Shifting chronotypes: Sleep patterns among adolescents living in industrial and pre-industrial environments

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Sleep patterns among adolescents living in industrial and pre-industrial environments

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Abstract

Using biosocial, cross-cultural, anthropological perspectives, this research compares sleep patterns of adolescents (aged 11-16) in one industrial society and two non-industrial societies in Mexico to help unravel evolutionary and cultural aspects shaping contemporary adolescent sleep. Specifically, this study examines whether the shift in the adolescent sleep-wake cycle reported among industrialized populations is replicated in non-industrialized societies with little access to electronic and/or electrical devices and whether sleep sufficiency is greater in non-industrial settings.

Adolescents (n=145) wore Motionlogger Micro Watch units for 24 hours over ten days and completed sleep diaries to obtain sleep measurements of sleep timing and duration. Data about the participant's sleep environment were assembled through semi-structured interviews and ethnographic observation. Information from the Pubertal Developmental Scale was used to discuss changes in adolescent sleep. The between-population variation in sleep measures was investigated by fitting different types of three-level models.

Pubertal development was associated with a delay in sleep timing during non-school days, and this was significant in all but one of the non-industrial sites. Sexual maturation was also associated with a shorter sleep duration during school nights, but no such association was identified for adolescents in the industrial site. Short sleep quotas were as prevalent in non-industrial-site teenagers as in their industrial-site counterparts. Sleep timing and duration were more responsive to natural light-dark cycles and social sleep in non-industrial settings.

Results provide novel evidence of flexible sleep-wake patterns in adolescents and highlight the influence of social activities on the expression of human sleep behaviour. Adolescent circadian plasticity might result from life-history trade-offs related to the switchover to future investment in reproduction. Circadian plasticity might have been advantageous in ancestral human environments, benefitting individual and group fitness. Any sleep interventions to improve contemporary adolescent wellbeing should address individual and community needs to develop more equitable and effective health policies and practices.

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Declaration and Statement of Copyright

The work presented in this thesis was developed at the Department of Anthropology at Durham University, United Kingdom. The material contained in this thesis has not been previously submitted for a degree elsewhere, and it is my own work except where otherwise noted in the text.

In Totonac houses, the moon enters the kitchen... it illuminates our dreams

Manuel Espinosa-Sainos, 2021-Totonac poet

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1. INTRODUCTION

Human adolescence is a unique phase of life history among mammalian species involving bio-psycho-socio-cultural changes that accompany the transition from childhood to adulthood (Bogin & Smith 1996; Arnett 2000; Goldberg 2001; Davey, Yücel & Allen 2008). This developmental stage presumably evolved in response to the growing complexity of human social organization (Bogin & Smith 1996). Adolescence is characterized as a sensitive period for brain remodelling and maturation (Davey, Yücel & Allen 2008; Asato, Terwilliger, Woo, *et al.* 2010; Blakemore, Burnett & Dahl 2010), and an adolescent phase would have enhanced reproductive fitness by allowing developing humans to acquire and practice cognitive abilities necessary to build the complex social skills that enable effective survival and parenting (Bogin & Smith 1996). In this sense, sleep constitutes a cornerstone for adolescent development, since it is linked with restorative functions, cognition and memory consolidation, energy conservation and affective processing (Worthman 2008; McNamara, Barton & Nunn 2009; Samson & Shumaker 2013; Barton & Capellini 2016). Nevertheless, the issue of how much sleep is enough for it to be functional and beneficial for human development is still unclear (Worthman 2008; Wolf-Meyer 2011).

As with many other human-life domains (e.g., eating, reproducing, breastfeeding, walking, running, laughing, playing, etc.), human sleep is a biocultural product (Mauss 1973; Worthman & Melby 2002). Within the paradigmatic framework used by sleep researchers and sleep medicine, the cultural and individual flexibility of sleep is commonly regarded as a deviation of the "natural" (i.e., genetic) physiological, behavioural and biochemical sleep parameters (Horne 2011; Wolf-Meyer 2011; Touitou 2013; Rutters, Lemmens, Adam, *et al.* 2014). Although a good night's sleep is undeniably important for human health and wellbeing, researchers from a range of disciplines have posited that clinical and public health practitioners advocate ideal sleep parameters based on Western cultural assumptions and practices and, thus, fail to reflect on sleep adaptability to environmental cues, pressures and constraints (Ekirch 2005; Meadows 2005; Worthman 2008; Galinier, Monod Becquelin, Bordin, *et al.* 2010; Horne 2011; Wolf-Meyer 2011; Glaskin & Chenhall 2013; Ball 2017).

Re-examining the nature of sleep through a cross-cultural perspective represents one way to better inform sleep nuances (Glaskin & Chenhall 2013; Worthman & Brown 2013), and therefore, broaden our understanding of human development and evolution. Comparative studies of sleep ecology are required to understand, not only the structural and cultural factors shaping adolescent sleep, but also their potential interrelationship with functional and dysfunctional health outcomes (Worthman 2008; Horne 2011).

Using biosocial, cross-cultural, anthropological perspectives, this research is oriented to better understand the nuances of sleep by re-examining current assumptions of adolescent "natural" sleep. Undertaking field research in one industrial and two non-industrial societies in Mexico to inform sleep ecological parameters and sleep behaviour patterns, I examined three main issues advanced by sleep studies in contemporary, industrialized societies, namely whether: 1) the reported phase delay in adolescent sleep-wake cycles--characterized by increasingly later times for sleep onset and wakening--is replicated across cultures (Thorleifsdottir, Björnsson, Benediktsdottir, *et al.* 2002; Ohayon, Carskadon, Guilleminault, *et al.* 2004); 2) access to electric light and electronic devices has shifted the natural timing and duration of human sleep (Peixoto, da Silva, Carskadon, *et al.* 2009; Touitou 2013; Touitou, Touitou & Reinberg 2017); and 3) social and cultural demands faced by adolescents for time, energy and attention may be altering natural circadian rhythms and preventing optimal sleep quotas, facilitating unhealthy patterns of sleep deprivation (Carskadon 2011; Touitou 2013; Castilhos Beauvalet, Quiles, Braga de Oliveira, *et al.* 2017).

Three general questions guided the research: i) Do early adolescents in non-industrialized and industrialized societies go through a sleep phase delay? ii) Do adolescents in non-industrialized and in industrialized societies experience sleep deprivation? And, iii) How might characteristics such as working/schooling, access to electronic media, daily exposure to natural light, and the practice of social sleep alter the timing and duration of adolescent sleep? The resulting thesis, structured as a collection of papers, has six chapters, an overall reference section and an appendix section.

The current introduction serves as a preamble to the work presented and provides an outline of its structure. The second chapter presents the rationale for the study and the general aims of the research. The third chapter describes the methodological tools used during fieldwork, the locations in which it was carried out, and the study groups. Along with the study design, protocol, and data collection, this section provides details regarding the data processing and statistical methods.

Chapters 4 and 5 are composed of two research papers prepared for publication submission presenting the study results. Chapter 4, which will be submitted to *Nature Ecology & Evolution*, addresses adolescent sleep timing and examines whether the shift in reported sleep-wake cycles of adolescents in industrialized populations is replicated in non-industrialized societies. Chapter 5, which is prepared for submission to *Scientific Reports*, focuses on sleep duration and tests the idea that “modern” lifestyles and technological advances are associated with sleep insufficiency in adolescents. In addition, these chapters investigate the influence of sexual maturation, natural and artificial light, and social sleep practices on adolescents' sleep timing and duration, respectively. References, figures, tables and supplementary information for each research paper are provided at the end of their corresponding chapters.

Lastly, Chapter 6 presents the overall conclusions of this study, discusses its strengths and limitations, and indicates directions for future research. The final reference section provides a complete list of the bibliographic sources cited in the thesis. The appendices section contains the sleep diary, the interview guide, the standardized questionnaires, the Information sheet and the Consent form employed in this study.

2. BACKGROUND

Sleep is characterized as an amalgam of physiologic and behavioural processes that complete the vital functional overview of human circadian cycle (Carskadon & Dement 2011); its hallmark being a reversible perceptual disengagement from the environment, as well as unresponsiveness to it (Tononi & Cirelli 2014). Sleep deprivation studies in human and non-human models have proven he importance of sleep for human wellbeing. Lacking even one day's sleep, we become emotionally irritable, tired and our cognitive functions are impaired (Walker & Stickgold 2006; Worthman 2008). Chronic sleep deprivation can lead to metabolic disorders, depression, immune dysfunctions, and chronic disease while complete sleep deprivation leads to death (Institute of Medicine 2006). On the other hand, a good night's sleep is linked with restorative functions, cognition and memory consolidation, energy conservation and improved affective processing (Worthman 2008; Walker 2009; Samson & Shumaker 2015; Barton & Capellini 2016).

Adult human sleep is composed of two states that alternate cyclically over a sleep episode: rapid eye movement (REM) sleep and non–REM (NREM) sleep (Institute of Medicine 2006). A cornerstone notion in sleep studies is "sleep architecture", which refers to the quantitative structure of sleep as much as to the sleep patterns (Nunn, Samson & Krystal 2016). Hence, it includes variables pertaining to the amount of time spent in NREM and REM sleep, the duration of the NREM-REM cycles, the total sleep duration (sleep quotas), and the way in which sleep is distributed and organized across the 24-h period (phasing of sleep) (Capellini, Preston, McNamara, *et al.* 2010; Nunn, Samson & Krystal 2016). Importantly, human sleep patterns result from the complex interplay of distinct processes, including the circadian and homeostatic sleep regulatory mechanisms, the sleep entrainment to socioecological cues, maturation and development, and behavioural phenomena (Carskadon 2002; Touitou 2013).

With the aim of reviewing adolescent sleep, the next sections will provide an overview of the sleep structure and the sleep mechanisms relevant to the aims of this research, followed by an outline of current views on adolescent sleep.

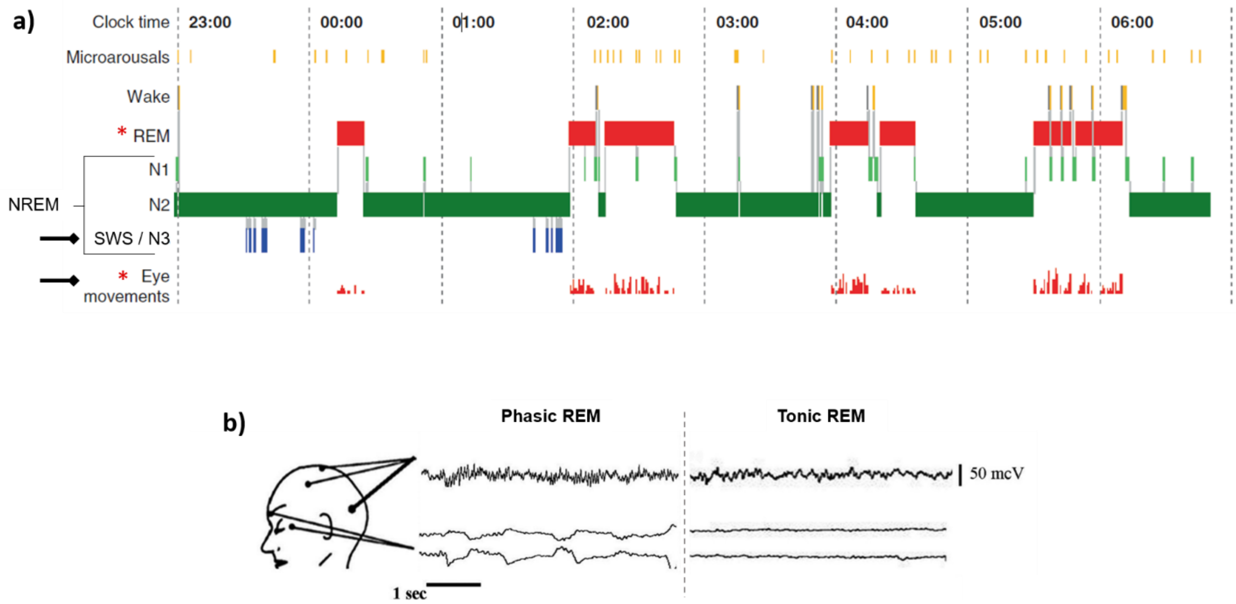


Figure 1. a) Sleep histogram representing the progression of human sleep stages throughout the night in a healthy adult (Riemann, Krone, Wulff, *et al.* 2020). Slow-wave sleep (SWS) and eye movements (indicative of phasic REM sleep) are signalled as the stages with higher arousal thresholds. b) Neuronal and muscular electrical activity during phasic and tonic REM sleep as recorded by electroencephalographic (EEG) and electrooculographic (EOG) measurements in a healthy adult (Campana, Zubler, Gibbs, *et al.* 2017). Phasic REM is characterized by rapid eye movements, cardiorespiratory variability, and distal muscle twitches. Tonic REM has no eye movements, atonia, and decreased EEG amplitude.

2.1 Sleep architecture

NREM and REM sleep are defined by specific physiological and behavioural characteristics (Worthman 2008). NREM sleep is characterized by stages N1, N2 and N3 (Samson & Nunn 2015). NREM depth-of-sleep is ascertained by the arousal thresholds detected during stages N2 and N3, being lowest in N2 and highest in N3 (Samson & Nunn 2015). The intensity of sleep is indicated by the amount of slow wave activity during NREM sleep (delta, ~0.5-4.5 Hz) (Hummer & Lee 2016). Interestingly, N3 not only has the highest arousal threshold but also the highest proportion of delta wave activity (Carskadon & Dement 2011). Consequently, stage N3 is also referred to as deep sleep or slow-wave sleep (SWS) (Samson & Nunn 2015).

Named after the periodic appearance of rapid eye movements, REM is largely associated with dreaming (Nir & Tononi 2010). REM sleep is subclassified into tonic and phasic REM. In a similar way to NREM stages N2 andN3, arousal thresholds are lower in tonic sleep and higher in phasic sleep (Ermis, Krakow & Voss 2010). Usually, a human young adult would experience four to six REM episodes while sleeping during the night, with each episode lengthening across the night (Carskadon & Dement 2011) (Figure 1).

2.2 Circadian and homeostatic sleep

The circadian and the homeostatic regulatory mechanisms of sleep are independent but interacting processes (Figure 2). These mechanisms, also known as process C, for circadian, and process S, for sleep pressure, are characterized below:

Process C

The circadian process (Process C) is capable of running in an autonomous manner along periods of 24-24.5 hours (Mendoza 2007; Hofstra & de Weerd 2008; Hummer & Lee 2016). This process relies on the activity of the hypothalamic suprachiasmatic nuclei (SCN), which drives an internal time-keeping system that promotes wakefulness at certain times of the day (Hummer & Lee 2016). Along with the sleep-wake cycle, the SCN generates and maintains other psychological and physiological daily rhythms, including feeding, blood pressure, hormones synthesis and secretion (such as melatonin and cortisol), core body temperature and task performance (Committee on Improving Birth Outcomes 2003; Hofstra & de Weerd 2008; Hummer & Lee 2016). In particular, the melatonin secretory cycle is key for inducing sleep. Under day-night conditions, melatonin levels stay low during daytime and increase after darkness onset, reaching its peak between 23:00h and 3:00h and falling steeply before light onset (Hofstra & de Weerd 2008). Melatonin secretion is suppressed by light but, under constant darkness conditions, its cycle continues to run (Institute of Medicine 2006; Hofstra & de Weerd 2008). Still, normally the endogenous SCN activity will synchronize with exogenous environmental cues (known as zeitgebers, meaning time-givers in German), adjusting or entraining the circadian rhythms to our 24-hour daily cycle (Touitou 2013).

Zeitgebers

Light is the most powerful zeitgeber known (Roenneberg, Wirz-Justice & Merrow 2003). When interacting with our circadian mechanism at certain times of the day, light has important phase-shifts effects, not only by suppressing melatonin but also by triggering alertness (Mendoza 2007; Horne 2011; Hummer & Lee 2016). Its greater entraining impact happens at dawn and dusk, having a lesser impact at midday (Hummer & Lee 2016). On the other hand, overexposure to light at early night will evoke phase delays while light exposure at late night will elicit phase advances (Mendoza 2007). In addition to the aforementioned temporal conditions, the magnitude of response to light exposure also depends on its intensity, wavelength, pattern, and duration (Hofstra & de Weerd 2008; Roenneberg, Wirz-Justice & Merrow 2003).

Additional examples of zeitgebers are external temperature, the demands related to feeding, reproduction, rearing, and the avoidance of life-threatening or harmful situations (e.g., predators, human assaults, etc.) (Institute of Medicine 2006; Capellini, Barton, McNamara, *et al.* 2008). This means that, under certain ecological conditions, humans shift their daily cycles in order to survive, changing their sleep timing as well as its duration (Horne 2011; Capellini, Barton, McNamara, *et al.* 2008). As individuals, each of us presents a certain entrainment phase to our environment termed chronotype (Castilhos Beauvalet, Quiles, Braga de Oliveira, *et al.* 2017). Our personal entrainment is derived from a combination of genetic, development and environmental factors (Roenneberg, Wirz-Justice & Merrow 2003; Castilhos Beauvalet, Quiles, Braga de Oliveira, *et al.* 2017).

Chronotypes

Circadian types or chronotypes vary from extreme early (morning-types or larks) to extreme late (evening-types or owls) (Castilhos Beauvalet, Quiles, Braga de Oliveira, *et al.* 2017). Most individuals have no strong preferences for extreme sleep-wake schedules, and are therefore considered intermediate or midrange chronotypes (Lack, Bailey, Lovato, *et al.* 2009; Castilhos Beauvalet, Quiles, Braga de Oliveira, *et al.* 2017). Presumably, chronotypes are easier to distinguish during free (non-work or non-school) days, when individuals are able to decide their own sleep-wake schedules in the absence of external social pressures

(Castilhos Beauvalet, Quiles, Braga de Oliveira, *et al.* 2017). Compared to morning-type individuals, owls will have later sleep-wake schedules, later diurnal peaks of alertness and later sleep onsets (Hofstra & de Weerd 2008). Furthermore, extreme owls will experience a greater sleep inertia, defined as the time it takes the individual to feel fully awake (Roenneberg, Wirz-Justice & Merrow 2003). Such differences are mostly driven by differences in the rhythm timing of core body temperature, melatonin, and cortisol (Lack, Bailey, Lovato, *et al.* 2009).

According to Roennenberg et al (2003), chronotype variability in a population may be greater or lesser depending on the amount of sunlight exposure; the longer the exposure, the narrower the chronotypes distribution. Based on this idea, it has been argued that rural lifestyles, with greater exposure to sunlight, favour narrow chronotype distributions (Roenneberg, Wirz-Justice & Merrow 2003). Recent studies among Hadza hunter-gatherers and an agricultural society in Madagascar support this idea, although research in high-latitude environments is advocated for better informing variability in sleep-wake patterns (Samson, Crittenden, Mabulla, *et al.* 2017b; Samson, Manus, Krystal, *et al.* 2017).

Still, our sleep is not solely shaped by exposure to light or other zeitgebers. An individual's previous sleep-wake history is a central aspect of sleep regulation as well (Hummer & Lee 2016). This history is the basis of the homeostatic sleep mechanism.

Process S

The homeostatic process (Process S or sleep pressure) is responsible for our need or drive to sleep (Hummer & Lee 2016). This drive rises during wakefulness and dissipates during sleep (Hummer & Lee 2016), working independently from the time of the day, eliciting and diminishing the need to sleep in direct proportion to the length and amount of prior wakefulness or sleep (Carskadon 2011). No neuroanatomical locus has been identified for homeostatic sleep (Carskadon 2011). Instead, a connection between metabolite clearance and sleep pressure has been suggested, according to which sleep enhances the removal of toxic metabolites built up during wakefulness in the central nervous system (Xie, Kang, Xu, *et al.* 2013; Weljie, Meerlo, Goel, *et al.* 2015). In this sense, Process S activity resembles a debt accumulation with the more time spent without sleep, the greater the need (Samson & Nunn 2015).

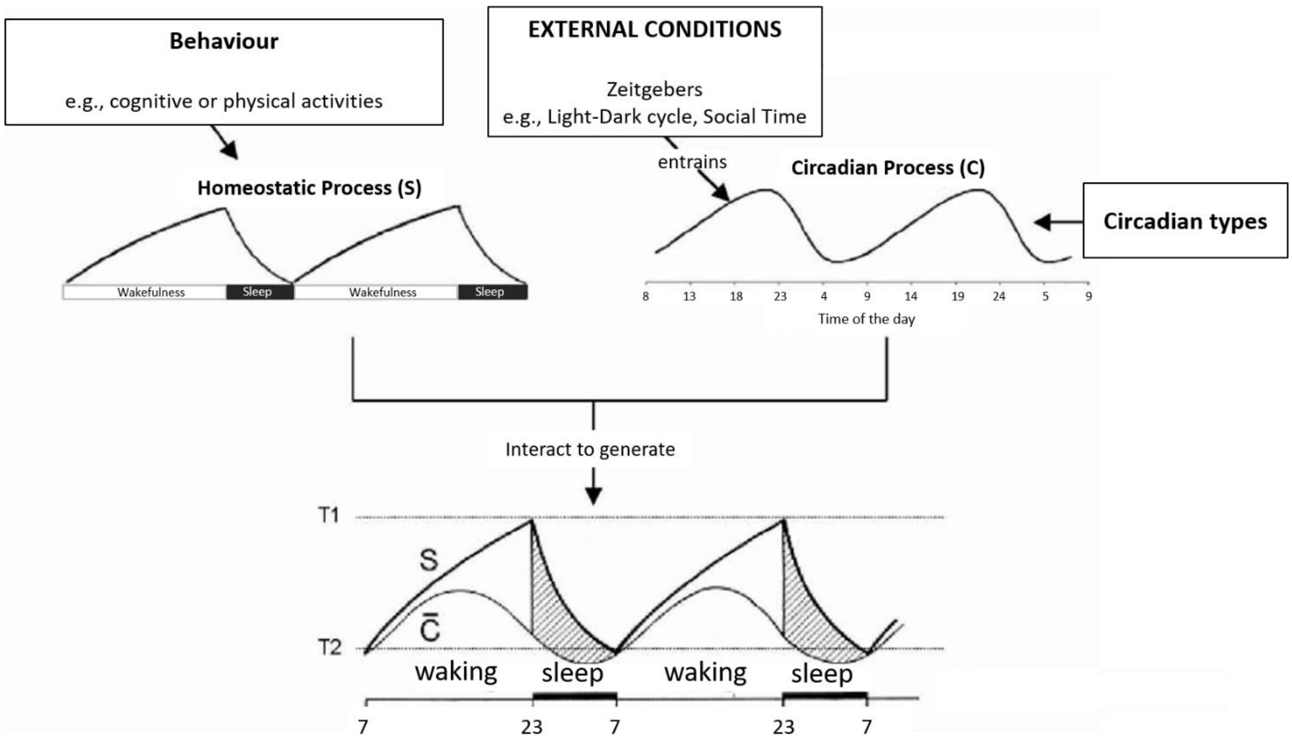


Figure 2. Representation of the circadian and the homeostatic regulatory mechanisms of sleep (Schmidt, Collette, Cajochen, *et al.* 2007). The circadian process (C) modulates the thresholds (T1and T2), delimiting the homeostatic process (S).

After experiencing great sleep pressure (homeostatic load) our sleep architecture will normally present with an increased duration of SWS, a bigger proportion of delta waves and a quicker sleep onset (Carskadon & Dement 2011; Hummer & Lee 2016). This means that, depending on the homeostatic load, sleep may gain or lose depth, intensity and onset speed (Hummer & Lee 2016; Samson & Nunn 2015). Accordingly, speed in falling asleep and daytime sleepiness are employed as markers for assessing sleep pressure (Hummer & Lee 2016).

Experimental studies involving sleep restriction revealed that, after total or partial sleep deprivation during one or several days, subsequent sleep not only gains onset speed, depth and intensity, but also duration (McNamara & Auerbach 2010; Blunden & Galland 2014). This phenomenon (sleep rebound) has been interpreted as an effort to compensate for lost sleep (McNamara & Auerbach 2010). It is generally agreed that the extended duration of sleep rebound is proportional to the extent of sleep loss (Blunden & Galland 2014), which under this reasoning would constitute a sleep debt.

The sleep debt notion is built upon the assumption that there exists an optimal baseline amount of sleep needed for healthy bodily functioning and performance (Blunden & Galland 2014). However, calculating optimal sleep quotas is not straightforward considering that daily sleep duration is normally distributed in a healthy adult population and sleep architecture will inevitably vary along the lifespan in as much as the body-environment interplay is a dynamic process (Horne 2011). Thus, the issue of what are the limits of sleep variation beyond which it becomes unhealthy draws much scientific debate (Wolf-Meyer 2011).

