for timemarks relative to noon and timemarks relative to WSR. This is also noted in Figure 1 (top) as NTUS data can be boxed in vertical and slanted strips; and in Table II observing the variability of NTUS data. The issue here is that in this subset the span of D_w is some two hours, hence the span of WSR, $\beta D_w \sim 1\,\mathrm{h}$. There is simply not enough range in the predictor to elucidate which synchronizer —noon or WSR— best explains data. However, WSA at risetimes sustains the null hypothesis and risetimes are located in the close vicinity of winter sunrise, suggesting that WSR plays a leading role.

IV. DISCUSSION

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

The first idea aligns the sleep/wake cycle to sunrise —the ancient time reference— not to noon —the modern time reference. Also that makes human bedtimes differ from natural sunset by at least $2T/3 - T/2 = T/6$ (four hours) at the Equator. Wakefulness during the scotoperiod is then preferred after sunset, and avoided before sunrise.

As people moved poleward in a tilted planet, the abhorrence for a sleep offset earlier than sunrise is dominated by the latest sunrise of the year (WSR) and its gradient $-\beta$. Within a gently range of latitudes, this constrain efficiently works and has not been reshaped by artificial light. It is only below $D_w \sim 7\,\mathrm{h}$ (or above 55°) that people must awake significantly before WSR as evidences based in the "sleep and other personal care" cycle suggest.[13,23]

WSR synchronization dominates sleep timing throughout the day. This suggest that sleep timing is regulated by a circadian mechanism like the homeostatic sleep pressure[24]. 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 start being dictated by winter sunset WSS.[13]

If sleep timing keep homeostaticly tied to WSR then human bedtimes increasingly deviate from WSS —therefore wakefulness during winter scotoperiod increases— as D_w decreases. Bedtimes are delayed from WSS by $T/6$ at the Equator; increasing with decreasing D_w at a rate 2β. Similarly wakeful noon times delay by $T/12$ from solar noon at the Equator; increases with decreasing D_w at a rate β. Here "delay" is not intended to mean circadian misalignment.

Pre-industrial, tropical bedtimes can be boxed in a one-hour slanted strip centered $\delta t_s = 3.5$ h after WSS, see dash-dot-dotted lines in Figure 1 (top). The strip is a plausible guess for bedtimes linked to a photoreceptive mechanism, like melatonin onset, which would shut down human activity. Within the range of pre-industrial latitudes this strip overlaps with an homeostatic bedtime centered 8.3 h before risetimes and tied to WSR, as observed in the figure. It is worthy to mention, though probably incidental, that Toba/Qom people with no access to electricity (TQN) lie in the photoreceptive strip, whereas Toba/Qom people with access to electricity (TQE) delay bedtimes by one hour (see Table II) and find accommodation in the homeostatic strip. It should also be mentioned that European countries —from $|\phi| = 60°$ to $|\phi| = 40°$— meet dinner time some three hours after WSS[13], within the photoreceptive strip shown in Figure 1 (top).

The centers of the homeostatic strip and the photoreceptive strip match to each other at $D_w \sim 11.25$ 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 these two mechanisms. The lack of efficient, cheap artificial light, temperature and intense physical labor at that time would have favored the photoreceptive mechanism; however, still in that case, its closeness to risetime would have played against if the homeostatic sleep pressure is a 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[25,26].

Summer day, that with the shortest scotoperiod, is the worst case scenario for natural sleeping. Evidence in Figure 1 (bottom panel) suggests people sleeping during the photoperiod is fine as long as it happens after sunrise, and avoided before sunset. It is the counterpoint to the winter preference, when wakefulness during the scotoperiod is preferred after sunset, but not before sunrise. Either case it is the late events (WSR and SSS) that shape the restrictions.

Human activity above $D_w \sim 11$ h (or $|\phi|$ below 20°) hardly notice the seasonal evolution of the sunrise/sunset times since they change by one hour at most. Yet, they may notice the seasonal variation of the photoperiod, which amounts to two hours. The only pre-industrial people below $D_w \sim 11$ h and hence prone to seasonal variation is the Toba/Qom people, living just over the Tropic of Capricorn where sunrise times sweep ~ 1.5 h from winter to summer. Correspondingly,[6] reported Toba/Qom summer risetimes advanced one hour relative to winter values. On the contrary, summer bedtimes delayed by 20 min (TQE) or did not change (TQN).