2.3 Adolescent sleep architecture

Human growth and development involve physical, neurobiological, psychological and social changes (Colrain & Baker 2011). Consistently, sleep architecture (and even dream features) expresses substantial changes across lifespan (Carskadon 2002; Nir & Tononi 2010). Most of what is known about sleep changes related to human ontogeny come from laboratory studies and survey studies performed in industrial populations from Europe, Asia, North America and Australia (Worthman & Melby 2002; Ohayon, Carskadon, Guilleminault, *et al.* 2004; Colrain & Baker 2011). That is to say that current knowledge of sleep development is based on data from WEIRD and WEIRD-like societies (Western, Educated, Industrial, Rich, Democratic).

Because the focus of this PhD is on adolescent sleep, attention is drawn towards sleep changes during this developmental period. It should be noted that, as adolescence is a bio-psycho-socio-cultural category designating the transition from childhood to adulthood (Arnett 2000; Davey, Yücel & Allen 2008), there is no agreement on what changes either mark the beginning and end of adolescence or characterise stages of adolescent development (namely, pre, early, mid and late) (Hummer & Lee 2016). This PhD uses puberty as a reference point to discuss the changes in adolescent sleep.

Puberty and brain development

In humans, pubertat onset is signalled by the activation of the hypothalamic-pituitary-gonadal-axis, while its end is defined by the completion of gonadal maturation (Colrain & Baker 2011). This developmental stage usually begins earlier for females (ages 8-14 years), than for males (ages 9-15 years) (Colrain & Baker 2011). Although puberty is most known by a growth spurt and the development of secondary sexual characteristics, there are also important neurophysiologic changes happening, presumably corticoid-dependent (Richardson & Tate 2002).

During adolescence the brain shifts from being highly plastic, interconnected and high in energy use, to be faster at processing, more efficient and with lower energy use (Colrain & Baker 2011). This shift results from an important synaptic pruning and increase in myelination, a process that eliminates infrequently used neural connections and strengthens those frequently used (Davey, Yücel & Allen 2008). These changes are regional-specific, generally following a posterior-anterior progression where motor and primary sensory areas develop earlier than association ones (Davey, Yücel & Allen 2008; Colrain & Baker 2011).

Adolescent brain development ends in the third decade of life (Davey, Yücel & Allen 2008). The completion of the maturation and remodelling of the dopaminergic reward system and the prefrontal cortex is a milestone in adolescent development for they are key for the pursuit of non-immediate rewards and the acquisition of complex social skills (Bogin & Smith 1996; Davey, Yücel & Allen 2008). Such features enable the adaptation to increasingly complex social milieus (Davey, Yücel & Allen 2008).

Adolescent sleep duration

According to existing evidence, normal sleep total duration ranges between 8.5-10 hours in children (5 years old onwards) (National Sleep Foundation 2000; Institute of Medicine 2006; Touitou 2013) and between 7-9 hours in adults (18-40 years old) (Ohayon, Carskadon, Guilleminault, *et al.* 2004; Horne 2011). Notably, adolescents sleep as much as children on their free days, suggesting that their sleep requirements do not change until they become young adults (Ohayon, Carskadon, Guilleminault, *et al.* 2004). This seems counterintuitive, since, on the other hand, on school nights adolescents typically express a progressive shortening of their sleep of up to 2-3 hours (Carskadon 2011; Gradisar, Gardner & Dohnt 2011; Touitou 2013). This shortening is driven, not by lesser sleep requirements, but by convergent biological, psychological and socio-cultural factors (Carskadon 2011).

Changes in sleep phasing and homeostatic pressure of sleep

Researchers have identified a shift in adolescent sleep patterns that is potentially associated with sexual and cognitive maturation (Hummer & Lee 2016). It appears that the sleep-wake cycles of adolescents in many countries in Europe, Asia, North America and in Australia undergo a phase-delay expressed through increasingly later times for sleep onset and wakening (Loessl, Valerius, Kopasz, *et al.* 2008; Ouyang, Lu, Wang, *et al.* 2009; Gradisar, Gardner & Dohnt 2011; Touitou 2013). Along with this delay, around age 13 adolescents express a chronotype shift towards eveningness (Colrain & Baker 2011), returning to morningness in the third decade of life (Crowley 2013; Touitou 2013). Corresponding to sex differences in puberty onset, females begin and reach the greatest magnitude of the chronotype shift at younger age than males (Hummer & Lee 2016). On the other hand, adolescent males usually exhibit a more extreme preference for late sleep-wake schedules (Hummer & Lee 2016).

The changes in adolescents' endogenous clock could be explained by changes in their intrinsic circadian period (i.e., internal day light length) or by alterations in their sensitivity to light (Carskadon 2011). In this regard, it has been observed that during adolescence, there exists a "diluted" melatonin secretion that could be affecting sleep timing (Carskadon 2002;

Touitou 2013). However, there is no clear evidence-based support for these explanations (Hummer & Lee 2016). Instead, changes in the homeostatic mechanisms regulating sleep pressure appear to underlie this adolescent phase-delay (Carskadon 2011; Hummer & Lee 2016) as a less robust build-up of sleep pressure has been documented during waking hours (allowing adolescents to stay up longer); while a less robust decay occurs during sleep (permitting adolescents to sustain their sleep later in the morning) (Hummer & Lee 2016).

Additionally, behaviourally induced changes in the timing and/or amount of light exposure can enable the adolescent phase-delay (Carskadon 2011). Explicitly, an increased exposure to blue-light coming from the display screens of electronic media devices (television, computers, tablets, or mobile phones) in the early night can block melatonin secretion and, in turn, delay sleep onset (Touitou, Touitou & Reinberg 2017). Likewise, a decreased exposure to sun light in the early morning due to sleeping areas shielded from environmental cues prevents adolescent circadian entrainment to day-night cycle (Worthman & Melby 2002).

From the above, it becomes clear that, in the case of “modern” societies, adolescent sleep patterns arise from the numbness or override of their circadian clock due to homeostatic and socio-cultural influences. Such disruptions have fuelled a myriad of studies, boosting the emergence of a research field focused on examining what is currently termed as social jetlag (SJL) (Castilhos Beauvalet, Quiles, Braga de Oliveira, *et al.* 2017).

The social jetlag hypothesis and adolescent sleep loss

The term social jetlag was initially coined by Wittman et al (2006) and is now used to refer to the misalignment between the endogenous circadian clock, and the social clock (i.e., social zeitgebers) which is dependent on school schedules, social activities and individual choice (Wittmann, Dinich, Merrow, *et al.* 2006; Carskadon 2011; Gradisar, Gardner & Dohnt 2011; Touitou 2013; Rutters, Lemmens, Adam, *et al.* 2014; Castilhos Beauvalet, Quiles, Braga de Oliveira, *et al.* 2017). It is called a misalignment because the social clock does not necessarily match the day-light cycle, which is the main circadian entrainer. This is particularly true in industrial societies, characterized by access to electric lights that enable continued activity until late night, as well as by its sedentary, indoors lifestyle, shielded from environmental changes relative to temperature, humidity, noise, wind and moon/sun light (Worthman & Melby 2002).

Importantly, it has been observed that, although the social clock is key for setting the beginning and the end of our waking life, its strength as a zeitgeber is not enough to advance our circadian clock (ergo, our phase of sleep) (Roenneberg, Wirz-Justice & Merrow 2003). This becomes relevant for evening chronotype people, who must adapt to societies that schedule their daily activities according to morning chronotype wake-sleep patterns (Roenneberg, Wirz-Justice & Merrow 2003). Due to their endogenous circadian preference, evening types will continue to express a late sleep onset, while complying with a "forced" early awakening (Rutters, Lemmens, Adam, *et al.* 2014). The result is a chronic sleep debt expressed in excessive daytime sleepiness, and in a sleep rebound whenever the opportunity arises (Wittmann, Dinich, Merrow, *et al.* 2006).

Given the aforementioned scenario, “modern” adolescents, who are oriented towards a late chronotype and must comply with early-morning schooling schedules, are especially vulnerable to sleep deprivation (Carskadon 2011). This vulnerability grows amidst an increasingly hierarchical and complex social life that poses great demands in terms of time, energy and attention (Carskadon 2002), and is further underpinned by ready access to screen-based electronic media devices (Touitou, Touitou & Reinberg 2017). In addition, during adolescence parents stop setting their children bedtimes, and adolescents gain autonomy for setting their own sleep times (Carskadon 2011). Surprisingly, Gradisar *et al* (2011) suggest that social jetlag symptoms can be aggravated by cultural factors even within “modern” societies. After performing a meta-analysis of 41 surveys addressing adolescent sleep patterns worldwide, they found that East Asian adolescents have a later sleep onset than USA and European adolescents, obtaining less sleep and reporting higher rates of sleepiness (Gradisar, Gardner & Dohnt 2011).

To sum up, early adolescents go through a phase delay due to endogenous/internal factors that retard sleep onset and awakening times, but, because of exogenous/external factors (i.e., socio-cultural demands and lifestyle), they also face sleep deprivation (Figure 3). The amount of sleep they lose in the process ranges from 2-3 hours during school nights

(Carskadon 2011; Gradisar, Gardner & Dohnt 2011; Touitou 2013), a debt for which they compensate at weekends (Touitou, Touitou & Reinberg 2017). Nonetheless, as long as optimal sleep quotas remain uncertain, the extent of sleep loss and its impact on their wellbeing is still unclear (Carskadon 2011; Blunden & Galland 2014).

According to SJL hypothesis, "modern" lifestyles constitute a disruptive sleep environment that prevent adolescents from fulfilling "biological/natural" circadian cycle and sleep quotas (Peixoto, da Silva, Carskadon, *et al.* 2009; Pereira, Louzada & Moreno 2010). Therefore, it is hypothesized that adolescents living in non-industrial settings will also sleep longer in order to comply with their "biological/natural" circadian cycle (Peixoto, da Silva, Carskadon, *et al.* 2009; Pereira, Louzada & Moreno 2010). Yet, studies examining normal adolescent sleep in these settings are scarce. An anthropological perspective is needed to help bridge this gap by addressing and comparing adolescent sleep timing across cultures and populations.

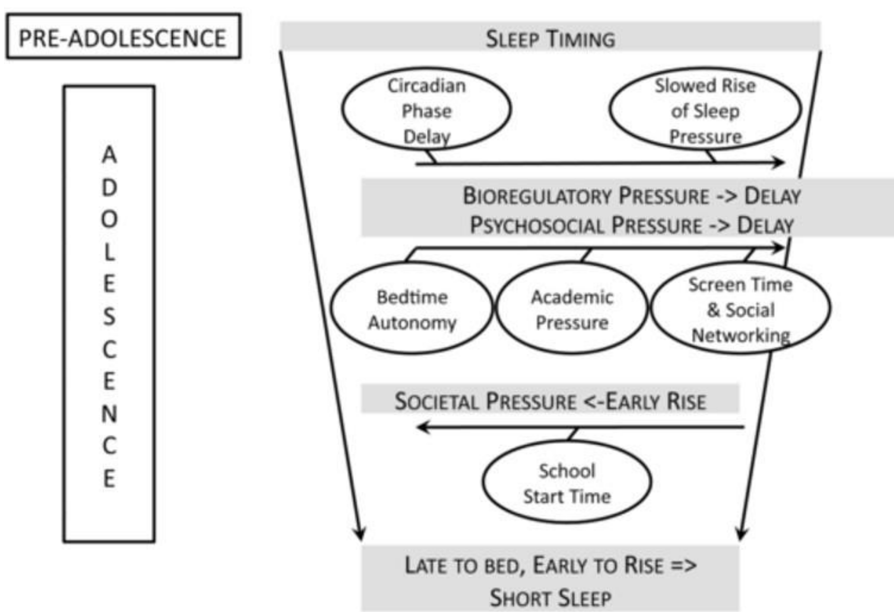


Figure 1. Factors involved in shaping the sleep of adolescents through their development (Carskadon, 2011).

2.4 Sleeping in context: insights from anthropology

Sleep remains an understudied phenomenon in human societies particularly by anthropologists; we know comparatively little about "normal" sleep patterns and architecture and how these might have evolved during human evolution (Worthman & Melby 2002). Recent exceptions include studies in the elderly, suggesting older people experience short, disrupted sleep enabling some individuals to remain awake and alert for protective purposes in the kinds of environments in which humans evolved (Samson, Crittenden, Mabulla, *et al.* 2017a). Other studies have examined the sleep of contemporary hunter-gatherers (e.g., Toba/Qom and Native Terena groups), finding that protected and comfortable environments shielded from sleep disruptors, along with co-sleeping habits, and group participation in economic activities, are factors that facilitate consolidated sleep bouts and homogeneous sleep activity among the social group (Reimao, Souza, Gaudioso, *et al.* 2000; de la Iglesia, Fernández-Duque, Golombek, *et al.* 2015). Since the mid-2000s, some studies have focused on adolescent sleep patterns as described below.

Previous research examining sleep of adolescents from rural and non-industrial populations have been conducted in Germany, China, Egypt, Uganda, Brazil and Argentina (Louzada & Menna-Barreto 2003, 2004; Loessl, Valerius, Kopasz, *et al.* 2008; Ouyang, Lu, Wang, *et al.* 2009; Peixoto, da Silva, Carskadon, *et al.* 2009; Pereira, Louzada & Moreno 2010; Worthman & Brown 2013; de la Iglesia, Fernández-Duque, Golombek, *et al.* 2015; Christoph, Grigsby-Toussaint, Baingana, *et al.* 2017). These studies have reported a wide variation in adolescent sleep duration, from 7-10.67 hours/ day, sometimes below the sleep quota recommended by specialists and clinicians (8.5-10 hours/day) (Touitou 2013; National Sleep Foundation 2000; Institute of Medicine 2006). The observed variation was explained by access to electricity, school demands, daily and pre-sleep activities, bed-sharing habits, and daylight seasonal variations. However, results are difficult to compare because of differences in age groups, the instruments and definitions used to calculate sleep duration, and study durations. These studies add to the assessment of adult sleep in non-industrial societies, which report sleep durations that range between 5.7 to 8.5 hours/ day (Reimao, Souza, Gaudioso, *et al.* 2000; Evans, Snitker, Wu, *et al.* 2011; Worthman & Brown 2013; Knutson 2014; de la Iglesia, Fernández-Duque, Golombek, *et al.* 2015; Moreno, Vasconcelos, Marqueze, *et al.* 2015; Yetish, Kaplan, Gurven, *et al.* 2015; Beijamini, Knutson, Lorenzi-Filho, *et al.* 2016; Beale, Pedrazzoli, Gonçalves, *et al.* 2017; Samson, Crittenden, Mabulla, *et al.* 2017c; Samson, Manus, Krystal, *et al.* 2017) (Figure 4).

Notably, the aforementioned studies have demonstrated that traditional societies are ideal settings for comparative sleep studies. Characterized as non-industrial, small-scale societies, they are relatively isolated geographically, socially and/or culturally, without ready access to electricity or electronic devices, and where human sleep-wake cycles are more entrained with natural exposure to light (de la Iglesia, Fernández-Duque, Golombek, *et al.* 2015; Yetish, Kaplan, Gurven, *et al.* 2015; Samson, Crittenden, Mabulla, *et al.* 2017c; Samson, Manus, Krystal, *et al.* 2017; Rattenborg, de la Iglesia, Kempenaers, *et al.* 2017). Moreover, adolescents living in traditional social environments face distinct school and working demands compared to those adolescents living in industrial contexts (Arnett, 2000; Lew-Levy *et al.*, 2022). It is presumed that such differences in the daily allocation of time and energy might also affect adolescent sleep patterns (Worthman & Melby 2002).

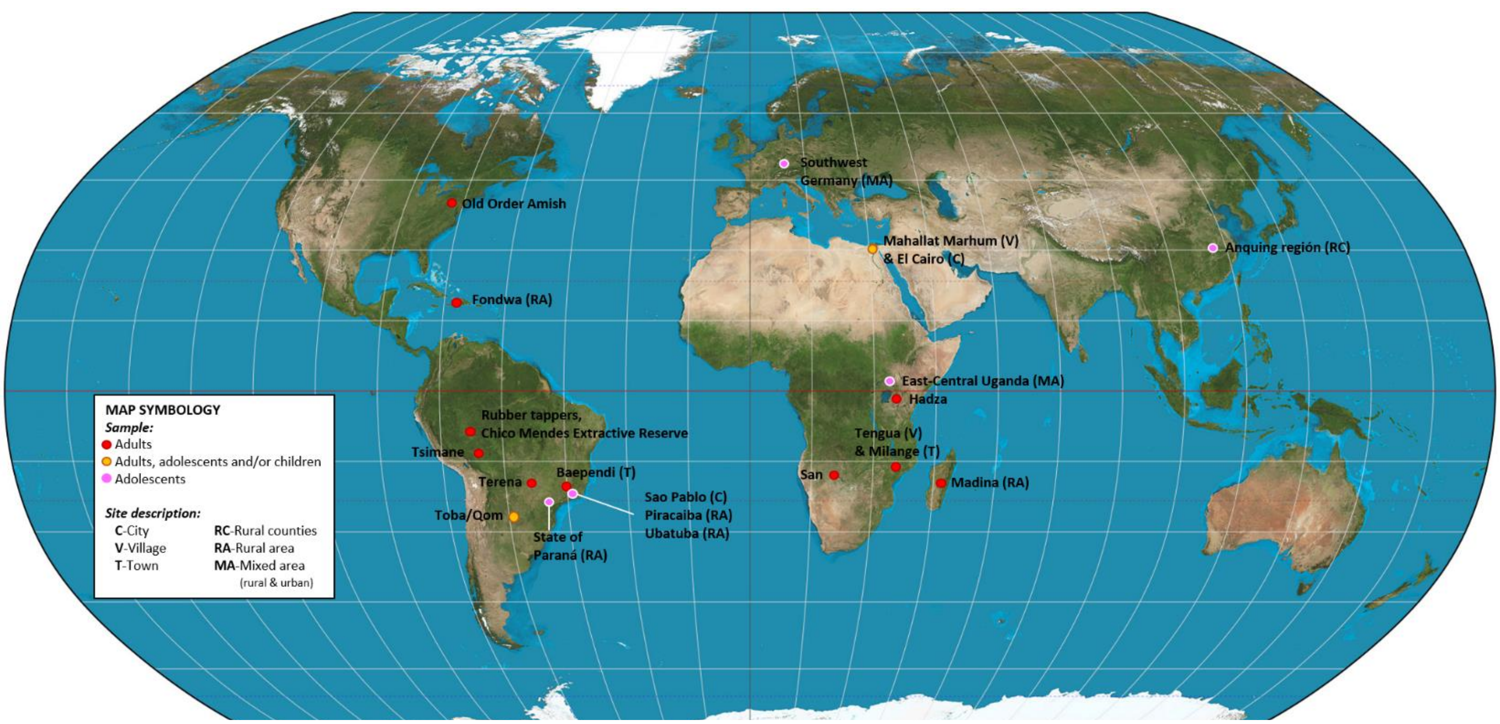


Figure 2. Sleep research in rural and non-industrial populations

Sleep variability and adaptive significance

Based on the assumption that "modern" human sleep patterns are suited to a particular environment in which humans and hominids evolved (i.e., the so-called Environment of Evolutionary Adaptedness, or EEA), non-human primates and contemporary hunter-gatherers have generally been considered ideal proxies for the ancestral environment where human sleep behaviour evolved (Foley, 1995; Irons, 1998; Yetish *et al.*, 2015). This idea boosted a plethora of research aimed at reconstructing the "biological/natural" circadian cycle and sleep quotas of Pleistocene humans (Matricciani *et al.*, 2012; Piosczyk *et al.*, 2014; Yetish *et al.*, 2015). Moreover, the belief in ideal sleep parameters also lies at the core of the SJH. Nevertheless, there is a major issue challenging such an assumption: the evolutionary history of the hominoid lineage was not a static process located in one given geographical area but the product of population dispersal and discontinuity (Foley, 1995). This means that the evolution of human sleep behaviour and physiology was driven by dynamic ecological factors, and as a consequence, it is phenotypically plastic (Horne, 2011).

Several researchers have pointed out that, instead of trying to find the Pleistocene Holy Grail of sleep, studies aimed at understanding human sleep evolution should focus on the role of ecological factors in shaping sleep behaviour and physiology (Worthman, 2008; Horne, 2011; Knutson, 2014; Nunn, Samson and Krystal, 2016; Rattenborg *et al.*, 2017; Ball, Tomori and McKenna, 2019). Current inferences about the ecological history of human sleep have been drawn from comparisons with other mammals and among human societies with different means of subsistence (such as hunter-gatherers, agropastoralist groups, and horticulturalists) (McNamara, Barton and Nunn, 2009; Samson and Nunn, 2015; Nunn, Samson and Krystal, 2016). For example, Worthman (2008) and Samson & Nunn (2015) have highlighted the critical relationships between changes in sleep parameters (i.e., sleep phasing, duration, and REM to NREM ratio) in human evolution as well as changes in predation risks, body mass, metabolism, activity patterns, hair loss, technological innovations (such as the use increasingly of complex sleeping platforms and fire), subsistence, and social interactions and organization.

After comparing the existing evidence for humans and other primates using phylogenetic analysis, Samson & Nunn (2015) identified four unusual traits that characterize human sleep on a gross level: 1) sleep is located in terrestrial and not arboreal environments, 2) individuals engineer a "nest" or sleeping platform for resting purposes, 3) human sleep duration is the shortest recorded among primates, and 4) human REM to NREM ratio is the highest of all primates (Figure 5). Based on their observations, these authors proposed the Sleep Intensity Hypothesis, stating that early humans faced selective pressures that induced them to fulfil their sleep requirements in the shortest possible time (Samson and Nunn, 2015). A more efficient, shorter sleep would have benefited individuals by decreasing risks of predation and intergroup conflict in terrestrial environments, and increasing social interactions around sleeping times (Nunn, Samson and Krystal, 2016). Furthermore, such changes in sleep would have also impacted human cognition, as extended active periods might have boosted the acquisition and transmission of new knowledge and skills, with deeper sleep also heightening their consolidation (Samson and Nunn, 2015).

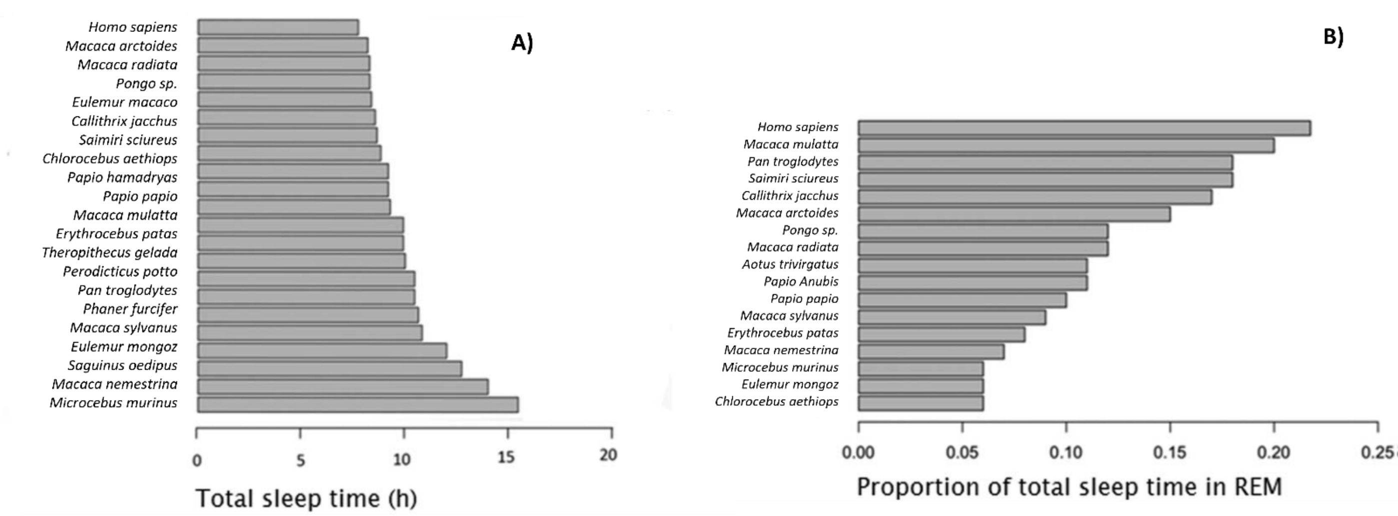


Figure 5. Human sleep relative to that of nonhuman primates. A) Sleep duration, and B) REM to NREM ratios (Samson and Nunn, 2015).

Despite evidence pointing to various important effects of sleep on the evolution and development of our neural and cognitive functioning (Barton and Capellini, 2016), and even though the strong ties between human cognition, culture, sociality and ontogenetic development are widely recognized (Hernández-Ochoa and Vergara-Silva, 2022), very little is known about the role of culture on sleep patterning, architecture and overall development, nor its impact on sleep quantity, quality, memory consolidation, restorative functions and mental health (Worthman and Melby, 2002). In this regard, James McKenna was one of the first anthropologists who began studying sleep using a developmental, cross-cultural perspective. McKenna questioned the perceived paediatric wisdom that infants and young children should be separated from their parents and sleep on separate surfaces as a risk reduction strategy against sudden infant death syndrome (SIDS) and to help forge independent individuals (Mckenna, 1996; Ball and Klingaman, 2008). Using an anthropological, evolutionary theoretical framework, evidence provided by mother-infant bed-sharing studies revealed a clash between the evolved needs and proclivities of infants and caregivers, and cultural (Western) notions regarding how infant-parent relationships ought to be sustained during the night (Ball, Tomori and McKenna, 2019). Overall, these studies have found that bed-sharing practices facilitate breastfeeding and can decrease risk factors for SIDS (Ball and Klingaman, 2008).

More recently, Worthman has advocated the development of an evolutionary ecology of sleep based on comparative, cross-cultural studies, to shed light on how cultural contexts structure the developmental, social and physical conditions of sleep, shaping its nature and quality (Worthman and Melby, 2002; Worthman, 2008). Worthman builds upon the theoretical work of Bronfenbrenner (1977), Whiting (1993), Super & Harkness (1994), Weisner (1997), and Konner (2002) to propose the Developmental Microniche Framework (Figure 6), aimed at studying human diversity and the role of the bio-eco-cultural milieu in its genesis and consequences (Bronfenbrenner, 1977; Whiting, 1993; Harkness and Super, 1994; Weisner, 1997; Konner, 2002; Worthman, 2010). This niche concept serves the goal of examining the interrelationship between the developing individual and its micro- and macro-bioecocultural context and then to trace the resulting outcomes (Worthman, 2010).

For example, taking into account the micro and macro-ecology of sleep, Worthman conducted a study among Egyptian families living in Cairo and in an agrarian village looking into daily sleep quotas and sufficiency, the effects of napping and co-sleeping on sleep adequacy, and how bedtimes, wake-times, gender and sex influence sleep sufficiency

(Worthman & Brown 2013). The findings suggested that urban Egyptians have more variable bedtimes and night sleep than villagers, but a similar daily sleep, that co-sleepers had more regular sleep schedules and shorter total sleep, that napping importantly contributed to sleep quotas and that sleep quotas recommended by U.S. health organisms neglect sleep flexibility (Worthman & Brown 2013). Such findings question current Western assumptions on what constitutes a healthy sleep and highlight the influence that social contexts have on sleep behaviour and quality.

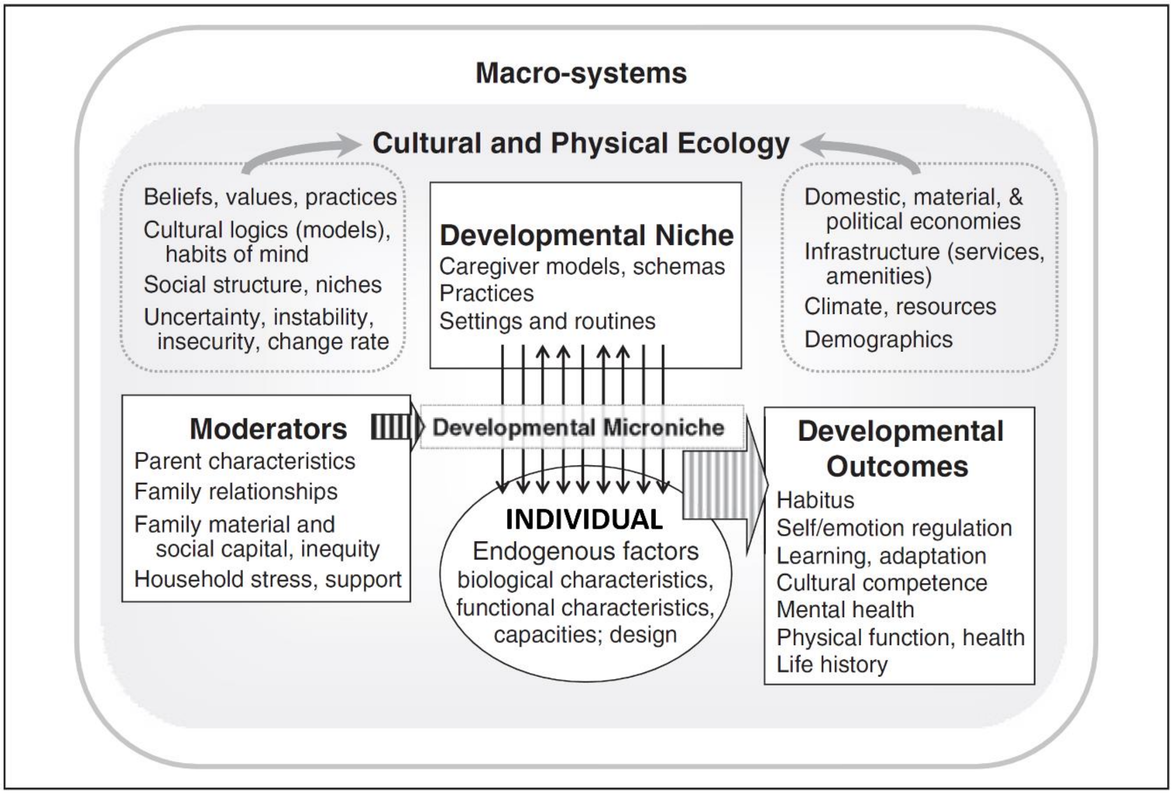


Figure 6. Diagram of Worthman's biocultural model highlighting the elements and pathways of embodiment in human development (modified from Wothman, 2010).

It is worth noting that Worthman's model follows a broader evolutionary developmental biology (evo-devo) perspective (Müller, 2007), which gives explicit consideration to the relevance of behaviour, development and environment as sources of phenotypic plasticity and soft inheritance (i.e. systems of heredity that are not determined by the DNA sequence, such as epigenetic and ecological inheritances) (Haig, 2007; Laland *et al.*, 2014). Within this framework, sleep variability constitutes a form of phenotypic plasticity, where a single genotype is capable of producing different phenotypes in response to changing external conditions (Müller, 2007). The set of phenotypes that can be expressed from that given genotype is known as a reaction norm (Stearns and Koella, 1986). Importantly, the selection of those phenotypes can operate during several stages of ontogeny, and an individual's fitness (both, personal and inclusive) can vary across different environments and changing conditions.

With this in mind and using a cross-cultural perspective, my PhD is oriented to understand the nuances of sleep better by re-examining current assumptions of adolescent "natural"/optimal sleep and, thereby, to contribute to our understanding of human sleep evolution. Specifically, this PhD addresses and compares adolescent sleep patterns in two non-industrial societies and one post-industrial society in Mexico. The study investigates whether the shift in the reported sleep-wake cycle of adolescents in industrialized populations is replicated in non-industrialized societies, and, what bio-socio-cultural environmental factors influence sleep timing and duration in these settings.

It should be noted that, in the following chapters, the term non-WEIRD societies (an acronym for Western, educated, rich, industrialised and democratic) will be used to name the broad range of human diversity in opposition to the overrepresentation of privileged minorities of neo-colonialist populations portrayed in current hegemonic scientific production (Clancy and Davis, 2019; Ghai, 2021). The term WEIRD was introduced in 2010 to raise consciousness concerning the inherent biases leading researchers to generalise findings from a small proportion of humanity to all human groups (Broesch *et al.*, 2020). However, although the term has served the purpose of shedding light on the critical importance of having sample diversity in science, it has also been criticised for oversimplifying human heterogeneity by dichotomising it and masking the extent of underrepresentation even within so-called WEIRD societies (Clancy and Davis, 2019).

Despite encompassing many facets of human diversity, the concept WEIRD is almost as ambiguous and arbitrary as those geopolitical concepts of Caucasian, White or Western, which have also been used to distinguish between members of affluent colonialist populations and the rest of the world (Appiah, 2016; Moses, 2017; Clancy and Davis, 2019). Arguably, the term is not to blame for researchers lumping diversity, but rather our cognitive biases and the underrepresentation of minorities in science (Clancy and Davis, 2019; Ghai, 2021). Oversimplification can only be overridden by adding more voices to science, representing other cultures, ethnicities, social strata, religions, sexual orientations, gender, etcetera (Ghai, 2021). In acknowledgement of the above, this work, written by an educated, heterosexual, Mexican woman in her mid-30s, pays special attention to describing the different socio-cultural features characterising each population participating in this study.

2.5 Aims of the research

Research aims

1) To describe and analyse whether the shift in the adolescent sleep-wake cycle reported among industrialized populations is replicated in non-industrialized societies with limited access to electronic and/or electrical devices.
2) To describe and examine bio-socio-cultural environmental influences on sleep timing and duration.

Research questions

i) Do early adolescents in non-industrialized and in industrialized societies go through a phase delay expressed in later sleep onset and awakening times?
ii) Do adolescents in non-industrialized and in industrialized societies experience sleep deprivation?
iii) How might characteristics such as working/schooling, access to electric light and electronic devices, daily exposure to natural light, and the practice of social sleep alter timing and duration of adolescent sleep?

Research hypotheses

i) Advanced puberty will be associated with an adolescent sleep phase delay in industrial and non-industrial societies.

ii) Sleep deprivation will be rare in non-industrial settings and more frequent in industrial environments.

iii.a) School schedules, access to electric light and electronic devices and social sleep will be associated with later sleep onsets and negatively impact sleep duration during school days.

iii.b) Daily exposure to natural light will be associated with earlier sleep onsets and longer night-time sleep durations during school days.

iii.c) Sleep duration will be significantly affected by environmental factors on school days but not on free days.

3. METHODS

3.1 Study sites, participants & recruitment

Fieldwork was conducted in 2019 in two Mexican traditional societies (situated in Bolonchen, Campeche and Huehuetla, Puebla) with low access to electronic and/or electrical devices and one industrial site -Mexico City. Each site is characterized in Table 1. The study ran from February 1st to April 8th, in Mexico City, from May 31st to July 5th, in Campeche, and from September 6th to November 11th, in Puebla.

Study site	Geographic location	Economy	Inhabitants and ethnic composition	Main language
Mexico City (South and Northeast urban areas)	19.42847, -99.12766 The city is located in a highlands plateau, 2,303 m above sea-level.	Metropolis with a predominantly service-based economy. Participants belonged to relatively affluent and educated families whose occupations comprised trades (such as driver, shopkeeper or merchant) to professions (accountant, engineer, teacher, doctor, dentist, among others).	~8.9 million inhabitants Mexico City has an admix ethnic background composition, with 89% identifying as "mestizos", 9% belonging to an indigenous group and 2% as Afro-descendants.	Spanish
San Juan Ozelonacaxtla, Huehuetla, Puebla	20.183333, -89.833333 The village lies 834 m above sea-level at the intersection of two mountain systems.	Agricultural Totonac community. By the end of the 1980s electricity and running water were introduced, followed by better roads, schools and a local health centre. Because regional orographic characteristics prevented the adoption of mechanized agriculture, traditional farming techniques have prevailed. Household economies mainly depended on agriculture (typically growing coffee, pepper and corn) and animal breeding (chicken, ducks, pigs and cattle), but also trades (such as shopkeeper or baker) and remittances from migrant family members working in Mexico City or Puebla de Zaragoza in construction or domestic work. Generally, children and adolescents with migrant parents stayed in the community under the care of close relatives.	~1,368 inhabitants Population in San Juan Ozelonacaxtla identify as Totonac, Mexico's tenth largest ethnic group.	Highland Totonaku
Xculoc, Hopelchen, Campeche	20.046944, -97.613611 The village is located in the Yucatan Peninsula plain, 69 m above sea level.	Small agricultural Maya community undergoing demographic and economic transitions with the recent introduction of running water, electricity, new farming techniques for intensive agriculture, schools and roads. Still, the site remains isolated from public transport. Household economies largely depended on subsistence agriculture and crop sales (such as peanuts, corn and squash), animal breeding (ducks, chicken and sheep), apiculture, construction labor, or work in in neighboring village restaurants.	~835 inhabitants Population in Xculoc identify as "Mayeros" or Maya, Mexico's second largest ethnic group.	Peninsular Maya

Table 1. Fieldwork sites

The three study sites were chosen following four main criteria to allow ecological comparisons of adolescent sleep:

1. Rural populations should belong to non-industrial, small-scale societies, relatively isolated geographically, socially and/or culturally, without ready access to electricity or electronic devices.
2. The urban population should belong to affluent, educated households, depending on industrial/post-industrial economies, living in densely populated areas with ready access to electricity or electronic devices.
3. Due to time constraints, each site had to have a gatekeeper (i.e., fellow researchers) who was contacted before the start of the study to ease communication with local populations.
4. All three sites had to be located outside high-risk areas of Mexican territory according to the U.S and U.K. advisory travel guidelines (https://travel.state.gov/content/travel/en/traveladvisories/traveladvisories/mexico-travel-advisory.html, https://www.gov.uk/foreign-travel-advice/mexico).

Although none of the rural sites was completely isolated from the market-led economy in Mexico, the three study sites reflect a gradient between “modern” societies and “traditional” in terms of sleep environments and access to technology (Table 2). This gradient is also seen regarding schooling since Mexican rural education varies greatly depending on the local State/Municipal resources and the communities’ expectations and restraints (Bautista Rojas, 2018; Red Temática de Investigación de Educación Rural, 2018). Therefore, while lax schooling was observed in Campeche, more structured teaching was found in Puebla, and a fully structured schooling system operated in Mexico City. The educational contexts in which participants were embedded at each site are addressed more thoroughly below.

Given that the Maya site in Campeche was not accessible by public transport and had a small population, the Municipality had assigned only six teachers to the local elementary and secondary schools. Hence, these teachers taught in multigrade classrooms at the elementary level and were in charge of teaching all specific subjects at the secondary level. On occasions, teachers were observed arriving late or absent from class during the study due to sickness or transport issues, as none lived in the community. Additionally, students' lack of punctuality was viewed permissively and, although parents made sure their children attended school, most did not have the time, interest, skills, or knowledge to assist them with their homework.

In comparison, the Totonac site in Puebla was better connected by road and public transport to neighbouring villages, which facilitated teachers commuting to the local schools. In this case, elementary and secondary schools had at least one teacher per grade, school schedules were strictly observed, and school demands were higher regarding schoolwork and homework. However, as happened in Campeche, even though parents demanded their children attend school, most did not assist them with their homework. Moreover, many parents did not trust the school staff, who were seen as condescending outsiders who did not respect their local culture and way of life.

Sleep ecology	%	Mexico City	Puebla	Campeche
Access to screen-based devices †	Mobile phones	94	67	57
	Tablets	54	35	9
	Computers	94	18	9
	TV	100	96	98
Darkness/Light	Dark	76	39	68
	External illumination ††	18	24	16
	Indoors light	6	37	16
Social sleep	Solitary sleep	72	33	11
	Social sleep	28	67	89
Materiality of sleep	Sleeping surface	Bed	Bed or traditional wooden surface	Hammock
	Housing materials	Concrete, steel, and bricks	Concrete, steel, bricks, rocks, wood, and cardboard	Concrete, steel, bricks, raw earth, palm, wood and cardboard
School demands	School Day Start	7:30 hrs	8:00 hrs	8:00 hrs
	Commuting times	5-50 minutes*	5-10 minutes**	5-10 minutes**

† Unlike urban participants, most Totonac and Maya adolescents from Puebla and Campeche did not personally own screen-based devices but borrowed them from a family member. Consequently, their access to such devices was more restricted than participants from Mexico City.
†† Streetlights or moonlight are considered as external sources of night lighting.
*By walk, car, public transport, or school bus
**By walk

Table 2. Micro- and Macro-ecological characteristics of participants' sleep by sites. Data are represented as percentages relative to each sample group.

Contrastingly, in Mexico City the study was carried out in two private schools in the south and northeast urban area. In both schools, each subject was taught by a specialist at the secondary level (e.g., history, mathematics, biology, chemistry, literature, geography, etc.). Furthermore, these schools had classrooms with blackboards, projectors, equipped laboratories, libraries, auditoriums, computer areas, snack areas, drinking fountains, electrical installations and access to the Internet among their facilities and services. Urban schools had strict schedules and demanding workloads. Staff and students would often live in the school vicinity.

Overall, it is reasonable to assert that contemporary rural Mexican schools are based on identical prejudices and face similar challenges and obstacles to those first rural schools established by the Public Ministry of School (SEP) at the beginning of the 20th century (Loyo B., 2006). To encourage "progress" and State unity, these schools were created to "erase" cultural differences through the transmission of "civilized" lifestyles, language (i.e., Spanish), and values (Loyo B., 2006). Since the beginning, school absence was a common problem since children and adolescents were expected to fulfil their workloads inside and outside the house (Bazant, 2003; Loyo B., 2006). With rare exceptions, school was seen as an alien and unnecessary burden for households' economies (Bazant, 2003).

To prevent absenteeism and school dropout, basic education (i.e., preschool, primary and secondary education) was declared mandatory by the Mexican government in 1993 (SEGOB, 1993). In addition, a scholarship scheme for rural students was launched in 1997 as part of the Education, Health and Food Program (Progresa) (Mex.Gov., 2016). Since 2019, these scholarships are known as "Becas para el Bienestar Benito Juárez". All the rural adolescents participating in the study were recipients of this financial stimulus.

3.2 Sample size

The sample population age ranged between 11 and 16 years old (mean age 13.7 ± 1.21). I worked with 163 participants (females=78) from three sites in Mexico, one urban, post-industrial and two rural, non-industrial (Mexico City, n=67, San Juan Ozelonacaxtla, Puebla, n=51, and Xculoc, Campeche, n=45). Participants of both sexes were recruited at each site through Secondary schools. At the request of the participant schools' directives, data collection was not performed during school testing periods to avoid adolescents being distracted from schoolwork and potentially lowering their performance.

Table 3 provides descriptive data for sex, age, pubertal development and chronotype for each study site. Not all sample characteristics are homogeneous across sites, something to be expected for chronotype and pubertal development according to previous cross-cultural research (Roenneberg, Wirz-Justice and Merrow, 2003; Worthman, Dockray and Marceau, 2019). The information about data collection on participants' pubertal development stage and chronotype is provided below.

Sample characteristics		**Mexico City**	**Puebla**	**Campeche**
Sex	Girls	24	27	21
	Boys	26	24	23
Age	Mean (SD)	13.8 (1.3)	13.5 (1.1)	14 (1.3)
	Minimum	11.2	11.8	11.6
	Maximum	16.5	15.8	16.7
Pubertal Development Stage %	Pre/Early puberty	20	14	23
	Mid puberty	22	31	29
	Advanced puberty	58	55	48
Chronotype %	Morning type	30	22	50
	Neither type	48	74	48
	Evening type	22	4	2

Table 3. Sample composition at each site.

3.3 Data collection

Adolescent sleep was examined using a cross-sectional, prospective study design via a mixture of qualitative and quantitative data. Quantitative data on sleep patterns and architecture (i.e., time in bed, sleep onset, sleep end, total sleep duration, sleep disruption, sleep segmentation, sleep efficiency, and napping), environmental factors (i.e., exposure to seasonal variations in temperature and light, access to electricity, use of electronic devices, bedding characteristics, social or solitary sleeping practices) and daily activities (i.e., working and/or schooling efforts) were collected. Qualitative data about the cultural expectations of sleep (i.e., ideas on the function of sleep, ideas on when and how sleep should take place) were also assembled. This type of design is relatively cheap compared to longitudinal studies, allowing the assessment of current and past sleep patterns of adolescents over a short period of time.

Data collection relied on actigraphy, sleep diaries, semi-structured interviews, observations and two standardized questionnaires. An overview on the data collection and specific tools that were used are given in Table 4.

Data collection tools	Variables
Actigraphy	* Time in bed, sleep onset, sleep offset, sleep duration, total sleep duration, sleep disruption, sleep segmentation, sleep efficiency and napping * Daily physical activity and ambient light
Questionnaires	* Chronotype (via Morningness-Eveningness Reduced Scale-MERS) * Pubertal maturation (via Pubertal Development Scale-PDS)
Sleep diaries	* Time in bed, sleep onset, sleep offset, sleep duration, total sleep duration, sleep disruption, sleep segmentation, sleep efficiency and napping * Sleep quality * Sleepiness during the day
Semi-structured interviews and observation	* Daily use of time * Household size and group composition * Access to electricity and/or screen-based devices * Sleeping habits (via Pittsburgh Sleep Quality Index-PSQI) * Sleeping environment (i.e., bedding characteristics, social or solitary sleeping practices) * Sleep experience and knowledge (i.e., ideas on the function of sleep, ideas on when and how sleep should take place)

Table 4. Target variables according to data collection tool

Actigraphy

Data on sleep behaviour, daily physical activity and ambient light was collected via Motionlogger Micro Watch units (Ambulatory Monitoring Inc., US) (Figure 7). The actigraphs were set for 1-min epochs in the Zero Crossing Mode (ZCM). A total of 147 participants wore the actigraphy devices during 10 days (six work days and four free days) for 24 hours. Adolescents were asked to press the event logger button before any sleep event across the study. As two teenagers did not have valid actigraphy data due to watch malfunctions, our final sample was reduced to 145 participants (Mexico City, n=50; Puebla, n=51; Campeche, n=44), with 72 being females.

A total of 1405 sleep observations were collected, of which 618 were non-school nights and 787 school nights. The accuracy of all the monitoring devices was further validated against sleep diaries as it is generally recommended (Short, Gradisar, Lack, *et al.* 2012; de la Iglesia, Fernández-Duque, Golombek, *et al.* 2015). This enabled detecting "false" wake-like or sleep-like entries (Samson, Yetish, Crittenden, *et al.* 2016). The actigraphy data was analysed using the Sadeh algorithm with the ActionW 2.7 to characterize the sleep-wake behaviour of adolescents (Figure 8).

Actigraphy is increasingly being used to measure sleep in various human populations (Samson, Yetish, Crittenden, *et al.* 2016; Rattenborg, de la Iglesia, Kempenaers, *et al.* 2017). Compared to polysomnography (PSG), which remains the gold standard for quantifying sleep, actigraphy devices are non-cumbersome, easy to apply with ambulatory populations, and less expensive (Samson, Yetish, Crittenden, *et al.* 2016). In addition, actigraphy devices can capture continuous data during days, weeks or more while subjects perform their normal daily routines (Rattenborg, de la Iglesia, Kempenaers, *et al.* 2017). This method has proven to be particularly useful for quantifying rest-activity rhythms, sleep duration, timing, and sleep segmentation (i.e., nighttime wake-bouts and daytime napping) (Peixoto, da Silva, Carskadon, *et al.* 2009; de la Iglesia, Fernández-Duque, Golombek, *et al.* 2015; Beale, Pedrazzoli, Gonçalves, *et al.* 2017; Moreno, Vasconcelos, Marqueze, *et al.* 2015; Samson, Crittenden, Mabulla, *et al.* 2017c; Samson, Manus, Krystal, *et al.* 2017).

Figure 7. Illustration of Motionlogger Micro Watch units and their size relative to an adult wrist.

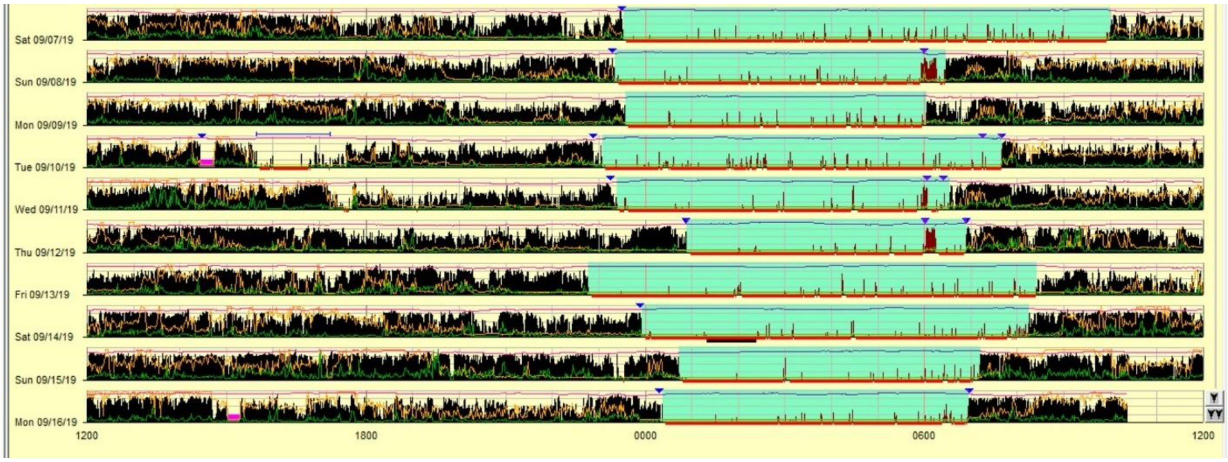


Figure 8. Actogram representing 10-days actigraphy data in ActionW 2.7

Sleep diaries

Sleep diaries were used to collect data on sleep behaviour, subjective sleep quality and sleepiness during the day. The diaries, based on the Consensus Sleep Diary (Carney, Buysse, Ancoli-israel, *et al.* 2012) and the Paediatric Daytime Sleepiness Scale (PDSS), used a simple design with images, colours and scales to allow participants with limited literacy to complete them (see Appendix 1). The Consensus Sleep Diary was developed by experts in insomnia in an attempt to enable comparisons across sleep studies; the PDSS is a brief 8 item questionnaire validated for Spanish-speaking children and early adolescents that examines sleepiness across distinct moments of the day (Perez-Chada, Perez-Lloret, Videla, et al. 2007.). All participants were asked to complete their 10-day sleep diary before and after each nightly sleep (Figure 9).