Interestingly enough NTUS/Industrialized risetimes exhibit the same degree of seasonal variation as in the Toba/Qom community: one hour, induced by DST. Yet lying at $D_w \sim 9.5$ h and below, sunrise times in NTUS/Industrial countries sweep 3 h to 5 h, depending on latitude. Moreover, NTUS/Industrial summer bedtimes also advance by one hour, induced by DST; in sharp contrast with the observation for the Toba/Qom people.

It is a question to understand if human activity at mid-latitude and in ancient times varied seasonally by a larger amount than present day one-hour variation. However risetimes can not easily swing from WSR to SSR below $D_w \sim T/3 = 8$ h (above $|\phi| \sim 50°$) where summer photoperiod amounts to $2T/3$. At that level tying risetimes too close to SSR would have led to sleep onset earlier than sunset, unless the sleep/wake cycle were segmented (naps). And as long as bedtimes required some delay relative to sunset, the critical level would have been closer to the Equator.

In any case one-hour seasonal variation was not an oddity in Europe once social timing started being tied to clocks. As early as 1810, the regulation 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)"[27]. The same regulation remains nowadays silent, only induced by DST. Both of them require of two unpleasant transitions, which are linked to our preference for (nonseasonal) clocks and for whole hours.

Mid-latitude seasonal variation of sleep timing operates reducing the delay in human sleep timing induced by the delay in winter sunrise as D_w decreases. Kantermann *et al.* argued[28] that DST is a geographical translocation which moves industrialized timing "equatorward". However it must be noted that it is the subsolar point —where the Sun is perceived in the zenith— that moves poleward in summer. A measure to note is subsolar latitude which lies within the hemisphere under test in summer, see the cross circle in Figure 1 (bottom). In winter it lies in the opposite hemisphere. As a result the daily maximum solar altitude $\max(z)$ —which always occurs at solar noon— monotonicly decreases in winter with increasing distance to the Equator while, in summer, $\max(z)$ is stationary at $|\phi| = \varepsilon$.[29] As a result summer day is not only less challenging to human activity but also more alike within this range of distance to the

Equator. It should not be a surprise that sleep timings were also more alike and close to meridional synchronization.

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) of the year. They accommodate the golden rule: a day —as perceived by the average person— shall not start before sunrise and shall not end before sunset. This rule is not broken in the observed range of latitudes and social development.

Artificial light notably impacted human activity increasing, for instance, night shifts, which rose concerns on the impact of circadian misalignment in human health. Also more than certainly artificial light impacted the way the average person handles her wakefulness during the scotoperiod, after sunset. Yet it did not break the golden rules, neither in winter nor in summer, as long as the angular distance to the Equator is not too large.

A question to address is whether sleep timing should sustain noon synchronization in winter (extending summer time year round), with winter risetimes increasingly advancing relative to sunrise as distance to the Equator increases; or it should sustain late synchronization in summer (extending winter time year round), with summer risetimes increasingly delaying from sunrise as distance to the Equator increases; or it should seasonally swing, in which case clock changing —which is on public debate in Europe and America— is an appropriate option for societies tied to clock.

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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 2ε, 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*	*Respondents*	*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* $\delta = \Delta - T\lambda/C$
NTUS/Industrial						
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		$\Delta\{x_i\}_{\min}^{\max}$	17.2°	148 min	74 min	66 min
Variability		$2s(\{x_i\})$	12.5°	107 min	54 min	47 min
Pre-industrial						
Toba/Qom[6]	TQE	10	23.8°	10.66 h	∓5.33 h	67 min
Toba/Qom[6]	TQN	10	23.3°	10.69 h	∓5.35 h	67 min
San[7]	SAN	10	14.9°	11.24 h	∓5.62 h	
Tsimane[7]	TSI	10	14.9°	11.24 h	∓5.62 h	
Chico Mendes[5]	CME	300	10.7°	11.50 h	∓5.75 h	−26 min
Hadza[7]	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		$\Delta\{x_i\}_{\min}^{\max}$	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		$\Delta\{x_i\}_{\min}^{\max}$	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 Moreno *et al.*[5], de la Iglesia *et al.*[6] and Yetish *et al.*[7]. 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 $T/2 = 12$ 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 IV.