Questionnaires

In addition to actigraphy and sleep diaries, information about adolescents' sleeping habits and chronotype were obtained through the Morningness-Eveningness Reduced Scale (MERS) (Adan & Almirall 1990). Importantly, the MERS was selected because it is considered suitable for cross-cultural examinations, because of its short length and because it has been validated in Spanish-speaking populations (Díaz-Morales & Sorroche 2008; Adan & Almirall 1990). Along with sleep diaries, data collected through this standardized questionnaire helped to validate further the accuracy of actigraphy measurements and overcome technical difficulties, including watch removal episodes.

Similarly, data about pubertal maturation was collected through the Pubertal Development Scale (PDS). The PDS is a self-report instrument that provides a non-invasive assessment of pubertal status (Robertson, Skinner, Love, *et al.* 1992). In conjunction with data about sex and chronotype, this information served to characterize the participants and explore whether their sleep patterns were a function of pubertal development or if they resulted from an interaction effect (Colrain & Baker 2011). To ensure the assembly of good quality data, both questionnaires were verbally explained to participants and any questions answered (Appendix 3).

Figure 9. Participant filling in her sleep diary while wearing an actigraphy watch

Semi-structured interviews and ethnographic observation

Semi-structured interviews, based on the work of Grandner *et al* (2014), were used to obtain information about the sleep environment in which adolescents were embedded. Questions about the adolescents' daily use of time were included, as well as items coming from the Pittsburgh Sleep Quality Index test (PSQI), a standardized questionnaire that measures the quality and patterns of sleep based on one month recalls (see Appendix 2). It is important to note that, as with the MERS, the PSQI is considered suitable for cross-cultural examinations due to its length and because it has been validated in Spanish-speaking populations (Jiménez-Genchi, Monteverde-Maldonado, Nenclares-Portocarrero, *et al.* 2008).

Overall, the semi-structured interviews were aimed at 1) describing the current sleep-wake patterns and sleep quality of the participants, 2) describing culturally normative ideas and practices about sleep, 3) comparing the characteristics and cultural settings in which participant adolescents sleep, and 4) identifying access to electricity and/or electronic devices to further examine if such access alters the quality, timing and duration of adolescent sleep (Grandner, Jackson, Gooneratne, *et al.* 2014). The initial topics discussed were intended to develop a profile of the participant and his/her family. General topics were addressed at the beginning of the interview, while more specific ones were addressed at the end. The interviews had an approximate duration of 45 minutes.

Observations inside and outside the school environment helped to further explore adolescents' social roles, their peer relationships, their daily way of life and their attitudes towards sleep. A field diary was used to record daily activities, observations, casual conversations, notes about interviews, and comments about the research development.

Calculation of meteorological and solar variables

Latitude and longitude coordinates were determined with Google maps for the three sites. Coordinates were used with the NASA Langley Research Center (LaRc) POWER Project funded through the NASA Earth Science/Applied Science Program (https://power.larc.nasa.gov/) to obtain daily data on precipitation, humidity, surface pressure, minimum and maximum temperature, sky insolation incident and the Insolation Clearness Index. Meanwhile, based on the methods provided in Iqbal (1983), daily data on the sunrise, sunset and day length were obtained through a solar geometry study (Iqbal 1983).

3.4 Data analysis

Data analyses involved mixed methods. Descriptive statistics served to make initial comparisons between sites, followed by multilevel statistics in consultation with the biomedical statisticians from the Anthropology Department and the Research Methods Centre at Durham University. Qualitative analyses were used to compare data collected from interviews, observations, sleep diaries and questionnaires. A flow diagram summarizing the study protocol is provided in Figure 10.

The values for the sleep characteristics detailed in Table 5 were calculated for each participant based on actigraphy data collected during fieldwork. These calculations were further analysed to address the study research questions. All statistical analyses were conducted with significance levels set at 0.05 using R software version 3.6.3. Statistical inferences were established using confidence intervals and p-values.

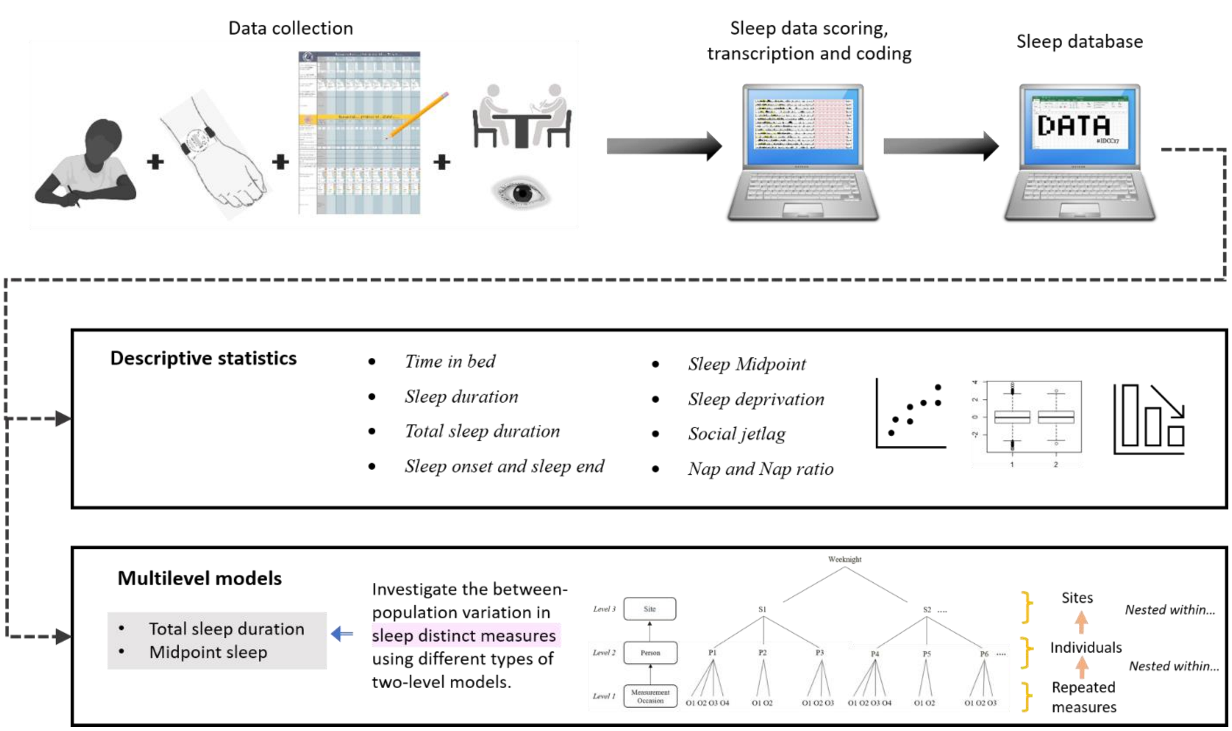


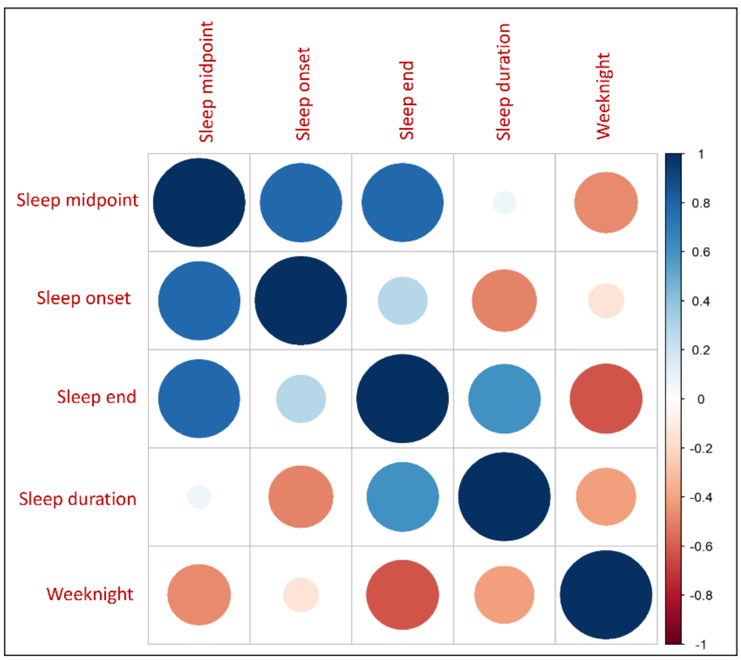
Figure 10. Flow diagram of study protocol

Descriptive statistics characterized daytime napping, sleep timing and sleep duration in our sample population. To investigate whether the shift in the reported sleep-wake cycle of adolescents in industrialized populations was replicated in non-industrialized societies, we focused our analysis on variation in participants' sleep-midpoint values. Likewise, to examine whether adolescents in non-industrialized societies experience sleep deprivation, we focused on the variation of participants' sleep duration.

Importantly, sleep-midpoint has been proposed as a phase marker from which dim light melatonin onset (DLMO) can be readily estimated when sleep times are minimally shaped by school, work, or family commitments ("free" nights) (Hofstra & de Weerd 2008; Crowley 2013). Additionally, this sleep measurement was highly correlated with the participants' sleep onset and sleep endpoint values (Figure 11), mirroring their chronotype results from the MERS during free nights (Figure 12). Therefore, sleep-midpoint is considered an adequate proxy for investigating the variation in adolescent sleep timing.

To evaluate whether there were significant differences in the participants' sleep midpoint and sleep duration values between school and non-school nights, paired t-tests were used. To determine if these values significantly differed between our three sites, ANOVAs were used. All tests were two-tailed.

Figure 11. Correlation matrix between sleep midpoint, sleep onset, sleep end, sleep duration and night type values. Sleep midpoint has a high positive relationship with sleep onset (.78) and sleep end (.82). The measurement is also negatively correlated with weeknights (-.48), with sleep midpoints farther from midnight on free nights.



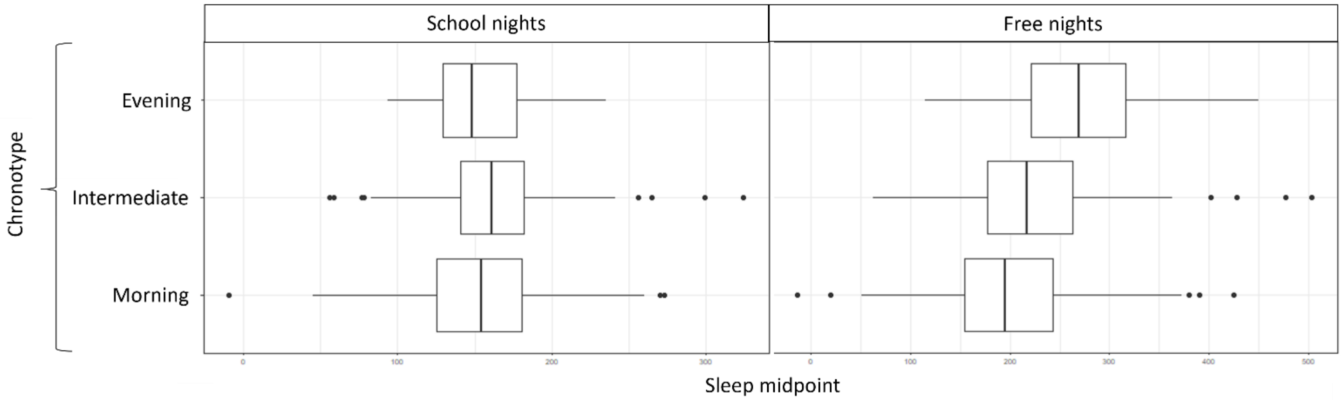


Figure 12. Distribution of sleep midpoint actigraphy values according to the participants' chronotypes. Sleep midpoint distribution agrees with chronotype during free nights, when adolescent sleep has been previously described as little influenced by school, work, or family commitments (Rutters, Lemmens, Adam, et al. 2014).

Sleep characteristic	Definition
Sleep duration	The interval between when the participant goes to bed to sleep, and the time she/he gets out of bed. We scored a period of inactivity in our actigraphy data as time in bed if it exceeded 210 minutes (Samson, Crittenden, Mabulla, *et al.* 2017b).
Total sleep duration	The total amount of time spent sleeping day, including daytime naps.
Sleep onset and sleep end	The clock time when time in bed starts and when the final morning awakening takes place, respectively, reported as minutes before or after midnight. It can be expressed as a negative value prior to midnight, a 0 value when midnight, and a positive value past midnight.
Sleep deprivation	Sleep of shorter duration than the presumed basal need per night of 9-10 hours in early adolescence. The extent of sleep debt is conventionally calculated by subtracting of Total sleep duration (TSD) on Workdays from the TSD on Free days.
Sleep Midpoint	The halfway point between the sleep onset and the sleep end. Reported as minutes before or after midnight. It can be expressed as negative, positive, or equal to 0 values.
Social jetlag	Calculated using the conventional formula for estimating the extent of misalignment between human chronotype and social sleep schedules, namely subtracting the Sleep Midpoint on work nights from the Sleep Midpoint on free nights.

Nap	Period of sleep typically occurring during daylight separate from the main sleep bout. We scored a period of inactivity in our actigraphy data as a nap episode if it fell within the threshold of 15 to 210 minutes and separate by at least an hour from a main big sleep (Samson, Crittenden, Mabulla, *et al.* 2017b).
Nap ratio	The proportion of actigraphy-assessed nap days, calculated as the total number of days with at least one observed nap divided by the number of days with actigraphy data.

Table 5. Definitions of sleep characteristics

Sleep timing and circadian misalignment

The SJH posits that adolescent chronotypes are freely expressed during non-school days, when teenagers can fulfil their "biological/natural" circadian cycle and sleep quotas (Randler, Vollmer, Kalb, *et al.* 2019). To estimate the extent of misalignment between the participants' alleged chronotypes and social sleep schedule (i.e., social jetlag), the mean for each individual's sleep midpoint during school nights was subtracted from their mean of their sleep midpoint during free nights. A Kruskal-Wallis test was used to ascertain whether the resulting values differed significantly between the three sites in this study. Post hoc tests were used to further assess where differences lay between sites.

Sleep duration and sleep deprivation

Two of the most utilized approaches to evaluate sleep sufficiency were employed: 1) to assess if participants slept a minimum of 9 hours per night as recommended by USA advisory bodies (Institute of Medicine 2006; Pereira, Louzada & Moreno 2010; Worthman & Brown 2013), and 2) to evaluate sleep curtailment during school days measured as the difference in adolescents' total sleep duration (TSD) mean values between school nights and free nights (Wolfson & Carskadon 1998; Carskadon 2011; Gradisar, Gardner & Dohnt 2011). The first approach is based on the findings of two seminal studies investigating the effect of different sleep durations on adolescent daytime sleepiness (Carskadon, Harvey, Duke, *et al.* 1980; Mercer, Merritt & Cowell 1998). The latter is supported by two meta-analyses reporting that TSD decreases with age only when recordings take place on school nights, remaining constant and sufficient on free nights from pre to late adolescence (Ohayon, Carskadon, Guilleminault, *et al.* 2004; Gradisar, Gardner & Dohnt 2011).

To gauge sleep curtailment on school days, each participant's TSD mean during school days was subtracted from their TSD mean during free days. An ANOVA was used to determine if the resultant values differed significantly between the three sites. All tests were two-tailed and Benjamini-Hochberg post hoc tests were used to determine specific differences between sites.

Bio-socio-cultural influences on sleep

The between-population variation in sleep measures (i.e., sleep-midpoint and sleep duration) between school nights and free nights was investigated by fitting different types of three-level models¸ with repeated measures at level 1, nested within individuals at level 2, nested within study sites at level 3. Additionally, site-specific models were fitted to unravel the specific influences of the predictor variables on the adolescents' sleep measures, with repeated measures at level 1, nested within individuals at level 2, nested within "weeknights" (i.e., school nights and free nights) at level 3 (Figure 11). The predictor variables that were tested in these models are shown in Table 6, and included individual characteristics and behaviour, distinct exposures to artificial and natural light, temperature and types of social sleep practices. The assumed interaction between predictor variables, control variables and outcome variables is schematized in Figure 12.

The *MuMin* R-package (Barton 2020) was employed for fitting and selecting the final models using the Akaike Information Criteria (AIC) and the Bayesian Information Criterion (BIC). The residuals of all the best-fitted models were normally distributed. Table 7 displays the performance of the resulting final models for assessing variation in sleep-midpoint and sleep duration, comparing them against the full raw models.

The multilevel technique is particularly useful when addressing "nested", "clustered", or "grouped" data that violate assumptions of "independence of observations" (Field 2009). Data with such dependencies are more highly correlated, making it difficult to estimate correct standard errors and increasing the likelihood of a Type 1 error (i.e., to infer that the predictor has “a real effect” on the outcome when such an effect could be due to chance) (Field 2009).

Generally, multilevel modelling is used to account for complex social systems because it allows variation among groups in the analysis. By using individual and group characteristics, the multilevel modelling helps to illustrate how individual and group characteristics affect the outcomes of interest, and even how group characteristics influence individual characteristics that in turn affect the outcomes of interests given certain contexts (Paterson & Goldstein 1991). However, the multilevel approach is also useful when addressing data coming from repeated measurements across time because quite strong correlations are expected within individuals (Maas & Snijders 2003). Since this technique explicitly accounts for dependency across time, it is advantageous when analysing the extent and nature of variation between individuals in their sleep patterns over time.

Furthermore, given that the research study design involved each site being sampled successively instead of simultaneously, the multilevel approach allowed controlling for seasonal or time-period differences (e.g., variations in temperature, day length, and agricultural or school workloads) in addition to population-level differences. This was achieved by nesting individuals (at level 2) within study sites (at level 3), as well as by testing seasonal ecological variables, such as sunrise times, sunset times, day length, clear sky conditions, and minimum temperature, in the statistical models as predictor variables. These ecological variables were included in the final models whenever they were significant. In addition, the ethnographic records were kept to understand the farming/working and school efforts that adolescents faced at each site. This information was crucial for interpreting results from the statistical analyses.

3.5 Ethical considerations

The study protocol was approved by the Ethics Committee of the Department of Anthropology at Durham University. Verbal and written informed consent were obtained from minors and their legal guardians respectively (see Appendix 4). All procedures were in accordance with the Declaration of Helsinki, complying with the guidelines established for the execution of health research projects in Mexico by the Mexican General Health Regulation on Health Research Matters and the Mexican Official Standard NOM-012-SSA3-2012.

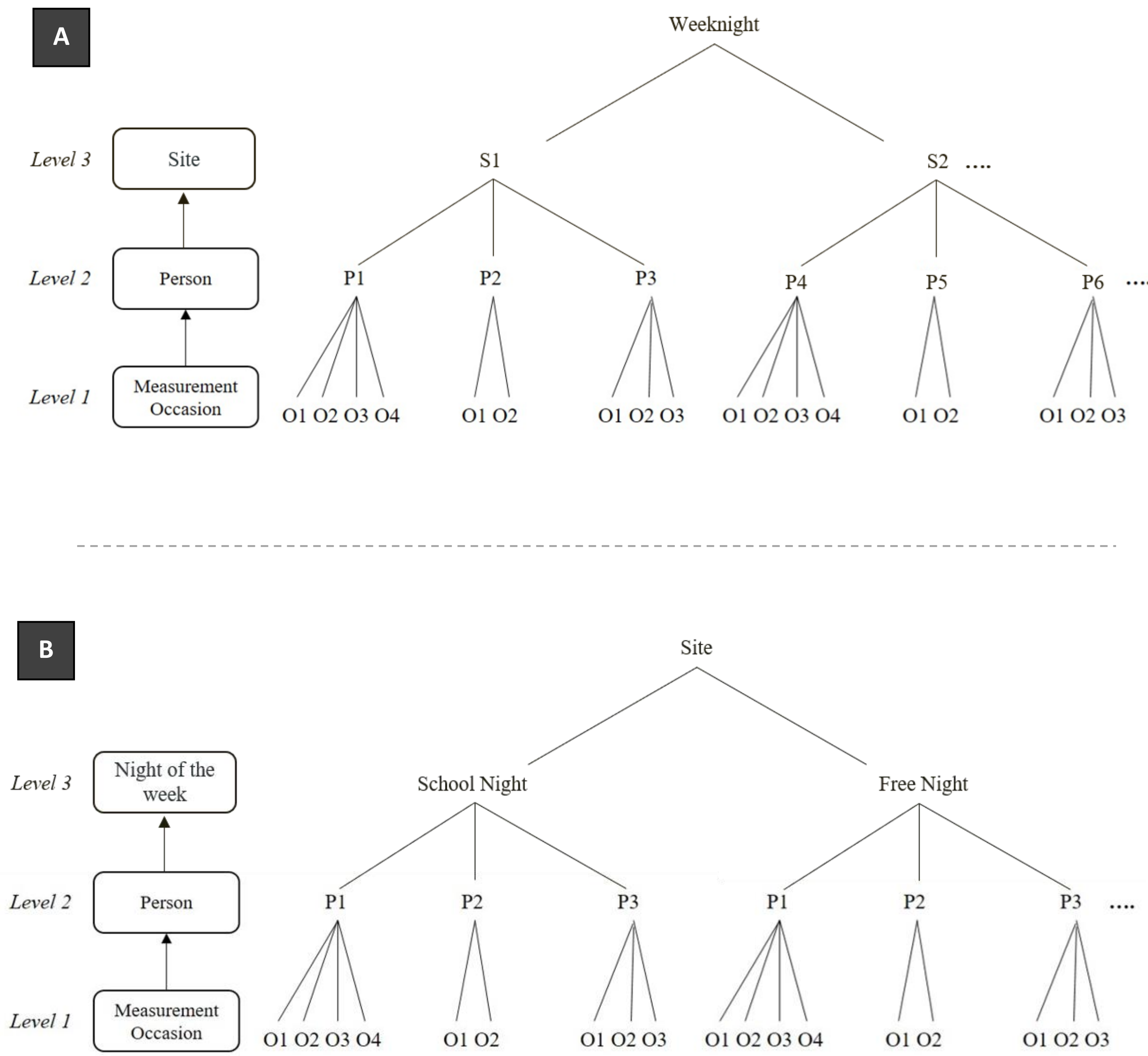


Figure 11. A) Classification and unit diagram for a three-level repeated measures design focused on investigating the between-population variation during school nights and free nights. B) Site-specific three-level repeated measures design.