Sleep timing in industrial and pre-industrial societies (winter)									
Country/People	Label	*Risetime* to noon t_1	to WSR $t_1-\beta D_w$	WSA z_w	*Wakeful noon* to noon t_2	to WSR $t_2-\beta D_w$	*Bedtime* to noon t_3	to WSR $t_3-\beta D_w-T$	to risetime t_3-t_1-T
NTUS/Industrial. Mean anual values. Winter time, no DST. Sample size, $N=8$									
Denmark	DNK	−5.1 h	−1.6 h	−12°	3.2 h	6.7 h	11.0 h	−9.5 h	−7.9 h
Ireland	IRL	−4.6 h	−0.8 h	−7°	3.5 h	7.3 h	11.2 h	−9.1 h	−8.3 h
United Kingdom	GBR	−4.7 h	−0.9 h	−7°	3.4 h	7.2 h	10.8 h	−9.3 h	−8.5 h
France	FRA	−5.5 h	−1.4 h	−13°	2.5 h	6.7 h	10.0 h	−9.8 h	−8.5 h
Canada	CAN	−5.3 h	−0.9 h	−9°	2.9 h	7.2 h	10.4 h	−9.2 h	−8.3 h
Italy	ITA	−4.9 h	−0.5 h	−5°	3.1 h	7.5 h	10.7 h	−8.8 h	−8.4 h
Spain	ESP	−5.0 h	−0.4 h	−5°	2.8 h	7.5 h	10.6 h	−8.7 h	−8.3 h
United States	USA	−5.3 h	−0.6 h	−7°	2.7 h	7.4 h	10.2 h	−9.1 h	−8.5 h
Average	$E(\{y_i\})$	−5.1 h	−0.9 h	−8°	3.0 h	7.2 h	10.6 h	−9.2 h	−8.3 h
Range	$\Delta\{y_i\}_{\min}^{\max}$	59 min	73 min	8°	64 min	53 min	69 min	65 min	36 min
Variability	$2s(\{y_i\})$	40 min	50 min	6°	43 min	40 min	47 min	42 min	23 min
Pre-industrial/Hunter-gatherer. Winter. Sample size, $N=7$									
Toba/Qom[6]	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[6]	TQN	−5.4 h	−0.0 h	−1°	1.6 h	7.0 h	8.6 h	−10.0 h	−10.0 h
San[7]	SAN	−5.9 h	−0.3 h	−5°	1.9 h	7.5 h	9.7 h	−8.7 h	−8.4 h
Tsimane[7]	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[7]	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[5]	CME	−6.8 h	−1.0 h	−15°	1.4 h	7.1 h	9.5 h	−8.7 h	−7.7 h
Hadza[7]	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. Sample size, $N=15$									
Average	$E(\{y_i\})$	−5.7 h	−0.8 h	−9°	2.3 h	7.1 h	10.0 h	−9.2 h	−8.4 h
Range	$\Delta\{y_i\}_{\min}^{\max}$	159 min	104 min	23°	167 min	70 min	151 min	81 min	138 min
Variability	$2s(\{y_i\})$	106 min	63 min	12°	110 min	44 min	100 min	51 min	69 min

Table II. Sleep timing in NTUS/Industrial (weekly averaged data for population aged 25 or more) and in pre-industrial societies from Moreno *et al.*[5], de la Iglesia *et al.*[6] and Yetish *et al.*[7]. Pre-industrial labels ending in "E" (TQE and CME) stands for subgroups with access to electricity. 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 show their winter solar altitude WSA. Bedtimes also include distance to next risetime. 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. Data are displayed in Figure 1 (top). They are the response in regression analysis results shown in Table IV.

Sleep timing in industrial and pre-industrial societies (summer)									
Country/People	Label	*Risetime*			*Wakeful noon*		*Bedtime*		
		to noon t_1	*to WSR* $t_1-\beta D_w$	*SSA* z_s	*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. Mean anual values. Summer time, DST. Sample size, $N=8$									
Denmark	DNK	−6.1 h	−2.6 h	18°	2.2 h	5.7 h	10.0 h	−10.5 h	−7.9 h
Ireland	IRL	−5.6 h	−1.8 h	22°	2.5 h	6.3 h	10.2 h	−10.1 h	−8.3 h
United Kingdom	GBR	−5.7 h	−1.9 h	21°	2.4 h	6.2 h	9.8 h	−10.3 h	−8.5 h
France	FRA	−6.5 h	−2.4 h	12°	1.5 h	5.7 h	9.0 h	−10.8 h	−8.5 h
Canada	CAN	−6.3 h	−1.9 h	14°	1.9 h	6.2 h	9.4 h	−10.2 h	−8.3 h
Italy	ITA	−5.9 h	−1.5 h	17°	2.1 h	6.5 h	9.7 h	−9.8 h	−8.4 h
Spain	ESP	−6.0 h	−1.4 h	15°	1.8 h	6.5 h	9.6 h	−9.7 h	−8.3 h
United States	USA	−6.3 h	−1.6 h	11°	1.7 h	6.4 h	9.2 h	−10.1 h	−8.5 h
Average	$E(\{y_i\})$	−6.1 h	−1.9 h	16°	2.0 h	6.2 h	9.6 h	−10.2 h	−8.3 h
Range	$\Delta\{y_i\}_{\min}^{\max}$	59 min	73 min	12°	64 min	53 min	69 min	65 min	36 min
Variability	$2s(\{y_i\})$	40 min	50 min	9°	43 min	40 min	47 min	42 min	23 min
Pre-industrial/Hunter-gatherer. Summer. Sample size, $N=7$									
Toba/Qom[6]	TQE	−6.2 h	−0.9 h	6°	1.8 h	7.1 h	9.9 h	−8.8 h	−7.9 h
Toba/Qom[6]	TQN	−6.3 h	−1.0 h	5°	1.2 h	6.5 h	8.7 h	−10.0 h	−9.0 h
San[7]	SAN	−5.6 h	+0.0 h	11°	2.7 h	8.3 h	10.9 h	−7.5 h	−7.5 h
Tsimane[7]	TSI	−7.9 h	−2.3 h	−19°	0.6 h	6.2 h	9.0 h	−9.4 h	−7.1 h
Chico Mendes[7]	CMN	−6.9 h	−1.2 h	−8°	1.0 h	6.7 h	8.8 h	−9.4 h	−8.2 h
Chico Mendes[5]	CME	−6.8 h	−1.0 h	−6°	1.4 h	7.1 h	9.5 h	−8.7 h	−7.7 h
Hadza[7]	HAD	−6.9 h	−1.0 h	−11°	1.2 h	7.2 h	9.4 h	−8.7 h	−7.7 h
Average	$E(\{y_i\})$	−6.7 h	−1.0 h	−3°	1.4 h	7.0 h	9.5 h	−8.9 h	−7.9 h
Range	$\Delta\{y_i\}_{\min}^{\max}$	137 min	137 min	30°	126 min	126 min	134 min	150 min	115 min
Variability	$2s(\{y_i\})$	86 min	80 min	22°	81 min	80 min	91 min	95 min	73 min
NTUS/Industrial and Pre-industrial. Sample size, $N=15$									
Average	$E(\{y_i\})$	−6.3 h	−1.5 h	7°	1.7 h	6.6 h	9.5 h	−9.6 h	−8.1 h
Range	$\Delta\{y_i\}_{\min}^{\max}$	140 min	157 min	41°	126 min	156 min	134 min	201 min	115 min
Variability	$2s(\{y_i\})$	73 min	82 min	25°	72 min	78 min	69 min	105 min	58 min

Table III. Sleep timing in NTUS/Industrial (weekly averaged data for population aged 25 or more) and in pre-industrial societies from Moreno *et al.*[5], de la Iglesia *et al.*[6] and Yetish *et al.*[7]. Pre-industrial labels ending in "E" (TQE and CME) stands for subgroups with access to electricity. 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 summer solar altitude SSA. Bedtimes also list distance to next risetime. 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. Data are displayed in Figure 1 (bottom). They are the response in regression analysis results shown in Table IV.