Predictor variable		Description
Individual characteristics and behaviour	Pubertal maturation	Typified as pre/early, mid-, and advanced puberty (categorical)
	Chronotype	Scored as morning, neither and evening type (categorical)
	Gender	Girls or boys (logical)
	Napping before the main sleep	Present or absent (logical)
Exposure to artificial and natural light	Nightly exposure to screen-based devices	NESDI-variable indexed according to the number of devices being used after 8 pm. Typified as NESDI 1, NESDI 2, and NESDI 3+ (categorical)
	Standard domestic ambient light at night	The percentage of count epochs from 20-499 Lux in relation to the participant's sleep duration (continuous)
	Dim ambient lightening at night	The percentage of count epochs of less than 20 Lux in relation to the participant's sleep duration (continuous)
	Sunset time	The time in the evening when the Sun disappears from the horizon and daylight fades (continuous)
	Sunrise time	The time in the morning when the Sun appears in the horizon and daylight emerges (continuous)
	Day length	The time duration between sunrise and sunset (continuous)
	Clear sky conditions	Assessed via the Insolation Clearness Index, with values close to 1 under clear, sunny conditions and to 0 under cloudy conditions (continuous)
Temperature	Minimum temperature (°C)	Daily lowest temperature recorded at the study sites (continuous)
Social sleep practices	Co-sleeping practices	The practice of bed-sharing or room-sharing (categorical)
	Co-sleepers' generation	The co-sleeper status as an adult or paediatric individual (categorical)
	Parent-set bedtime	Present or absent (logical)
	Assisted awakening	The use of an external agent, alarm or person, to wake up (logical)

Table 6. Description of the predictor variables tested in the three-level models

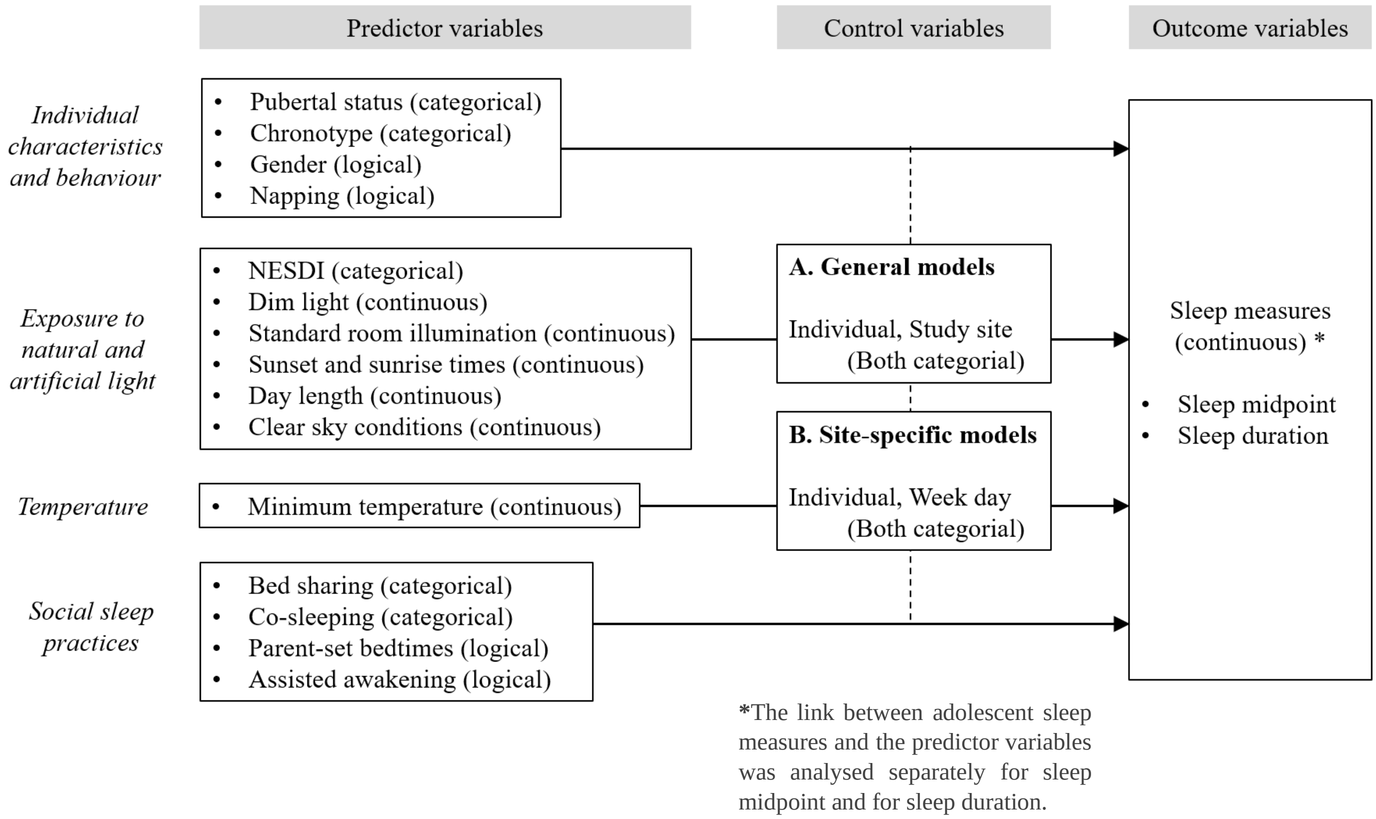


Figure 32. Schematic illustrating the interaction between predictor variables, control variables and outcome variables in our statistical analysis design.

	Model performance		df	AIC	BIC	Sigma	Observations per parameter	Participants per parameter
Assessment of sleep-midpoint variation	**School nights**	*Full*	20	7135.38	7227.37	26.30	35.6	8.1
		Final	11	7125.95	7176.55	26.33	101	22.8
	Free nights	*Full*	20	6439.57	6527.28	44.90	34.5	8.0
		Final	13	6421.77	6478.78	44.89	73.3	17
	Mexico	*Full*	17	4390.87	4459.39	37.90	32.0	3.7
		Final	13	4386.58	4438.98	37.89	46.2	5.4
	Puebla	*Full*	18	4315.95	4388.59	33.79	29.8	3.1
		Final	9	4307.54	4343.86	33.86	83.6	9.2
	Campeche	*Full*	19	3684.91	3758.64	35.72	23.8	2.8
		Final	12	3677.97	3724.54	35.51	44.75	5.3
Assessment of sleep duration variation	**School nights**	*Full*	13	6551.02	6608.31	46.78	67.3	15.2
		Final	11	6548.29	6596.77	46.77	86.6	19.6
	Free nights	*Full*	13	6911.93	6968.78	79.71	65.1	15.1
		Final	9	6907.01	6946.37	79.71	117.2	27.2
	Mexico	*Full*	21	4795.86	4880.50	68.75	24.5	2.9
		Final	13	4788.23	4840.63	68.70	46.2	5.4
	Puebla	*Full*	20	4781.69	4862.40	65.24	26.1	2.9
		Final	14	4775.29	4831.79	65.23	41.8	4.6
	Campeche	*Full*	21	3997.18	4078.67	54.60	21.1	2.5
		Final	11	3984.06	4026.75	54.66	51.1	6

Table 7. Performance of the fitted models for assessing variation in sleep-midpoint and sleep duration. The final models have fewer degrees of freedom, lower AIC and BIC values, and more observations/participants per predictor parameter than the full models. This means that the final models have an improved performance and statistical power, indicating that they predict values closer to the observed data at each site and have a lower risk of making a Type II error (i.e., believing that there is no effect in the population when there is one) (Field 2009).

4. MANUSCRIPT 1. SHIFTS IN ADOLESCENT SLEEP TIMING

Adolescent sleep in non-WEIRD environments. Is the phase shift a "modern" phenomenon?

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Abstract

Adolescent sleep research employing ecological, cross-cultural perspectives provides novel evidence regarding human circadian variation and "natural" sleep, stimulating a series of questions regarding the role of socio-cultural and environmental factors on sleep-wake behavioural evolution, development and health. Here we document adolescent sleep schedules (11-16 years old; 13.7 ± 1.21) using actigraphy, sleep diaries and standardized questionnaires in two non-industrial and one industrial site in Mexico (n=145) to investigate whether the shift in reported sleep-wake cycles of adolescents in industrialized populations is replicated in non-industrialized societies. Additionally, we use mixed-effects models to explore how working/schooling, access to screen-based devices, exposure to light, and social sleep practices alter the timing of adolescent sleep. The results suggest that the shift in adolescent sleep-wake cycles is contextual rather than universal. Sleep-wake cycles in non-industrialized settings were more stable and responsive to natural light and social cues. The findings indicate that different developmental niches where growing individuals express and develop their sleeping behaviour arise from the interplay of environmental, socio-cultural and technological features.

4.1 Introduction

Central to studies examining sleep changes during adolescence, researchers have identified a shift in adolescent sleep timing potentially associated with sexual and cognitive maturation (Hummer and Lee, 2016). The sleep-wake cycles of adolescents in many countries appear to undergo a phase-delay expressed through increasingly later times for sleep onset and awakening (Loessl *et al.*, 2008; Ouyang *et al.*, 2009; Gradisar, Gardner and Dohnt, 2011; Touitou, 2013). Along with this delay, at around age 13, adolescents express a chronotype shift towards eveningness (Colrain and Baker, 2011), apparently returning to morningness in the third decade of life (Crowley, 2013; Touitou, 2013).

Studies examining chronotype variation (i.e., an individual's preferred times for peak physical and cognitive performance) across the human lifespan in Germany, Switzerland and Iceland have suggested the transition towards eveningness begins in toddlerhood, with the largest change happening around puberty (Thorleifsdottir *et al.*, 2002; Roenneberg *et al.*, 2004; Randler, Faßl and Kalb, 2017). Corresponding to sex differences in pubertal onset, females begin and reach magnitude of their chronotype shift at younger ages than males, while adolescent males usually exhibit a more extreme preference for late sleep-wake schedules (Hummer and Lee, 2016). Importantly, observed changes in adolescent sleep-wake cycles result from a complex interplay of distinct processes, including circadian and homeostatic sleep regulatory mechanisms, sleep entrainment to socioecological cues, maturation and development, and various behavioral phenomena (e.g. physical activity levels, stimulant consumption and late-evening exposure to screen-based devices) (Carskadon, 2002; Touitou, 2013).

According to the Social Jetlag Hypothesis (SJH) (Peixoto *et al.*, 2009; Pereira, Louzada and Moreno, 2010), "modern" lifestyles constitute a disruptive sleep environment that prevent adolescents from fulfilling their "biological/natural" circadian cycle and sleep quotas. It is hypothesized that adolescents living in non-industrial settings more closely comply with their "biological/natural" circadian cycle and sleep quotas (Peixoto *et al.*, 2009; Pereira, Louzada and Moreno, 2010). Yet, little is known about sleep patterns in non-WEIRD societies (Western, Educated, Industrial, Rich, Democratic), and most research conducted with non-industrialized groups has focused on adults

(18y+) (Knutson, 2014; Ball, Tomori and McKenna, 2019; Samson, 2020). Moreover, few "naturalistic" studies have addressed biological and cultural interactions in the developmental ecology of human sleep (Worthman and Melby, 2002).

Previous research examining adolescent sleep in rural and non-industrial populations has been conducted in Germany, China, Egypt, Brazil, Argentina, and Uganda (Louzada and Menna-Barreto, 2003, 2004; Worthman and Brown, 2007, 2013; Loessl *et al.*, 2008; Ouyang *et al.*, 2009; Peixoto *et al.*, 2009; Pereira, Louzada and Moreno, 2010; Christoph *et al.*, 2017). These studies report a wide variation in adolescent sleep duration, from 7-10.67 hours/ day. Longer durations of sleep were generally associated with earlier bedtimes and sleep onset. Observed variation in sleep-wake timing was explained by aging, pubertal stage, access to electricity, weekday schedules, school demands, daily and pre-sleep activities, bed-sharing habits, and seasonal variation in daylight. However, results are difficult to compare because of differences in age groups, the instruments and definitions used to calculate sleep duration, and study durations.

Using a cross-cultural perspective, this paper is oriented to unravel sleep nuances by re-examining assumptions of adolescent “natural”/optimal sleep and, thereby, to enhance understanding of human sleep development. Specifically, we compared adolescent sleep patterns in two non-industrial and one postindustrial society in Mexico. The primary aims were to: (1) investigate whether the shift in reported sleep-wake cycles of adolescents in industrialized populations is replicated in non-industrialized societies, and (2) examine which bio-socio-cultural environmental factors influence sleep timing in these settings. Particularly, we explored how characteristics such as working/schooling, access to electric light and electronic devices, daily exposure to natural light, and the practice of social sleep might alter the timing of adolescent sleep.

4.2 Results

Sleep ecology

The three study sites reflect a gradient between “modern” societies and “traditional” in terms of sleep environments and access to technology. In Mexico City, 94% of participants had access to mobile phones, and all had broadband and mobile coverage. In Puebla, 67% had access to mobile phones, limited mobile coverage and no broadband. Meanwhile, in Campeche, 57% had access to a mobile, blackouts were common due to heavy rains, and there was no broadband nor mobile coverage.

Participants slept on beds in Mexico City, on beds or traditional wooden surfaces in Puebla, and on hammocks in Campeche. In Mexico City, most participants slept alone (72%); in contrast, this practice was rare in Puebla (33%) and Campeche (11%), where social sleep (co-sleeping or room sharing) was the custom. Although both urban and rural teenagers slept indoors, housing characteristics differed widely. In Mexico City homes of concrete, steel, and bricks predominated. Along with the materials above, buildings in Puebla were also constructed of rocks, wood, and cardboard, while in Campeche a mixture of modern and traditional materials, such a as raw earth, palm and wood, were used. As a result, urban adolescents slept in rooms with cement roofs where external sounds, light beams, air drafts, and temperature fluctuations were buffered by glass windows, curtains, and solid, sealed doors. Totonac adolescents in Puebla slept in rooms with roofs made of baked tiles, cement, corrugated metal or cardboard, while windows and doorways would not necessarily be glazed or wholly sealed. Maya adolescents mostly slept under roofs made of palm leaves and corrugated metal or cardboard, with few windows, curtains or sealed entrances.

Notably, 76% of urban participants reported sleeping in a dark environment, while 18% reported their rooms were illuminated at night by streetlights or moonlight, and 6% kept a light or their TVs on while sleeping. Similarly, 68% of the Maya adolescents slept in the dark, 16% reported an external source of light, and 16% kept an indoors light on at night. In contrast, 39% of the Totonac teenagers slept in the dark, 24% had an external source of light, and 37% indicated they slept with a light on. When asked about the reasons for keeping a light source on while sleeping, participants said they needed to watch images to fall asleep or that they kept the lights on because they or a family member was afraid of the dark.

Finally, respecting school demands, a notable aspect of adolescents' sleep macroecology, classes in Mexico City started at 7:30 hrs, while those in rural sites began at 8:00. Additionally, commuting times to school in Mexico City lasted between 5-50 minutes, either by walk, car, public transport, or school bus. Participants in Puebla and Campeche arrived at school after a 5-10 minutes' walk from their homes.

Sleep-midpoint and social jetlag

Sleep characteristics were calculated for each site (details in Material and methods) (Figure 1). During school nights, the participants from Mexico City had the shortest sleep duration (7.9 hr, SD=58 min), expressing the earliest sleep onset (22:23:47, SD=55 min) and sleep end (6:12:28, SD=27 min). In comparison, Maya participants from Campeche had the shortest sleep duration (8.9 hr, SD=89 min) during free nights, with the second latest sleep onset (23:05:15, SD=80 min) and earliest sleep end (7:59:38, SD=66 min).

We found a significant difference between the overall values for sleep midpoint (the halfway point between the sleep onset and the sleep end) during school and non-school nights (t=-19.3, df=889, $p < .05$) (Table 1). Likewise, there was a significant difference between values for sleep midpoint across sites during school nights and free nights (t-test, $p < .05$). Regarding the participants' social jetlag scores, we identified a significant difference between the teenagers from Mexico City (1.8 hr, SD=52 min) and those from both agricultural societies (Puebla: 0.5 hr, SD=29 min; Campeche: 0.6 hr, SD=26 min), but not between the latter (H=65.9, df=2, $p < .05$).

Bio-socio-cultural predictors of sleep timing

School nights

Our final model for school nights (Table 2) incorporated gender (boys being the reference category), napping before the main sleep, nightly exposure to screen-based devices (NESDI), and parent-set bedtime as predictor variables for the sleep-midpoint variance ($R^2_{Marginal\ /\ Conditional}$ = 0.103 / 0.558; $ICC_{Adjusted\ /\ Conditional}$ = 0.507 / 0.455, df = 596). The timing of sleep-midpoint was negatively influenced by gender and parent-set bedtime, and positively influenced by napping before going to sleep and NESDI.

Free nights

The predictor variables for sleep-midpoint variance during free nights in our final model were pubertal development, napping before the main sleep, NESDI, and assisted awakening ($R^2_{Marginal\ /\ Conditional}$ = 0.471 / 0.393; $ICC_{Adjusted\ /\ Conditional}$ = 0.166 / 0.559, *df* = 574). During non-school nights, sleep-midpoint was positively affected by pubertal development, nightly exposure to ambient lighting, and NESDI. Assisted awakening was the sole predictor negatively affecting sleep-midpoint.

Site-specific models

The final model (Table 3) for Mexico City included pubertal development, napping before the main sleep, NESDI, ambient light at night, sunrise timing, and assisted awakening as predictor variables for sleep-midpoint ($R^2_{Marginal\ /\ Conditional}$ = 0.214 / 0.723; $ICC_{Adjusted\ /\ Conditional}$ = 0.648 / 0.509, *df* = 403). Assisted awakening negatively affected sleep-midpoint values, while mid-puberty, naps before the main sleep, NESDI and exposure to ambient light at night had a positive influence on them (Figure 2). The model for the Totonac agricultural site (Puebla) comprised pubertal development, napping before the main sleep, nightly exposure to ambient light, and sunset timing as predictor variables ($R^2_{Marginal\ /\ Conditional}$ = 0.075 / 0.577; $ICC_{Adjusted\ /\ Conditional}$ = 0.543 / 0.503, *df* = 409). Here we found that sleep-midpoint was positively influenced by advanced-puberty, napping, and nightly exposure to light. Lastly, the best-fitting model for the Maya agricultural site (Campeche) incorporated napping before the main sleep, nightly exposure to ambient light, sunrise and sunset timing, assisted awakening and co-sleeping practices as predictor variables ($R^2_{Marginal\ /\ Conditional}$ = 0.136 / 0.455; $ICC_{Adjusted\ /\ Conditional}$ = 0.370 / 0.320, *df* = 346). Sleep timing in Campeche was negatively affected by sunrise timing and assisted awakening, while positively influenced by napping, nightly exposure to light, sunset timing and co-sleeping.

4.3 Discussion

“Modern” post-industrial lifestyles are thought to impair teen sleep, particularly during school days when teenagers cannot express their “biological/natural” circadian cycle. It is hypothesized that teenagers in non-WEIRD settings comply with their “biological/natural” sleep-wake cycle, presumably free of circadian misalignments between “social” and “biological clocks”. Our findings confirm a more stable sleep-wake cycle among rural adolescents than urban ones. The latter expressed more variability in sleep timing having the latest sleep midpoint during free nights, with a delay of almost 2 hrs. relative to weekdays. However, social jetlag was observable, although less so, in both agricultural societies with a sleep delay ranging between 31-36 minutes.

Only two other papers exist on sleep-wake habits of Mexican teenagers (13-16y) in Reynosa, north Mexico (Arrona-Palacios, García and Valdez, 2015; Arrona-Palacios and Díaz-Morales, 2017), where school also started at 7:30 am. Compared to our urban group, adolescents in Reynosa had a later sleep start during school (23:00, SD=71 min) and non-school days (00:30, SD=111 min), while waking at the same time during school days (6:11, SD=29 min) and later on free days (10:30, SD=107). Results from this questionnaire-based research accord with ours in finding wide variability in Mexican urban adolescents’ sleep timing. Previous research in rural Southern Brazil (Peixoto *et al.*, 2009) and East China (Ouyang *et al.*, 2009) also reported discrepancies in sleep timing between school and non-school nights concurring with our findings. Other studies among rural and urban students (Thorleifsdottir *et al.*, 2002; Loessl *et al.*, 2008; Christoph *et al.*, 2017) do not address differences in sleep timing between school and non-school nights.

Differences in sleep midpoint variability between our urban and rural sites might be partly explained by school schedules and commuting times since participants in Mexico City began classes 30 minutes earlier than those in rural areas and had longer commutes. Additionally, working demands and social commitments during non-school days could shape adolescent sleep. Unlike urban participants, sleeping until late morning during weekends was not standard among rural teenagers as many were expected to engage in their community’s religious or economic activities (Kramer, 2004; Masferrer-Kan, 2009). Furthermore, differences in sleep timing distribution might also respond to adolescents' exposure to light. Given that the phase entrainment of circadian systems largely depends on duration and intensity of light signals, rural lifestyles with greater exposure to natural light might favor narrower sleep midpoint distributions (Roenneberg, Wirz-Justice and Merrow, 2003).

We examined whether the delay in adolescent sleep-wake schedules reported in industrialized populations was replicated in non-industrialized societies. After controlling for gender, napping and environmental factors (i.e., lightning, screen-based devices use, and social sleep practices), pubertal development significantly influenced sleep-midpoint on free nights, but not on school nights. This may occur because school schedules homogenize teenagers' sleep timing, notwithstanding their developmental stage. However, the effects of pubertal development stages varied at each site. In Mexico City, mid-puberty significantly delayed sleep-midpoint while, in Puebla, advanced puberty had the same effect. In Campeche there was no significant impact of pubertal development on sleep timing. These findings suggest that the shift in adolescent sleep-wake cycles might be contextual rather than universal.

Other studies addressing changes in adolescent sleep and its potential association with sexual maturation in rural environments have used age (Pereira, Louzada and Moreno, 2010) or Tanner Stage (Ouyang *et al.*, 2009) as a proxy for individual developmental stage, instead of the PDS. Although most literature points towards an age-related sleep phase delay during adolescence, a questionnaire-based study among 1547 urban Taiwan students (9-16y), found no association between PDS and changes in sleep-wake patterns throughout school nights or free nights (Gau and Soong, 2003). Instead, variations in sleep schedules were related to growing academic demands. Additionally, the extent and timing of the adolescent sleep delay seem to vary depending on the population (Thorleifsdottir *et al.*, 2002; Worthman and Brown, 2007; Arrona-Palacios and Díaz-Morales, 2017). In this sense, our study adds to the literature documenting variability in adolescent sleep-wake cycles, suggesting that, although the phase delay may have a biological substrate, its expression is dependent on other ecological factors. Furthermore, contrary to earlier hypotheses[12,13], our least industrialized study site was furthest from what is commonly assumed as “natural” adolescent sleep.

We found that gender significantly predicted sleep-midpoint across school nights, with boys expressing a later sleep midpoint than girls; this difference was not observed on free nights. Although there was no significant effect of gender on sleep-midpoint across sites, girls in both Mexico City and Campeche tended to have an earlier sleep onset than boys during school nights. This trend was not observed in Puebla, where boys and girls went to sleep at similar times, with boys waking up later during weekdays and earlier during free days. Differences in sleep timing may be linked to different access to screen-based devices, the existence of structured bedtimes routines, time invested in getting ready for school, and gender-related participation in household activities.

While previous research found no gender differences in sleep timing of adolescents in Mexico (Arrona-Palacios, García and Valdez, 2015; Arrona-Palacios and Díaz-Morales, 2017), Egypt (Worthman and Brown, 2007), China (Ouyang *et al.*, 2009) and Iceland (Thorleifsdottir *et al.*, 2002), other studies have reported different sleep-wake schedules for boys and girls (Hummer and Lee, 2016). For example, rural girls in Southern Brazil (Pereira, Louzada and Moreno, 2010) woke up significantly earlier during school and non-school days than boys but bedtimes did not differ by gender. Similarly, Loessl *et al.* (2008) found that, while urban and rural boys in Southwest Germany had later bedtimes on school and non-school nights, girls woke up earlier on school days.

Whether sleep differences are underpinned by gender roles or sexual dimorphism remains debatable. Female-male sleep variation may arise from sex chromosome differences, disparities in circulating hormones, and specializations in receptor and ion channel expression (Bailey and Silver, 2014). However, a study comparing self-reported sleep duration by sex and ethnicity (African American, Hispanic, Asian and White) among 1543 students (11-14y) in Texas, USA (Marczyk Organek *et al.*, 2015), suggests socio-cultural factors sustain adolescent differences in sleep, providing evidence of the intersectionality of sleep disparities.

Daytime napping consistently delayed sleep-midpoint during school and non-school nights in both rural and urban sites. Although napping behaviour is an essential feature of adolescent sleep-wake cycles, few studies have addressed this (Gradisar *et al.*, 2008), especially in relation to nocturnal sleep timing. The effect of napping on sleep-midpoint aligns with results from previous studies examining daytime naps in rural and urban Egyptian teenagers (Worthman and Brown, 2007) (10-20y) and urban students (14-19y) in South Africa (Reid, Maldonado and Baker, 2002), US (Jakubowski *et al.*, 2017), Australia (Gradisar *et al.*, 2008) and Japan (Fukuda and Ishihara, 2002). Such delays might stem from a decreased homeostatic sleep drive allowing teenagers to stay awake later.

Later sleep onset may, in turn, lead to short sleep quotas, particularly during school nights, increasing sleep drive and potentially triggering new napping episodes. Although short naps are effective in maintaining alertness and recovery from strenuous activities (Horne, 2011), much of the existing literature has focused on their association with shorter sleep durations and possible adverse health outcomes (Jakubowski *et al.*, 2016). Still, napping is not a reliable indicator of "sleep debt" as adolescents might well nap for pleasure or to avoid over-exposure to mid-day heat (Horne, 2011).

We found that NESDI delayed sleep-midpoints during school and free nights. Yet, although it tended to retard the sleep-midpoint of rural adolescents, its effect was significant only among urban adolescents. The different impact of NESDI in urban and rural settings may lie in differential access to screen-based devices, internet and mobile coverage.

Similarly, we found that nightly exposure to dim ambient lightening (equal or lesser than 20 Lux) significantly delayed sleep-midpoint on free nights. Even though the impact of ambient lighting was significant at all sites, the effect was larger in Puebla, where keeping a light on while sleeping was common among Totonac agriculturalists (37%) compared to Maya (16%) or urban (3%) populations. Sunset and sunrise times exclusively affected sleep timing in Campeche, significantly advancing and delaying sleep-midpoint, respectively. These effects were not observed in Mexico City or Puebla, possibly because the housing of Maya agriculturalists provides less shielding from environmental-light cues.

The mechanisms underlying the delaying/advancing effects of light on nocturnal sleep timing have been addressed elsewhere (Roenneberg, Wirz-Justice and Merrow, 2003; Peixoto *et al.*, 2009; Carskadon, 2011; Touitou, 2013; Touitou, Touitou and Reinberg, 2017). However, the linkage of adolescent emotional-cognitive life with the (over)use of artificial light sources (i.e. screen-based devices or electric lightning) and its impact on sleep is often overlooked (Worthman and Brown, 2007). Interviews revealed that emotions, such as anxiety, fear and worry, influenced adolescents' reliance on light while sleeping. Participants "needed" to watch images to fall asleep or keep a light on to feel safe. Negative emotions, coupled with the effects of light on the human circadian system, may exacerbate adolescent sleep delay and difficulties. Furthermore, since adolescents' dopaminergic reward system and prefrontal cortex (key for the pursuit of non-immediate rewards and the acquisition of complex social skills) are still maturing and remodelling (Davey, Yücel and Allen, 2008), teenagers are particularly vulnerable to addictive behaviours (Touitou, Touitou and Reinberg, 2017). Therefore, the overuse of electronic media until late-night might emerge as a coping strategy to avoid problems and negative emotions.

Bedtimes set by parents significantly advanced sleep-midpoint on school nights, when awakening times were inflexible, and sleep was more sensitive to bedtime changes. Meanwhile, assisted awakening significantly advanced sleep-midpoint on free nights, when awakening times gained relevance in shaping sleep. The significant effects of assisted awakening were found in Mexico City and Campeche, but not Puebla while the influence of parent-set bedtimes was significant in Mexico City and Puebla, but not Campeche. Site differences in the impact of both variables might reflect differences in participants' autonomy and parents' involvement in teenagers' sleep schedules.

We found that co-sleeping, a common practice among rural households, significantly delayed the sleep-midpoint of Maya teenagers in Campeche. In contrast, co-sleeping arrangements tended to advance sleep-midpoint among Totonac teenagers in Puebla. The contrasting effects of social sleep practices on sleep timing may result from Maya housing quality, composed of one or two rooms serving simultaneously as social, eating and sleeping spaces. Under these conditions, individual sleep might be delayed by others' activities. In addition, distinct co-sleeping effects may be related to adolescents' cognitive-emotional state (Worthman and Brown, 2007). For instance, in Puebla, where many participants keep the lights on to feel safe at night, co-sleeping might help regulate arousal and promote sleep. Thus, depending on its context, co-sleeping could act to inhibit or excite alertness, thereby promoting or hindering sleep.

Although our results suggest social cues can significantly shape sleep-wake cycles, social aspects of adolescent sleep (beyond schooling demands) are rarely addressed in the literature (Worthman and Brown, 2007), being disregarded as minor influences in circadian cycles (Roenneberg, Wirz-Justice and Merrow, 2003). Nevertheless, previous research in infancy and early childhood have highlighted the importance of social sleep practices on circadian development and health outcomes (Ball, Tomori and McKenna, 2019). More attention should therefore be applied towards the value of social sleep for adolescent sleep regulation and development.

Overall, our findings suggest that the set of environmental, socio-cultural and technological features particular to each site create different developmental niches where growing individuals express and develop their sleeping behavior (Harkness and Super, 1994; Worthman and Melby, 2002). Furthermore, changes in adolescent sleep-wake cycles may arise from life-history trade-offs, reflecting how individuals allocate their energetic resources (Worthman, Dockray and Marceau, 2019). In this respect, resources are prioritized towards brain growth before puberty, suppressing the reproductive system (Stearns and Koella, 1986). However, shortly before puberty, neural pruning commences, and after its onset, an aggregate of investments in physical, cognitive and reproductive maturation initiate (Colrain and Baker, 2011; Worthman, Dockray and Marceau, 2019). Changes in sleep might be a key component of the switchover to investments in reproduction. Individuals with circadian and homeostatic plasticity can adapt to changeable living conditions, ensure food procurement, carry on child-rearing activities, and perform sentinel behaviors, thus, benefitting individual and group fitness. Further research is needed to test this idea and to understand better the impact of sleep ecology on circadian development and health outcomes. We advocate further developmental sleep research employing ecological, cross-cultural perspectives to understand global patterns of sleep. Documenting sleep variability among different cultures, social strata and age groups will help inform debates about what constitutes “normal”, healthy human sleep.

Our study has some limitations. Being a cross-sectional study, we lack longitudinal sleep data. Having information on different age group segments is crucial to draw comparisons or sleep developmental trajectories. Likewise, we were unable to account for seasonal variations in food availability, energy expenditure and allocation which presumably impact sleep characteristics. Our sample size was small, restricted by convenience sampling in urban and rural settings. Finally, the PDS, a self-report instrument of the pubertal status, may be less reliable than Tanner stage and thus, fail to reflect the precise developmental stage of the participants.

4.4. Material and methods

Study Sites and Participants

A convenience sample of 163 participants was recruited from three sites in Mexico, one urban, postindustrial (Mexico City, n=67) and two rural, non-industrial (San Juan Ozelonacaxtla, Puebla, n=51, and Xculoc, Campeche, n=45) (Figure 1). Participant recruitment was school based, focusing on students between 11 and 16 years old who were invited to take part in the study (mean age 13.7, SD ± 1.21). Nearly half of the sample were females (n=78, 48%). The study was conducted between February 1 and April 8, 2019, in Mexico City, between May 31 and July 5, 2019, in Campeche, and between September 6 and November 11, 2019, in Puebla (see Supplementary Table 1 for information about day length, precipitation and temperature).

Mexico City, with an estimated 8.9 million inhabitants (89% identifying as "mestizos", 9% belonging to an indigenous group and 2% as Afro-descendants), is located in a highlands plateau, 2,303 m above sea-level, with a predominantly service-based economy (INEGI, 2020). Participants were recruited from two private schools in the south and northeast urban areas. Students spoke Spanish as their first language and belonged to relatively affluent and educated families.

San Juan Ozelonacaxtla, Puebla, an agricultural Totonac community estimated at 1,368 people in 2010, lies 834 m above sea-level at the intersection of two mountain systems (INEGI, 2020). Electricity and running water were introduced by the end of the 1980 (Hernández-Loaeza, 2014), followed by better roads, schools and a local health centre. Notably, regional orographic characteristics prevented the use of mechanized agriculture, preserving traditional farming techniques (Hernández Loeza and Lemus de Jesús, 2017). Here, participants, who were recruited through two local public schools, spoke Totonaku as their first language and Spanish as their second. Household economies largely depended on agriculture (mostly growing coffee, corn and pepper) and animal breeding (ducks, chicken, pigs and cattle), but also trades (such as baker or shopkeeper), and remittances from migrant family members working in Puebla de Zaragoza or Mexico City in construction or as domestic helpers. Children and adolescents with migrant parents generally remained in the community with close relatives.

Xculoc, Campeche, is a small agricultural Maya community numbering 835 people in the Yucatan Peninsula plain, 69 m above sea level (INEGI, 2020). The community is undergoing a demographic and economic transition with the recent introduction of electricity, running water, new and intensive farming techniques, schools, and roads (Urlacher and Kramer, 2018), but remains isolated from public transport. Participants, recruited from the two local public schools, spoke Maya as their first language and Spanish as their second. Household economies predominantly depended on subsistence agriculture and crop sales (such as corn, peanuts and squash), apiculture, animal breeding (ducks, chicken and sheep), construction labor, or work in in neighboring village restaurants.

This study protocol was approved by the Ethics Committee of the Anthropology Department at Durham University. Participants and their parents gave written signed consent after receiving a verbal explanation of the study and reading the consent form. Consent was obtained in Maya and Totonaku with the support of local assistants who were fluent in either Peninsular Maya and Spanish or Highland Totonaku and Spanish. All procedures were performed following the guidelines of the Mexican General Health Regulation on Health Research Matters and the Mexican Official Standard NOM-012-SSA3-2012, which establish the criteria for the execution of health research projects.

Measurement tools

Adolescents participated in the study over a 10-day span, composed of six school days and four non-school days. Wrist actigraphy, sleep diaries, semi-structured interviews, observations and two standardized questionnaires were used to assemble information regarding the participants' sleep characteristics, (i.e. time in bed, sleep onset, sleep end, total sleep duration), environmental factors (i.e. exposure to seasonal variations in temperature and light, access to electricity, use of electronic devices, bedding characteristics, social or solitary sleeping practices), daily activities (i.e. working and/or schooling efforts) and pubertal maturation.

Wrist actigraphy

Actigraphy is increasingly being used to measure sleep in various human populations (Samson *et al.*, 2016; Rattenborg *et al.*, 2017). This non-invasive method has been proved useful for quantifying rest-activity rhythms, sleep duration, timing, and sleep segmentation (i.e. nighttime wake-bouts and daytime napping) (Peixoto *et al.*, 2009; de la Iglesia *et al.*, 2015; Moreno *et al.*, 2015; Beale *et al.*, 2017; David R. Samson, Crittenden, *et al.*, 2017; Samson, Manus, *et al.*, 2017). Compared to polysomnography (PSG), which remains the gold standard for quantifying sleep, actigraphy devices are non-cumbersome, easy to apply with ambulatory populations, and less expensive (Samson *et al.*, 2016). In addition, actigraphy devices can capture continuous data during days, weeks or more while subjects perform their normal daily routines (Rattenborg *et al.*, 2017).

Data on sleep characteristics and ambient light was estimated employing Motionlogger Micro Watch units (Ambulatory Monitoring Inc., US) set for 1-min epochs in the Zero Crossing Mode (ZCM). During 10 continuous days for 24 hours, 147 participants wore the actigraphy devices on their non-dominant wrist. They were asked to press the event logger button before any sleep event during the study. Two of the adolescents did not have valid actigraphy data as their watch failed to register any data. Therefore, a total of 145 participants were included in the analyses (Mexico City, n=50; Puebla, n=51; Campeche, n=44), with 49.6% of them being females (n=72). Given the fixed number of devices and time in each site, we could not include more participants in the actigraphy sample. We obtained 1405 sleep observations, of which 787 corresponded to school nights and 618 to non-school nights.

The actigraphy data were analyzed using the manufacturer's software (Action W 2.7) with the Sadeh algorithm to describe the adolescents' sleep-wake behaviour. We further validated the accuracy of the actigraphy measurements against sleep diaries as recommended (Short *et al.*, 2012; de la Iglesia *et al.*, 2015). To do so, sleep scores were scrutinized after being generated by the Action W 2.7 software. When the analyst identified missing data (due to a watch off-wrist period or malfunction), a nap episode (see Table 4 for sleep measurements definitions) or had additional information on the participant's sleep behavior drawn from the sleep diary, the scores were manually edited. This enabled us to detect "false" wake-like or sleep-like entries (Samson *et al.*, 2016).

Sleep diaries

Sleep diaries were used to collect data on sleep behavior and sleepiness during the day. We employed a modified, simplified version of the Consensus Sleep Diary (Carney *et al.*, 2012) and the Pediatric Daytime Sleepiness Scale (PDSS) that used a simple design with images, colors and scales to allow completion by participants who were not proficient in reading or writing. The Consensus Sleep Diary was developed by experts in insomnia to enable comparisons across sleep studies; the PDSS is a brief eight items questionnaire suitable for children and early adolescents and examines sleepiness across distinct moments of the day. All participants were instructed to fill the sleep diaries before and after their night sleep throughout the study's 10-day span.

Questionnaires

Each participant answered two standardized questionnaires which were verbally explained to them and any questions were clarified. We obtained information about the participants' sleep-wake preferences and chronotype through the Morningness-Eveningness Reduced Scale (MERS) (Adan and Almirall, 1990) which is relatively short, has been validated in Spanish-speaking populations, and is suitable for cross-cultural examinations (Adan and Almirall, 1990; Díaz-Morales and Sorroche, 2008). Along with sleep diaries, the data from MERS helped to validate the accuracy of the actigraphy measurements further and overcome technical difficulties, including watch removal intervals.

Data about pubertal maturation were collected using the Pubertal Development Scale (PDS). The PDS is a self-report instrument that provides a non-invasive assessment of pubertal status (Robertson *et al.*, 1992). We used puberty as a reference point to discuss changes in adolescent sleep responding to the issue that, since adolescence is a bio-psycho-socio-cultural category designating the transition from childhood to adulthood (Arnett, 2000; Davey, Yücel and Allen, 2008), there is no agreement on what changes mark the beginning, middle and end of adolescence (Hummer and Lee, 2016).

Semi-structured interviews and ethnographic observation

Semi-structured interviews, based on the work of Grandner *et al.* (2014), were used to obtain information about the sleep environment of each participant. Questions were included about the adolescents' daily use of time, along with items from the Pittsburgh Sleep Quality Index test (PSQI). This standardized questionnaire measures the quality and patterns of sleep based on one month recalls. Importantly, as happens with the MERS, the PSQI is considered suitable for cross-cultural examinations given that it is short and has been validated in Spanish-speaking populations (Jiménez-Genchi *et al.*, 2008).

The semi-structured interviews were specifically aimed at: 1) describing ongoing sleep-wake patterns and sleep quality of the participants, 2) describing culturally normative ideas and practices about sleep, 3) comparing characteristics and cultural settings in which participant adolescents slept, and 4) identifying access to electricity and/or electronic devices (Grandner *et al.*, 2014). The interviews had an average duration of 45 minutes. Additionally, observations inside and outside the school environment helped further explore adolescents' social roles, their peer relationships, their daily ways of life and attitudes towards sleep. A field diary was used to record daily activities, observations, casual conversations, notes about interviews, and comments about research development.

Calculation of meteorological and solar variables

Latitude and longitude coordinates were determined with Google maps for the three sites. Coordinates were used with the NASA Langley Research Center (LaRc) POWER Project funded through the NASA Earth Science/Applied Science Program (https://power.larc.nasa.gov/) to obtain daily data on precipitation, humidity, surface pressure, minimum and maximum temperature, sky insolation incident and the Insolation Clearness Index. Meanwhile, daily data on the times of sunrise, sunset and day length were obtained through a solar geometry study (see Supplementary Note to consult details about the calculations used to determine solar data).

Statistical analyses

Statistical analyses was conducted using R version 3.6.3 with significance levels set at 0.05. To investigate whether the shift in the reported sleep-wake cycle of adolescents in industrialized populations is replicated in non-industrialized societies, we focused our analysis on the variation of participants' sleep-midpoint values (i.e., the halfway point between the sleep onset and sleep end). The sleep-midpoint has been proposed as a phase marker from which dim light melatonin onset (DLMO) can be readily estimated when sleep times are minimally shaped by school, work, or family commitments ("free" nights) (Hofstra and de Weerd, 2008; Crowley, 2013).

We generated descriptive statistics to characterize sleep timing and duration in our sample population. We used a paired t-test to assess whether there were significant differences in the participants' sleep midpoint values between school and non-school nights. Next, we ran an ANOVA to determine if the sleep midpoint values significantly differed between our three sites. Both tests were two-tailed.

The SJH posits that adolescent chronotypes are freely expressed during non-school days, when teenagers can fulfill their "biological/natural" circadian cycle and sleep quotas (Randler *et al.*, 2019). To estimate the extent of the misalignment between the participants' alleged chronotypes and social sleep schedule (i.e., social jetlag), we subtracted each individual's sleep midpoint mean during school nights from their sleep midpoint mean during free nights. We ran a Kruskal-Wallis test to ascertain whether the resulting values differed significantly between our three sites. We then ran post hoc tests to further assess where the differences between sites lie.

To examine the effects of sexual maturation, exposure to natural and artificial light, and co-sleeping practices on participants' sleep-midpoint values during school nights and free nights, we fitted two linear mixed-effects models using the *lme4* package (Bates *et al.*, 2015). To control for repeated measures nested within individuals that are, in turn, nested within three different sites, we included "subject" and "site" as random effects. Additionally, we ran three site-specific models to break down the particular effects of our predictor variables on the participants' sleep-midpoint in each site. For these models, we controlled for repeated measures nested within individuals that vary within two different conditions (i.e., free nights and school nights) by including "subject" and "condition" as random effects.

In all our models, we tested pubertal development (scored as pre/early, mid, and advanced puberty), gender, napping before the main sleep, nightly exposure to screen-based devices (NESDI-variable indexed according to the number of devices being used after 8 pm), the nightly exposure to light (the percentage lux count epochs relative to the individual's sleep duration), sunset and sunrise times, co-sleeping practices (the practice of bed-sharing or room-sharing), co-sleepers' generation (the co-sleeper status as an adult or pediatric individual), parent-set bedtime and assisted awakening (the use of an external agent, alarm or person, to wake up) as predictor variables (see the online Extended Data, Tables 5 and 6, to consult the resulting full models). We employed the *MuMin* package (Barton, 2020) to select our final models using AIC and BIC as criteria. All the residuals of the best-fitted models were normally distributed. Our statistical inferences were based on confidence intervals and p-values.

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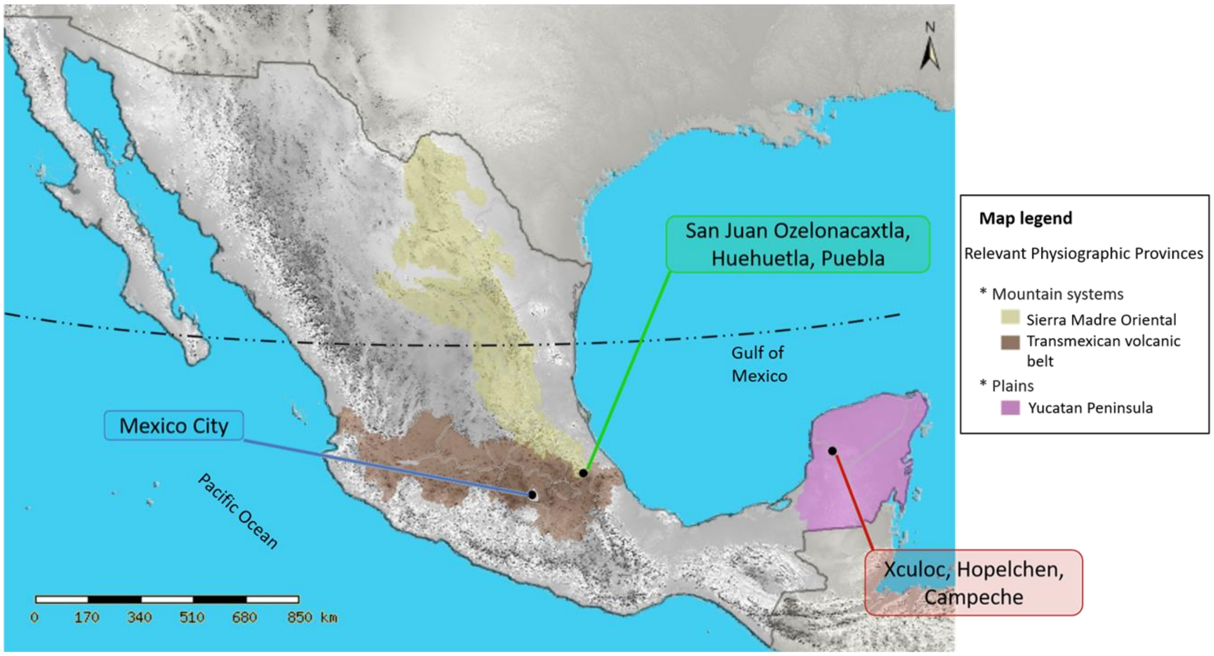
Figures and tables

A



B

Weeknight	Site	Start time	Sleep-midpoint	End Time	Sleep duration	Nap ratio
School night	Mexico City	-96.21 (54.58)	137.87 (33.05)	372.47 (27.12)	471.01 (57.94)	17.23 (22.04)
	Campeche	-71.04 (47.33)	172.5 (30.42)	416.61 (29.56)	488.66 (50.18)	20.12 (27.43)
	Puebla	-88.95 (65.94)	163.42 (38.97)	416.35 (28.45)	508.41 (65.36)	13.07 (18.05)
Free night	Mexico City	-29.52 (82.11)	247.95 (75.26)	525.95 (93.61)	556.47 (91.39)	14.78 (19.78)
	Campeche	-54.75 (80.01)	212.2 (57.99)	479.63 (65.58)	535.39 (89.16)	18.75 (26.85)
	Puebla	-86.78 (73.3)	197.09 (59.18)	481.51 (74.99)	571.06 (88.16)	13.56 (19.79)

Figure 1. (A) Location of study sites, based on cartographic data from INEGI (2021). (B) Values for sleep timing, duration and napping behaviour by sites. Data are represented as mean (standard deviation).

Site	Social jetlag	Sleep midpoint		
		School night	*Free night*	*Significance*
Global	60.67 (52.26)	158.95 (37.27)	221.6 (69.51)	t=-19.3, p < .05
Mexico City	108.97 (50.88)	137.87 (33.05)	247.95 (75.26)	t=-5.3, p < .05
Campeche	35.73 (25.88)	172.5 (30.42)	212.2 (57.99)	t=-13.6, p < .05
Puebla	31.47 (29.31)	163.42 (38.97)	197.1 (59.18)	t=-12.9, p < .05
Significance	H=65.9, p<.05	F=70.6, p < .05	F=38.1, p < .05	

Table 1. Comparison of sleep midpoint and social jetlag values between Maya (Campeche), Totonac (Puebla) and post-industrial (Mexico City) adolescent populations.

All-sites final models	**School nights**				**Free nights**			
Predictor	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*
Girls	-11.7	(-19.88, -3.52)	**0.005**	596				
Nap before big sleep	12.09	(5.48. 18.69)	**<0.001**	596	13.98	(2.52, 25.43)	**0.017**	574
NESDi (1)*	12.41	(1.82. 22.99)	**0.022**	596	21.94	(1.91, 41.98)	**0.032**	574
NESDi (2)*	15.79	(4.25, 27.32)	**0.007**	596	34.75	(13.11, 56.39)	**0.002**	574
NESDi (3+)*	28.73	(8.20, 49.25)	**0.006**	596	34.67	(-3.00, 72.34)	0.071	574
Parent-set bedtime	-9.03	(-17.90, -0.15)	**0.046**	596				
Mid puberty					24.4	(0.87, 47.94)	**0.042**	574
Advanced puberty					22.35	(0.98, 43.72)	**0.04**	574
Nightly exposure to light (<20 lux)					4.14	(3.22, 5.06)	**<0.001**	574
Assisted awakening					-28.07	(-49.59, -6.56)	**0.011**	574
Sites (Intercept)								
Mexico City	-17.92				18.83			
Puebla	4.58				-17.58			
Campeche	13.33				-1.25			

* The screen-based devices index accounts for the number of gadgets adolescents used to employ after 8 pm (e.g. mobiles, tablets, laptops or TVs).

Table 2. Bio-socio-cultural predictors of sleep midpoint values for school nights and free nights across sites. Negative coefficients indicate advanced sleep midpoints, while positive coefficients delayed sleep midpoints.