Regression analysis for sleep timing in industrial and pre-industrial societies					
Response	*Slope* m_s $\min \mathrm{h}^{-1}$	*Confidence interval* CI β	*Probabilistic value* p	*Pearson's coefficient* R^2	*Possible outliers*
NTUS/Industrial and pre-industrial hunter/gatherer. Winter (Table II), $N = 15$ $\lvert\phi\rvert$ *ranges from* $4°$ *to* $56°$; D_w *ranges from* 12 h *to* 7 h					
Risetimes to noon	$-26(11)$	$[-1.24, -0.49]$	$< 10^{-3}$	0.66	none
to WSR			0.46	0.043	none
WSA	$-0.8(22)^{\star}$	$[-3.05, +1.36]^{\star}$	0.42	0.05	TSI
Wakeful noon times to noon	$-30.6(80)$	$[-1.29, -0.75]$	$< 10^{-5}$	0.84	TSI
to WSR			0.88	$< 10^{-2}$	TSI
Bedtimes to noon	$-26.5(91)$	$[-1.19, -0.58]$	$< 10^{-4}$	0.75	TQN
to WSR			0.42	0.051	TQN
to risetimes	$0(12)$	$[-0.43, +0.40]$	0.94	$< 10^{-3}$	TQN
NTUS/Industrial and pre-industrial hunter/gatherer. Summer (Table III), $N = 15$ $\lvert\phi\rvert$ *ranges from* $4°$ *to* $56°$; D_w *ranges from* 12 h *to* 7 h					
Risetimes to noon	$-13(11)$	$[-0.79, -0.07]$	0.023	0.34	SAN TSI
Wakeful noon times to noon	$-14(10)$	$[-0.79, -0.11]$	0.014	0.38	SAN
Bedtimes to noon	$-5(12)$	$[-0.58, +0.23]$	0.37	0.063	SAN
to risetimes	$7.7(94)$	$[-0.06, +0.57]$	0.1	0.19	TQN TSI
NTUS/Industrial only, $N = 8$ $\lvert\phi\rvert$ *ranges from* $39°$ *to* $56°$; D_w *ranges from* 9 h *to* 7 h					
Risetimes to noon	$-10(20)$	$[-1.00, +0.33]$	0.27	0.2	none
to WSR			0.049	0.5	none
WSA	$1.6(29)^{\star}$	$[-1.37, +4.51]^{\star}$	0.24	0.22	none
Wakeful noon times to noon	$-16(18)$	$[-1.14, +0.04]$	0.064	0.46	FRA
to WSR			0.11	0.37	FRA
Bedtimes to noon	$-17(20)$	$[-1.24, +0.08]$	0.075	0.44	FRA
to WSR			0.17	0.29	FRA
to risetimes	$-7(10)$	$[-0.60, +0.10]$	0.13	0.33	DNK

Table IV. Multiple linear regression analysis for sleep timing in NTUS/Industrial (weekly averaged data for standard population) and in pre-industrial societies from Moreno *et al.*[5], de la Iglesia *et al.*[6] and Yetish *et al.*[7]. Predictor is always the shortest photoperiod D_w (see Table I). Responseses are listed in Table II (winter) and Table III (summer). Parentheses display a symmetric confidence semi-interval at the standard level $\alpha = 5\,\%$. Slopes are given in minutes per hour while confidence intervals are given in units of β, except for starred values (WSA) which display units of degrees per hour. Slopes and confidence intervals for distance to WSR can be obtained subtracting 30 and 1, respectively, to numerical values listed for distance to noon. Probabilistic values larger than the standard level 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 Tables II and III; both are on display in Figure 1.