Site-specific final models	**Mexico City·Post-industrial**				**Puebla·Totonac**				**Campeche·Maya**			
Predictor	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*
Mid puberty	28.97	(4.49, 53.45)	**0.02**	403	15.02	(-12.17, 42.21)	0.279	409				
Advanced puberty	14.29	(-7.87, 36.45)	0.206	403	28.55	(3.58, 53.51)	**0.025**	409				
Nap before big sleep	9.8	(-2.02, 21.62)	0.104	403	14.79	(4.06, 25.52)	**0.007**	409	13.22	(1.63, 24.80)	**0.025**	346
NESDi (1)	24.55	(2.34, 46.76)	**0.03**	403								
NESDi (2)	41.85	(17.23, 66.48)	**0.001**	403								
NESDi (3+)	52.12	(19.97, 84.27)	**0.001**	403								
Nightly exposure to light (<20 lux)	3.78	(2.93, 4.63)	**<0.001**	403	14.55	(5.98, 23.12)	**0.001**	409	2.47	(1.29, 3.65)	**<0.001**	346
Sunrise time	0.47	(-0.09, 1.04)	0.101	403					-8.6	(-14.41, -2.79)	**0.004**	346
Assisted awakening	-28.83	(-57.13, -0.54)	**0.046**	403					-14.06	(-26.27, -1.85)	**0.024**	346
Sunset time					0.18	(-0.04, 0.39)	0.107	409	5.14	(2.09, 8.19)	**0.001**	346
Co-sleeping with children									18.51	(-0.88, 37.90)	0.061	346
Co-sleeping with adults									45.47	(16.87, 74.08)	**0.002**	346
Co-sleeping with children & adults									4.83	(-14.58, 24.23)	0.626	346
Night type (Intercept)												
School night	-37.25				-14.84				-16.45			
Free night	37.25				14.84				16.45			

Table 3. Bio-socio-cultural predictors of sleep midpoint values for each study site across weeknights.

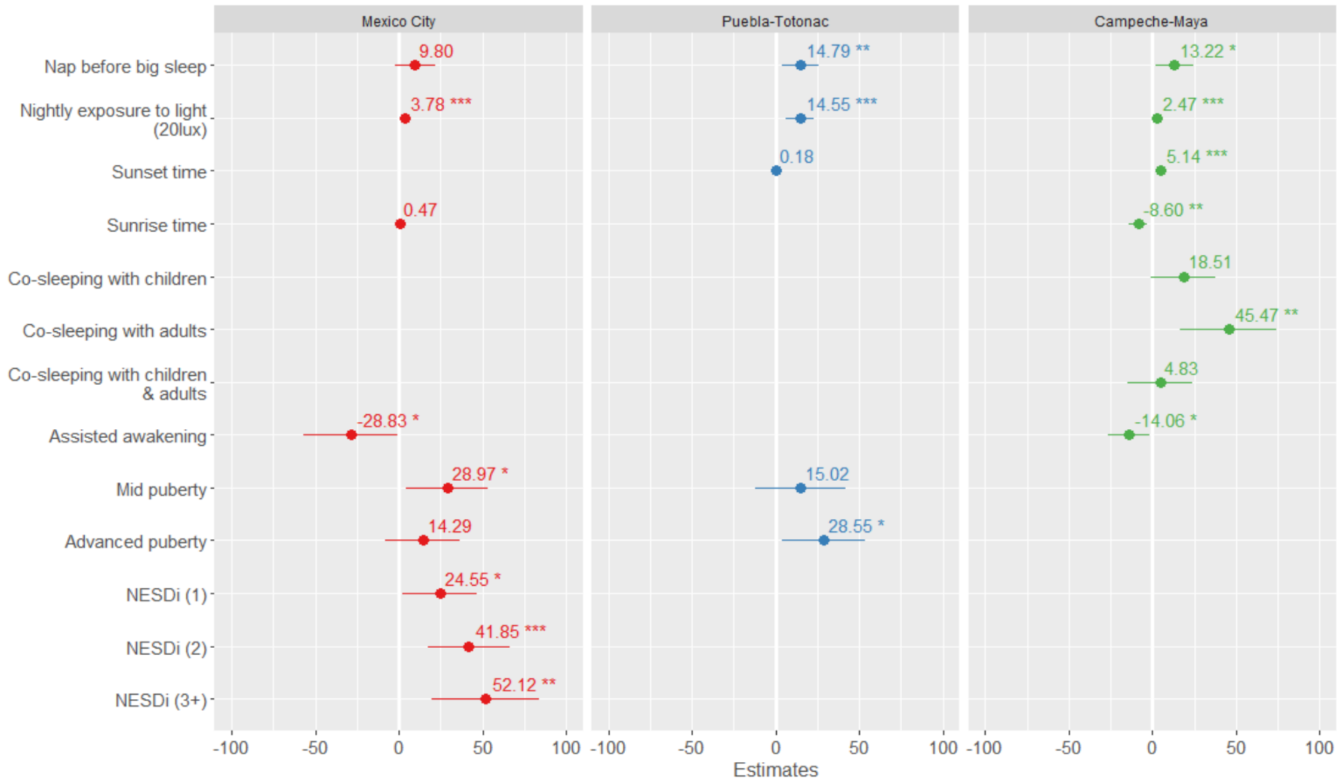


Figure 2. Effect sizes for the site-specific models

Sleep measure	Definition
Sleep duration	The interval between the participant goes to sleep, and the time she/he awakens. We scored a period of inactivity in our actigraphy data as time in bed if it exceeded 210 minutes.
Sleep onset and sleep end	The clock time when the time in bed starts and when the final morning awakening takes place, respectively. Reported as minutes before or after midnight. It can be expressed as a negative value prior to midnight, a 0 value when midnight, and a positive value past midnight.
Sleep Midpoint	The halfway point between the sleep onset and the sleep end. Reported as minutes before or after midnight. It can be expressed as negative, positive, or equal to 0 values.
Social jetlag	The subtraction of the Sleep Midpoint on work nights from the Sleep Midpoint on free nights is the conventional formula for estimating the extent of the misalignment between human chronotype and social sleep schedules.

Nap	Period of sleep typically occurring during daylight outside a main big sleep bout. We scored a period of inactivity in our actigraphy data as a nap episode if it fell within the threshold of 15 to 210 minutes and occurred at least an hour distance from a main big sleep.
Nap ratio	The proportion of actigraphy-assessed nap days, calculated as the total number of days with at least one observed nap divided by the number of days with actigraphy data.

Table 4. Definitions of sleep measurements

Supplementary information

Supplementary Table 1. Day length, precipitation and temperature in Mexico City, Campeche and Puebla

Site	Day	Sunrise	Sunset	Day Length	Precipitation (mm/day)	Maximum Temperature (ºC)	Minimum Temperature (ºC)	Average Temperature (ºC)
Mexico City	01-02-2019	07:14:58	18:24:24	11:09:25	0	20.24	5.08	12.27
	02-02-2019	07:14:41	18:25:00	11:10:18	0	22.72	6.72	13.96
	03-02-2019	07:14:23	18:25:36	11:11:12	0	23.93	7.83	14.72
	04-02-2019	07:14:04	18:26:11	11:12:06	0	24.47	7.55	15.14
	05-02-2019	07:13:44	18:26:46	11:13:01	0	25.95	6.74	15.89
	06-02-2019	07:13:23	18:27:20	11:13:57	0	26.16	9.21	16.55
	07-02-2019	07:13:00	18:27:54	11:14:54	0.01	27.03	9.75	16.95
	08-02-2019	07:12:37	18:28:28	11:15:51	0.37	23.25	8.02	14.57
	09-02-2019	07:12:12	18:29:01	11:16:48	0.07	22.24	5.63	12.83
	10-02-2019	07:11:46	18:29:34	11:17:47	0	23.71	5.29	13.72
	11-02-2019	07:11:20	18:30:06	11:18:46	0	24.13	7.72	14.92
	12-02-2019	07:10:52	18:30:37	11:19:45	0.57	23.94	6.72	14.83
	13-02-2019	07:10:23	18:31:08	11:20:45	1.4	21.82	8.05	14.2
	14-02-2019	07:09:53	18:31:39	11:21:45	0.01	24.43	9.07	15.86
	15-02-2019	07:09:23	18:32:09	11:22:46	0	26.7	9.54	17.2
	16-02-2019	07:08:51	18:32:39	11:23:47	0	27.99	9.83	17.83
	17-02-2019	07:08:18	18:33:08	11:24:49	0	27.85	9.86	17.48
	18-02-2019	07:07:44	18:33:36	11:25:51	0.01	27.29	10.09	16.99
	19-02-2019	07:07:10	18:34:04	11:26:54	0	25.14	7.07	15.27
	20-02-2019	07:06:34	18:34:31	11:27:57	0	25.19	8.12	15.51
	21-02-2019	07:05:58	18:34:58	11:29:00	0	25.03	6.96	14.92
	22-02-2019	07:05:20	18:35:24	11:30:04	0	22.82	8.8	15.25
	23-02-2019	07:04:42	18:35:50	11:31:07	0.05	24.81	8.61	16.2
	24-02-2019	07:04:03	18:36:15	11:32:12	0.79	25.38	9.69	16.25
	25-02-2019	07:03:23	18:36:40	11:33:16	1.37	25.65	8.86	16.35
	26-02-2019	07:02:43	18:37:04	11:34:21	0.14	26.64	9.97	17.36
	27-02-2019	07:02:01	18:37:28	11:35:26	0.02	27.31	10.22	17.47
	28-02-2019	07:01:19	18:37:51	11:36:31	0	27.41	8.86	17.38
	01-03-2019	07:00:36	18:38:13	11:37:36	0	27.82	9.17	17.66
	02-03-2019	06:59:53	18:38:35	11:38:42	0	27.79	9.98	17.98
	03-03-2019	06:59:09	18:38:57	11:39:48	0	29.35	10.43	19.18
	04-03-2019	06:58:24	18:39:18	11:40:54	1.49	27.53	9.63	18.06
	05-03-2019	06:57:38	18:39:39	11:42:00	1.45	27.85	11	18.13
	06-03-2019	06:56:52	18:39:59	11:43:06	0.55	26.7	8.21	16.79
	07-03-2019	06:56:06	18:40:19	11:44:13	0.37	27.97	10.25	18.09
	08-03-2019	06:55:18	18:40:38	11:45:19	0.02	28.28	10.28	18.22
	09-03-2019	06:54:31	18:40:57	11:46:26	0.06	28.7	10.68	19.07
	10-03-2019	06:53:43	18:41:15	11:47:32	0.05	28.65	11.51	19.29
	11-03-2019	06:52:54	18:41:33	11:48:39	0.02	29.57	11.04	18.9
	12-03-2019	06:52:05	18:41:51	11:49:46	0.01	28.06	8.8	17.44
	13-03-2019	06:51:15	18:42:09	11:50:53	0	28.19	8.74	17.75
	14-03-2019	06:50:25	18:42:26	11:52:00	0	28.5	10.42	18.61
	15-03-2019	06:49:35	18:42:42	11:53:07	0.21	26.73	8.82	17.67
	16-03-2019	06:48:44	18:42:59	11:54:14	0.04	25.96	10.52	17.51
	17-03-2019	06:47:54	18:43:15	11:55:21	0.03	25.69	9.92	17.24
	18-03-2019	06:47:02	18:43:30	11:56:28	0.2	23.79	11.36	16.56
	19-03-2019	06:46:11	18:43:46	11:57:35	0.02	24.37	8.76	15.61
	20-03-2019	06:45:19	18:44:01	11:58:41	0.01	25.19	7.73	15.64
	21-03-2019	06:44:27	18:44:16	11:59:48	0.33	24.5	8.34	16.03
	22-03-2019	06:43:35	18:44:31	12:00:55	1.51	24.91	8.37	16.1
	23-03-2019	06:42:43	18:44:46	12:02:02	0.07	25.77	8.04	16.3
	24-03-2019	06:41:51	18:45:00	12:03:09	0.05	27.09	8.63	17.39
	25-03-2019	06:40:59	18:45:15	12:04:15	0	28.65	9.59	17.69
	26-03-2019	06:40:07	18:45:29	12:05:22	0.01	26.96	5.2	15.41
	27-03-2019	06:39:14	18:45:43	12:06:28	0	27.07	4.46	15.34
	28-03-2019	06:38:22	18:45:57	12:07:35	0	27.92	6.21	16.69
	29-03-2019	06:37:30	18:46:11	12:08:41	0	28.89	8.36	17.9
	30-03-2019	06:36:37	18:46:25	12:09:47	0.01	28.54	8.85	18.07
	31-03-2019	06:35:45	18:46:39	12:10:53	0.06	27.24	8.79	17.69
	01-04-2019	06:34:53	18:46:53	12:11:59	0.01	27.32	9.14	17.44

Site	Day	Sunrise	Sunset	Day Length	Precipitation (mm/day)	Maximum Temperature (ºC)	Minimum Temperature (ºC)	Average Temperature (ºC)
Mexico City	02-04-2019	06:34:01	18:47:07	12:13:05	0.02	27.38	9.25	17.71
	03-04-2019	06:33:10	18:47:21	12:14:10	0.17	26.72	9.25	17.37
	04-04-2019	06:32:18	18:47:34	12:15:16	0.24	27.41	8.73	17.87
	05-04-2019	06:31:27	18:47:48	12:16:21	0.39	26.31	9.98	17.48
	06-04-2019	06:30:36	18:48:03	12:17:26	0.17	24.48	10.4	16.92
	07-04-2019	07:29:45	19:48:17	12:18:31	0.01	26.9	11.08	17.81
	08-04-2019	07:28:55	19:48:31	12:19:35	1.13	27.01	8.53	17.25
Xculoc, Hopelchen, Campeche	31-05-2019	06:22:47	19:30:26	13:07:39	14.03	31.64	25.67	28.01
	01-06-2019	06:22:40	19:30:50	13:08:09	27.57	32.09	25.3	27.95
	02-06-2019	06:22:35	19:31:13	13:08:37	31.91	31.35	25.17	27.31
	03-06-2019	06:22:31	19:31:36	13:09:05	7.81	31	24.83	27.47
	04-06-2019	06:22:28	19:31:59	13:09:31	5.54	34.64	23.86	28.89
	05-06-2019	06:22:25	19:32:22	13:09:56	0	35.1	23.71	29.37
	06-06-2019	06:22:24	19:32:44	13:10:19	0	36.9	23.93	30.24
	07-06-2019	06:22:24	19:33:06	13:10:41	0.01	37.08	24.41	30.66
	08-06-2019	06:22:25	19:33:27	13:11:02	0.01	38.04	25.07	31.24
	09-06-2019	06:22:26	19:33:49	13:11:22	0.05	38.77	26.38	31.96
	10-06-2019	06:22:29	19:34:09	13:11:40	6.27	36.95	26.33	30.46
	11-06-2019	06:22:33	19:34:30	13:11:56	25.29	36.35	24.73	29.4
	12-06-2019	06:22:37	19:34:49	13:12:12	11.98	35.04	23.24	28.43
	13-06-2019	06:22:43	19:35:09	13:12:25	20.07	32.03	24.34	27.37
	14-06-2019	06:22:49	19:35:27	13:12:38	1.84	31.54	23.4	27.31
	15-06-2019	06:22:56	19:35:45	13:12:49	3.24	30.41	23.8	26.7
	16-06-2019	06:23:04	19:36:03	13:12:58	0.27	32.06	23.93	27.71
	17-06-2019	06:23:13	19:36:20	13:13:06	0.17	32.2	24.42	28.23
	18-06-2019	06:23:23	19:36:36	13:13:13	0.05	35.59	24.37	29.68
	19-06-2019	06:23:33	19:36:52	13:13:18	3.1	34.88	24.8	29.74
	20-06-2019	06:23:45	19:37:07	13:13:22	0.04	36.28	25.45	30.53
	21-06-2019	06:23:57	19:37:21	13:13:24	0.02	36	25.72	30.56
	22-06-2019	06:24:10	19:37:35	13:13:25	0.09	35.91	26.13	30.71
	23-06-2019	06:24:23	19:37:48	13:13:24	0	37.41	25.81	30.97
	24-06-2019	06:24:37	19:38:00	13:13:22	0	38.33	24.64	31.14
	25-06-2019	06:24:52	19:38:11	13:13:18	0.01	37.21	24.68	30.85
	26-06-2019	06:25:08	19:38:21	13:13:13	0.56	36.49	24.79	30.53
	27-06-2019	06:25:24	19:38:31	13:13:07	2.35	34.78	24.95	29.03
	28-06-2019	06:25:41	19:38:40	13:12:59	8.6	34.34	23.96	28.03
	29-06-2019	06:25:58	19:38:47	13:12:49	43.01	34.31	23.36	27.67
	30-06-2019	06:26:16	19:38:54	13:12:38	24.49	29.17	23.59	26.23
	01-07-2019	06:26:34	19:39:00	13:12:26	5.84	31	24.36	27.31
	02-07-2019	06:26:53	19:39:06	13:12:12	0.55	34.23	23.54	28.48
	03-07-2019	06:27:12	19:39:10	13:11:57	0.93	33.94	23.02	28.3
	04-07-2019	06:27:32	19:39:13	13:11:40	1.86	34.73	22.81	28.41
	05-07-2019	06:27:52	19:39:15	13:11:22	15.15	31.91	24.39	27.49
San Juan Ozelonacaxtla, Huehuetla, Puebla	06-09-2019	7:19:14	19:39:00	12:19:46	5.98	27.04	18.43	22.05
	07-09-2019	7:19:25	19:38:06	12:18:40	3.83	28.54	17.62	22.08
	08-09-2019	7:19:37	19:37:11	12:17:34	1.2	29.43	17.68	22.67
	09-09-2019	7:19:48	19:36:16	12:16:28	2.12	29.99	17.83	23.32
	10-09-2019	7:19:59	19:35:21	12:15:21	8.05	29.71	19.56	23.39
	11-09-2019	7:20:11	19:34:25	12:14:14	12.24	27.04	18.6	22.01
	12-09-2019	7:20:22	19:33:30	12:13:07	13.11	25.8	17.82	21.05
	13-09-2019	7:20:33	19:32:34	12:12:00	17.81	25.64	17.28	20.97
	14-09-2019	7:20:44	19:31:38	12:10:53	9.76	26.33	17.86	21.31
	15-09-2019	7:20:55	19:30:41	12:09:46	0.54	28.03	15.62	21.4
	16-09-2019	7:21:06	19:29:45	12:08:38	0.58	28.98	16.94	22.48
	17-09-2019	7:21:17	19:28:49	12:07:31	0.84	29.76	19.13	23.27
	18-09-2019	7:21:29	19:27:52	12:06:23	3.24	27.69	18.7	22.91
	19-09-2019	7:21:40	19:26:56	12:05:15	1.41	26.93	19.6	22.58
	20-09-2019	7:21:51	19:25:59	12:04:07	0.43	29.1	18.81	22.95
	21-09-2019	7:22:03	19:25:03	12:02:59	0.74	28.52	17.83	22.41
	22-09-2019	7:22:15	19:24:06	12:01:51	0.23	28.9	17.05	22.19

Site	Day	Sunrise	Sunset	Day Length	Precipitation (mm/day)	Maximum Temperature (ºC)	Minimum Temperature (ºC)	Average Temperature (ºC)
San Juan Ozelonacaxtla, Huehuetla, Puebla	23-09-2019	7:22:27	19:23:10	12:00:43	2.47	28.94	15.89	21.94
	24-09-2019	7:22:39	19:22:14	11:59:35	1.06	29.18	18.51	23.01
	25-09-2019	7:22:51	19:21:18	11:58:27	2.93	28.4	20.15	23.45
	26-09-2019	7:23:03	19:20:22	11:57:18	1.87	30.13	20.02	23.81
	27-09-2019	7:23:16	19:19:27	11:56:10	0.41	29.48	18.52	23.15
	28-09-2019	7:23:29	19:18:31	11:55:02	11.74	29.2	18.61	23.13
	29-09-2019	7:23:42	19:17:36	11:53:54	3.93	24.76	19.52	21.96
	30-09-2019	7:23:56	19:16:42	11:52:45	3.78	29.39	19.38	23.26
	1-10-2019	7:24:10	19:15:47	11:51:37	9.43	27.43	19.46	22.41
	2-10-2019	7:24:24	19:14:53	11:50:29	2.93	27.64	17.71	21.91
	3-10-2019	7:24:39	19:14:00	11:49:21	5.55	27.12	17.6	21.61
	4-10-2019	7:24:54	19:13:07	11:48:13	3.98	28.3	16.84	21.92
	5-10-2019	7:25:09	19:12:14	11:47:04	5.58	28.58	17.62	22.23
	6-10-2019	7:25:25	19:11:22	11:45:56	2.8	28.34	17.86	22.27
	7-10-2019	7:25:41	19:10:30	11:44:49	36.81	26.53	17.79	21.59
	8-10-2019	7:25:57	19:09:39	11:43:41	16.74	24.71	16.52	20.42
	9-10-2019	7:26:14	19:08:48	11:42:33	0.51	27.25	16.19	21.17
	10-10-2019	7:26:32	19:07:58	11:41:25	1.02	27.99	18.25	22.57
	11-10-2019	7:26:50	19:07:08	11:40:18	18.18	27.39	19.97	22.81
	12-10-2019	7:27:08	19:06:20	11:39:11	19.07	21.77	15.42	18.61
	13-10-2019	7:27:28	19:05:31	11:38:03	0.61	25.34	14.99	19.69
	14-10-2019	7:27:47	19:04:44	11:36:56	0.07	26.04	16.72	20.71
	15-10-2019	7:28:07	19:03:57	11:35:50	0.26	26.77	17.19	21.35
	16-10-2019	7:28:28	19:03:11	11:34:43	19.35	23.67	17.41	20.85
	17-10-2019	7:28:49	19:02:26	11:33:37	25.07	21.17	18.1	19.6
	18-10-2019	7:29:10	19:01:41	11:32:30	1.61	25.47	17.97	21.36
	19-10-2019	7:29:33	19:00:58	11:31:24	2.82	26.39	19.43	22.32
	20-10-2019	7:29:55	19:00:15	11:30:19	0.43	28.74	19.68	23.41
	21-10-2019	7:30:19	18:59:33	11:29:13	4.28	27.66	19.91	23.18
	22-10-2019	7:30:43	18:58:52	11:28:08	12.95	24.03	18.94	21.01
	23-10-2019	7:31:07	18:58:11	11:27:04	10.26	23.09	18.11	19.83
	24-10-2019	7:31:32	18:57:32	11:25:59	0.76	24.28	17.33	20.18
	25-10-2019	7:31:58	18:56:54	11:24:55	9.73	20.87	13.13	17.09
	26-10-2019	7:32:24	18:56:16	11:23:51	0.65	19.16	11	15.04
	27-10-2019	7:32:51	18:55:40	11:22:48	0.3	23.97	15.11	18.81
	28-10-2019	7:33:19	18:55:04	11:21:45	0.3	25.1	16.46	20.16
	29-10-2019	7:33:47	18:54:30	11:20:43	1.01	26.07	16.84	21.25
	30-10-2019	7:34:15	18:53:57	11:19:41	14.19	26.14	18.89	21.9
	31-10-2019	7:34:44	18:53:24	11:18:40	20.81	20.23	8.32	12.8
	1-11-2019	7:35:14	18:52:53	11:17:39	0.51	18.74	8.47	13.13
	2-11-2019	7:35:44	18:52:23	11:16:38	9.37	19.11	12.09	15.23
	3-11-2019	7:36:15	18:51:54	11:15:38	5.23	20.41	13.51	16.1
	4-11-2019	6:36:46	17:51:26	11:14:39	0.37	23.84	14.15	18.6
	5-11-2019	6:37:18	17:50:59	11:13:40	4.27	24.02	16.56	19.55
	6-11-2019	6:37:50	17:50:33	11:12:42	5.98	24.56	16.87	19.91
	7-11-2019	6:38:23	17:50:08	11:11:45	0.77	24.65	15.57	19.69
	8-11-2019	6:38:56	17:49:45	11:10:48	7.85	21.91	13.7	17.4
	9-11-2019	6:39:30	17:49:23	11:09:52	1.3	19.76	12.39	15.46
	10-11-2019	6:40:04	17:49:01	11:08:57	0.94	23.1	13.75	17.76
	11-11-2019	6:40:39	17:48:41	11:08:02	1.58	25.64	15.68	19.97

Supplementary Note 1. Calculations used to determine solar data

We calculated our daily data on the times of sunrise, sunset and day length based on the methods provided in Iqbal (1983) for determining the extent of solar radiation incident on a given Earth surface.

Solar time is defined as the time based on the apparent angular motion of the sun across the sky with solar noon when the sun crosses the observer's meridian. As it does not coincide with local clock time, it is necessary to convert solar time to standard by applying three corrections:

First, there is a constant correction for the difference in longitude between the observer's meridian and the meridian on which the local standard time is based. The Sun takes 4 min to transverse 1° of longitude. The second correction is made through the equation of time, E, which considers the perturbations in the Earth's rotation rate that affect the time that takes the Sun to cross the observer's meridian. The third correction accounts for the implementation of daylight-saving time (DST), during which the clocks are set forward one hour from standard time during the summer months and back again in the fall to better use natural daylight.

The standard time in minutes is equal to

$$\text{Standard time} = \text{Solar time} - 4(L_{st} - L_{loc}) - E + V \text{ [min]}$$

where L_{st} is the standard meridian for the local time zone and L_{loc} is the longitude of the location in question, in degrees west ($0^{\circ} < L < 360^{\circ}$). The parameter E is the equation of time (in minutes) and V is the correction from the DST, which is equal to 60 (in minutes) when the DST is used, and 0 when it is not being used. The equation of time is taken from Spencer (1971), as cited by Iqbal (1983):

$$E = 229.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B) \text{ [min]}$$

where *B* is

$$B = (n - 1)360/365$$

and *n* is the day of the year ($1 \leq n \leq 365$).

The *Sun's declination* is the Sun's angular position when it passes a location's meridian with respect to the equator (north positive; $-23.45^{\circ} \leq \delta \leq 23.45^{\circ}$). For the smaller days in northern latitudes, its value is negative, for larger days its value is positive, and its value is zero during the equinoxes [Figure 1].

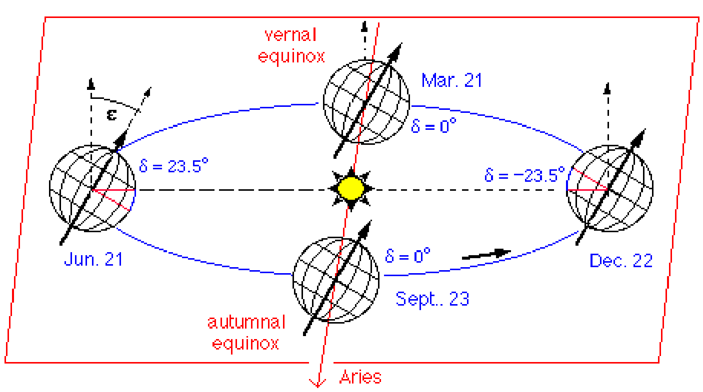


Figure 1. Illustration of the Sun's declination. Source: Giesen, J. (2008, January 2). *How to compute the length of a day*. Http://Www.Jgiesen.de/Astro/Solarday.Htm.

The local *latitude* and *longitude* are the angular location north or south (north positive; $-90^{\circ} \leq \varphi \leq 90$), and the angular location west to the standard meridian ($0^{\circ} < L < 360$), respectively [Figure 2].

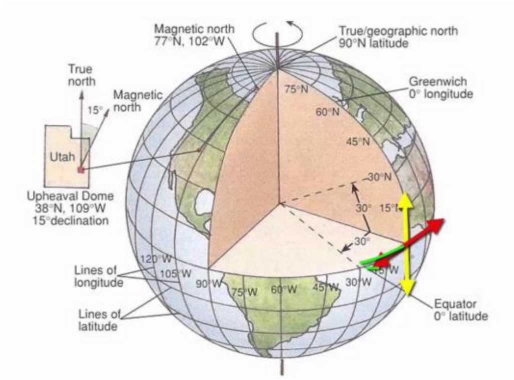


Figure 2. Illustration of the latitude and longitude coordinate system. Source: Wiese, K. (2022, March 16). *Latitude & Longitude. Geoscience Video Tutorial*. Https://Fog.Ccsf.Edu/~kwiese/Content/Classes/LatLong/LatLong.Mp4.

The *hour angle* is the Sun's angular displacement to the east or west of the local meridian due to the Earth's rotation on its axis, at 15º per hour [Figure 3]. The hour angle follows the Sun path through the sky; in the morning, it is reported as a negative value and, in the afternoon, as positive. Thus, the sunset hour and sunrise hour angles are equal but of different signs.

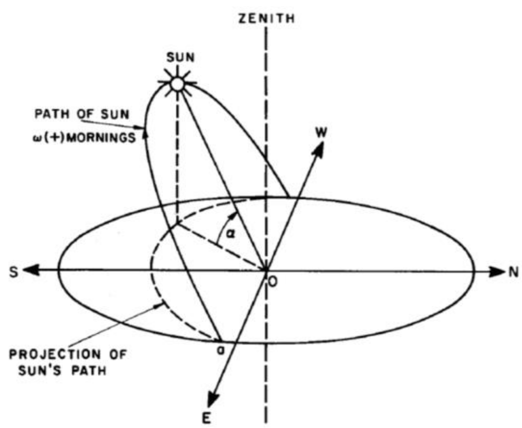


Figure 3. The hour angle (ω). Source: Al-Helaly, A., & Muhsin, I. J. (2018). Gaussian Equation to Describe the Percent of Shadow Length in Satellite Image. *International Journal of Engineering Research and Technology*, *11*, 1–20.

To obtain the *sunset hour*, we assume that the surface is horizontal and, consequently, that the angle between the vertical and the line to the sun (i.e., the angle of incidence of beam radiation on a horizontal surface) is equal to 90º at sunset. We obtain the *sunrise hour* using this same method. Meanwhile, since the earth rotates approximately 15º per hour and the time difference between sunrise and sunset is two times the sunrise hour, the duration of the day in minutes is

$$\text{Day Length} = 2/15\ w_s * 60 = 8\ w_s$$

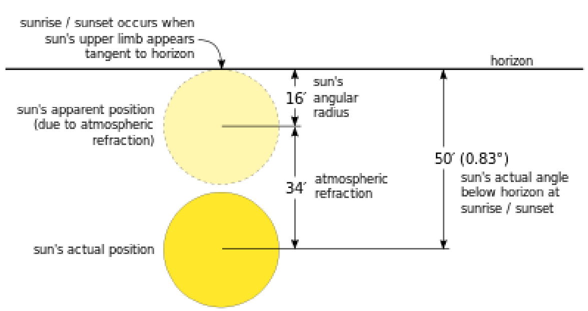


Figure 4. Sunrise diagram. Source: Alger, M. (2017, July 27). *Warming Back Up…And Just When Does Sunrise Occur?* Https://Mikealger.Net/2017/07/27/Warming-Back-up-and-Just-When-Does-Sunrise-Occur/.

The sunrise and sunset conventionally refer to the time when the upper or lower edge of the Sun disk appears or disappear tangent to the horizon. However, due to atmospheric conditions, also known as atmospheric refraction, the Sun may seem to be on the horizon when it is not [Figure 4]. Additionally, our model does not account for the curvature of the Earth, as we consider a horizontal surface. Therefore, our results for sunrise, sunset and duration of the day may be off around 2-4 minutes. However, these numbers represent good quantitative and qualitative meteorological estimates when actual measurements are lacking.

Supplemental Table 2. Resulting full models for school nights and free nights

All-site full models	**School nights**				**Free nights**			
Predictor	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*
Mid puberty	0.74	(-12.33, 13.80)	0.912	585	20.97	(-3.93, 45.87)	0.099	565
Advanced puberty	9.58	(-2.35, 21.50)	0.115	585	25.36	(2.60, 48.13)	**0.029**	565
Girls	-17.84	(-32.20, -3.47)	**0.015**	585	-8.9	(-35.18 ,17.38)	0.507	565
Nap before big sleep	11.78	(5.19, 18.37)	**<0.001**	585	14.13	(2.67, 25.58)	**0.016**	565
NESDi (1)	12.58	(1.81, 23.36)	**0.022**	585	21.65	(0.96, 42.34)	**0.04**	565
NESDi (2)	13.44	(1.60, 25.28)	**0.026**	585	31	(8.73, 53.26)	**0.006**	565
NESDi (3+)	26.64	(6.31, 46.97)	**0.01**	585	31.66	(-6.34, 69.67)	0.102	565
Nightly exposure to light (<20 lux)	0.77	(-0.33, 1.86)	0.169	585	4.15	(3.22, 5.08)	**<0.001**	565
Room sharing	-10.68	(-27.71, 6.36)	0.219	585	-0.78	(-33.70, 32.15)	0.963	565
Bed sharing	-9.59	(-28.64, 9.47)	0.324	585	-15.03	(-51.46, 21.40)	0.419	565
Parent-set bedtime	-9.18	(-18.04, -0.32)	**0.042**	585	-5.68	(-21.96, 10.60)	0.494	565
Assisted awakening	1.77	(-8.06, 11.59)	0.725	585	-30.25	(-52.09, -8.40)	**0.007**	565
Boys co-sleeping with children	10.29	(-10.55, 31.12)	0.333	585	5.79	(-33.84, 45.42)	0.775	565
Girls co-sleeping with children	11.59	(-5.82, 28.99)	0.192	585	1.78	(-31.83, 35.40)	0.917	565
Boys co-sleeping with adults	12.7	(-15.38, 40.78)	0.375	585	-4.36	(-58.06, 49.33)	0.873	565
Girls co-sleeping with adults	15.73	(-7.14, 38.60)	0.178	585	27.77	(-15.96, 71.49)	0.213	565
Boys co-sleeping with children & adults	-1.29	(-24.27, 21.69)	0.913	585	1.93	(-42.32, 46.18)	0.932	565
Sites (Intercept)								
Mexico City	-20.56				17.17			
Puebla	4.36				-16.96			
Campeche	16.20				-0.21			

Supplemental Table 3. Resulting full models for Mexico City, Puebla and Campeche

Site-specific full models	Mexico City				Puebla-Totonac				Campeche-Maya			
Predictor	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*
Mid puberty	26.18	(1.22, 51.15)	**0.04**	399	21.5	(-7.80, 50.80)	0.15	400	-1.66	(-19.14, 15.82)	0.852	339
Advanced puberty	12.83	(-9.85, 35.50)	0.268	399	31.18	(4.76, 57.61)	**0.021**	400	-5.96	(-22.66, 10.73)	0.484	339
Nap before big sleep	9.45	(-2.36, 21.26)	0.117	399	14.78	(4.05, 25.51)	**0.007**	400	14.48	(2.67, 26.30)	**0.016**	339
NESDi (1)	23.18	(0.77, 45.59)	**0.043**	399	15.26	(-8.09, 38.60)	0.2	400	10.5	(-5.35, 26.35)	0.194	339
NESDi (2)	35.03	(9.46, 60.61)	**0.007**	399	15.17	(-7.64, 37.99)	0.192	400	17.67	(0.49, 34.85)	**0.044**	339
NESDi (3+)	49.33	(16.64, 82.02)	**0.003**	399	N/A	N/A	N/A	400	19.95	(-15.90, 55.81)	0.275	339
Nightly exposure to light (<20 lux)	3.75	(2.90, 4.60)	**<0.001**	399	14.36	(5.75, 22.96)	**0.001**	400	2.33	(1.12, 3.53)	**<0.001**	339
Sunrise time	0.3	(-1.60, 2.20)	0.757	399	0.28	(-0.34, 0.89)	0.384	400	-8.13	(-14.32, -1.93)	**0.01**	339
Sunset time	-0.32	(-4.11, 3.47)	0.868	399	-0.05	(-0.49, 0.39)	0.83	400	4.21	(1.08, 7.35)	**0.008**	339
Room sharing	14.95	(-3.62, 33.52)	0.115	399	-27.98	(-55.23, -0.73)	**0.044**	400	10.49	(-11.14, 32.11)	0.342	339
Bed sharing	17.13	(-23.09, 57.35)	0.404	399	-15.96	(-40.14, 8.22)	0.196	400	3.9	(-20.11, 27.92)	0.75	339
Parent-set bedtime	-10.24	(-27.49, 7.02)	0.245	399	-13.95	(-34.72, 6.82)	0.188	400	-1.53	(-13.76, 10.69)	0.806	339
Assisted awakening	-31.95	(-60.24, -3.65)	**0.027**	399	6.32	(-13.82, 26.46)	0.539	400	-15.78	(-27.63, -3.93)	**0.009**	339
Co-sleeping with children	N/A	N/A	N/A	N/A	10.07	(-13.31, 33.45)	0.398	400	9.9	(-3.71, 23.50)	0.154	339
Co-sleeping with adults	N/A	N/A	N/A	N/A	8.85	(-22.02, 39.73)	0.574	400	39.05	(13.75, 64.35)	**0.002**	339
Night type (Intercept)												
School night	-35.18				-16.93				-16.47			
Free night	35.18				16.93				16.47			

5. MANUSCRIPT 2. ADOLESCENT SLEEP QUOTAS

The negotiated sleep. Adolescents and sleep deprivation in non-industrialized environments

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Abstract

Re-examining the nature of adolescent sleep outside industrialized settings through an ecological, cross-cultural perspective represents one way to inform sleep nuances and broaden our understanding of human development, wellbeing and evolution. Here we tested the idea that “modern” lifestyles and technological advances are associated with sleep insufficiency in adolescents. We documented the adolescent sleep duration (11-16 years old; 13.7 ± 1.21; n=145) in two non-industrial and one post-industrial society in Mexico to investigate whether adolescents in socio-ecologically distinct locations experience sleep deprivation. Sleep data was assembled with actigraphy, sleep diaries and standardized questionnaires. We used multilevel models to analyse how distinct biological and socio-cultural factors (i.e., pubertal maturation, chronotype, napping, gender, working/schooling, access to screen-based devices, exposure to light, and social sleep practices) shape adolescent sleep duration. Results suggest that the prevalence of adolescent short sleep quotas is not less in natural, traditional environments than in post-industrial societies, and highlight the influence of social activities on the expression of human circadian cycles. The current study challenges current assumptions about natural sleep and how adolescents slept before the modern era.

5.1 Introduction

Since the late 1970s, sleep researchers have warned against short sleep quotas among adolescents and its negative short- and long-term effects on their mental and physical health (Anders *et al.*, 1978; Matricciani *et al.*, 2012). Nonetheless, as long as optimal sleep quotas remain uncertain, the extent of sleep loss and its impact on adolescent wellbeing is still unclear (Carskadon, 2011; Blunden and Galland, 2014). Re-examining the nature of adolescent sleep outside industrialized settings through a cross-cultural perspective represents one way to better inform sleep nuances (Glaskin and Chenhall, 2013; Worthman and Brown, 2013), and therefore, broaden our understanding of human development, wellbeing and evolution.

According to existing evidence, normal sleep total duration ranges between 8.5-10 hours in children (5 years old onwards) (National Sleep Foundation, 2000; Institute of Medicine, 2006; Touitou, 2013) and between 7-9 hours in adults (18-40 years old) (Ohayon *et al.*, 2004; Horne, 2011). Notably, adolescents sleep as much as children on their free days, suggesting that their sleep requirements do not change until they become young adults (Ohayon *et al.*, 2004). This seems counterintuitive, since, on the other hand, on school nights adolescents typically express a progressive shortening of their sleep of up to 2-3 hours (Carskadon, 2011; Gradisar, Gardner and Dohnt, 2011; Touitou, 2013), a debt which they compensate for across weekends (Touitou, Touitou and Reinberg, 2017). This shortening is driven, not by lesser sleep requirements, but by convergent biological, psychological and socio-cultural factors (Carskadon, 2011).

"Modern" adolescents, who are oriented towards a late chronotype (i.e. individuals who have strong preferences for extreme late sleep-wake schedules, with later diurnal peaks of alertness and later sleep onsets compared to early and midrange chronotypes (Hofstra and de Weerd, 2008)) and must comply with early-morning schooling schedules, are especially vulnerable towards sleep deprivation (Carskadon, 2011). This vulnerability grows amidst an increasingly hierarchical and complex social life that poses great demands in terms of time, energy and attention (Carskadon, 2002), and is further underpinned by a ready access to screen-based electronic media devices (Touitou, Touitou and Reinberg, 2017). In addition, during adolescence parents stop setting their children bedtimes, and teenagers gain autonomy for setting their own sleep times (Carskadon, 2011). Surprisingly, Gradisar et *al* (2011) suggest that sleep deprivation can be aggravated by cultural factors even within "modern" societies. After performing a meta-analysis of 41 surveys addressing adolescent sleep patterns worldwide, they found that Asian adolescents have a later sleep onset than USA and European adolescents, obtaining less sleep and reporting higher rates of sleepiness (Gradisar, Gardner and Dohnt, 2011).

Although it is hypothesized that teenagers in "traditional" settings (i.e., non-industrial, small-scaled societies relatively isolated geographically, socially and/or culturally, without ready access to electricity or electronic devices (de la Iglesia *et al.*, 2015; Yetish *et al.*, 2015; Rattenborg *et al.*, 2017; David R. Samson, Crittenden, *et al.*, 2017; Samson, Manus, *et al.*, 2017) have sleep-wake cycles that are more entrained with natural exposure to light and are able to sleep longer in compliance with their "biological/natural" sleep quotas requirements(Peixoto *et al.*, 2009; Pereira, Louzada and Moreno, 2010), little is known about normal adolescent sleep in these environments. Previous research performed in rural and/or non-industrial populations in Germany, China, Uganda, Egypt, Brazil and Argentina reveal a wide variation in the sleep duration of adolescents, from 7-10.7 hours/day (Louzada and Menna-Barreto, 2003, 2004; Worthman and Brown, 2007, 2013; Loessl *et al.*, 2008; Ouyang *et al.*, 2009; Peixoto *et al.*, 2009; Pereira, Louzada and Moreno, 2010; Christoph *et al.*, 2017), sometimes below the sleep quota recommended by specialists and clinicians based on studies conducted in U.S.A populations (8.5-10 hours/day)(National Sleep Foundation, 2000; Institute of Medicine, 2006; Touitou, 2013). The observed variability in sleep was explained by several factors, such as aging, pubertal stage, weekday schedules, school workload, daily and pre-sleep activities, access to electricity, seasonal variations in daylight and bed-sharing habits. Notably, results from these studies are difficult to compare due to differences in study duration, age groups, instruments and definitions employed for calculating sleep duration.

Using biosocial, cross-cultural, anthropological perspectives to re-examine current assumptions of adolescent "natural" sleep, this paper is oriented to better understand the nuances of human sleep behaviour. Specifically, we address adolescent sleep in one post-industrial and two non-industrial societies in Mexico. The main objectives of this study were to: 1) examine whether adolescents in non-industrialized societies experience sleep deprivation, and 2) investigate what bio-socio-cultural factors influence sleep duration in our three samples. Namely, we assessed how working/schooling, daily exposure to natural light, access to electric light and electronic devices, and social sleep practices might alter the duration of adolescent sleep. Acknowledging that there is no agreement on the changes that mark the beginning, middle and end of adolescence (Hummer and Lee, 2016), we discuss changes in adolescent sleep duration using puberty as a reference point.

5.2 Results

Ecology of adolescent sleep

In terms of access to technology and sleep environments, the three study locations mirror a gradient between “modern” and “traditional” societies (details on the characteristics of participants' sleep settings in Table 1). In Mexico City, all participants had mobile coverage and broadband at home. In Puebla, they had limited mobile coverage but no broadband. In Campeche, where blackouts were frequent because of heavy rains, teenagers had no broadband nor mobile coverage.

Remarkably, a high proportion of rural adolescents (47%) reported sleeping either with the lights on or being illuminated at night by streetlights or moonlight compared to urban participants (12%). Particularly, 37% of the Totonac participants indicated they kept a light on while sleeping, and 24% had an external illumination source. When questioned about the rationale for keeping an illumination source while sleeping, adolescents indicated that they or a household member were afraid of the dark or needed to keep their screen-based devices on because watching images helped them fall asleep.

Regarding sleeping spaces, urban participants slept in areas designed for buffering external sound, wind, light, and temperature oscillations, while rural adolescents slept in spaces that provided a less effective buffering from external cues. While participants in Mexico City slept in cement roofed rooms, enclosed by curtains, glass windows, and robust, sealed doors, Totonac teenagers in Puebla slept under roofs made of baked tiles, corrugated metal, cardboard or cement, without windows and entrances being necessarily glazed or fully sealed. Similarly, Maya teenagers in Campeche slept in rooms with roofs made of corrugated metal, cardboard or palm leaves, having few curtains, windows or sealed doorways.

Duration and (in)sufficiency of sleep

Sleep characteristics were computed for each location (details in Methods) (Table 2). Participants from Mexico City expressed the shortest nightly sleep duration on school nights (7.9 hr, SD=58 min), while Maya participants from Campeche had the shortest sleep quotas on free nights (8.9 hr, SD=89 min). Respecting daytime sleep, the highest nap ratios were observed among Maya teenagers during both school and non-school days (20.1, SD=27.43 and 18.75, SD=26.8, respectively).

Sleep duration overall values were significantly different between school and free nights (t=-14.6, df=1012.9, $p < .001$). Likewise, we found significant differences between the participants' sleep duration and total sleep duration (TSD) values on school days and free days (t=-7.8, df=605, $p < .001$ and t=-7.3, df=585, $p < .001$, each). Additionally, sleep duration values across sites during both, school and non-school days, were significantly different ($F(2, 603) = 20.5$, $p < .001$ and $F(2, 583) = 6.8$, $p = .001$, respectively). We found identical statistical differences across sites for TSD values (Table 3).

Concerning sleep deprivation, we identified short sleep quotas during school nights and free nights in our three sites (Table 4). Short sleep quotas were least frequent in Puebla and most prevalent in Campeche, with 98% of Maya participants sleeping less than 9 hours per night on school nights and 49% on free nights. During school nights, short sleep quotas duration was significantly lower among urban adolescents (7.7 hrs, SD=39.3 min) compared to rural agricultural Totonac (8.2 min, SD=33.69 min) and Maya (8.1 min, SD=33.2 min) participants ($F(2, 119)$=9.51, $p < .001$). After calculating sleep curtailment values for each location (Table 3), we found that urban teenagers from Mexico City had the highest prevalence of sleep reduction during school days compared to participants from both agricultural societies. The sleep curtailment scores for Puebla and Campeche (-79.1 min, SD=46.9 min and -70.5 min, SD=44.6 min, each) significantly differed from those in Mexico City (-95.9 min, SD=59.7 min), but not between the two rural locations ($F(2, 133) = 3.8$, p =

.03). Finally, when adolescents were asked how frequently they had felt sleepy during school days over the past month, teenagers from Mexico City had the highest scores for daytime drowsiness and participants in Puebla the lowest.

Bio-socio-cultural factors shaping sleep duration

Weeknights

The final model for school nights (Table 5) incorporated pubertal development, gender, napping before the main sleep, ambient light at night, clear sky conditions, and assisted awakening as predictor variables for the sleep duration variance ($R^2_{Marginal\ /\ Conditional}$ = 0.11 / 0.39; $ICC_{Adjusted\ /\ Conditional}$ = 0.32 / 0.29, *df* = 595). The sleep duration was negatively influenced by pubertal development, napping before going to sleep, clear sky conditions and assisted awakening, and positively influenced by gender and ambient light at night. On the other hand, the model for free nights included gender, chronotype, napping before the main sleep, and clear sky conditions as predictor variables for sleep duration variance ($R^2_{Marginal\ /\ Conditional}$ = 0.04 / 0.23; $ICC_{Adjusted\ /\ Conditional}$ = 0.19 / 0.18, *df* = 577). On non-school nights, sleep duration was negatively affected by napping before going to sleep, clear sky conditions, and positively affected by gender and chronotype.

Site-specific models

The final model for Mexico City (Table 6) included gender, chronotype, napping before the main sleep, ambient light at night, clear sky conditions, minimum temperature, and assisted awakening as predictor variables for sleep duration ($R^2_{Marginal\ /\ Conditional}$ = 0.11 / 0.35; $ICC_{Adjusted\ /\ Conditional}$ = 0.27 / 0.24, *df* = 403). Gender, chronotype and standard domestic ambient light at night (between 20-499 Lux) positively affected sleep duration values, while naps before the main sleep, dim ambient light at night (< 20 Lux), clear sky conditions, minimum temperature and assisted awakening had a negative influence on them (Figure 1). The best-fitting model for Puebla's Totonac agricultural site comprised pubertal development, gender, nightly exposure to ambient light, clear sky conditions, minimum temperature, day length and social sleep practices as predictor variables ($R^2_{Marginal / Conditional}$ = 0.12 / 0.39; $ICC_{Adjusted / Conditional}$ = 0.31 / 0.27, *df* = 404). Here, sleep duration was positively influenced by gender, ambient light at night (dim and standard domestic), minimum temperature and social sleep, while negatively affected by advanced puberty, clear sky conditions, and day length. Lastly, the model for Campeche's Maya agricultural site incorporated pubertal development, gender, napping before the main sleep, clear sky conditions, minimum temperature, and assisted awakening as predictor variables ($R^2_{Marginal / Conditional}$ = 0.14 / 0.47; $ICC_{Adjusted / Conditional}$ = 0.39 / 0.33, *df* = 347). Sleep duration in Campeche was positively affected by gender and assisted awakening, and negatively influenced by advanced puberty, napping, clear sky conditions, and minimum temperature.

5.3 Discussion

One of this study objectives, building on the Social Jetlag Hypothesis (SJH), was to examine whether adolescents in non-industrialized societies experience sleep deprivation. The SJH posits that adolescents living in "traditional" non-industrial environments will more closely fulfil their "biological/natural" sleep requirements (Peixoto *et al.*, 2009; Pereira, Louzada and Moreno, 2010). Additionally, it argues that adolescent "biological/natural" sleep quotas and circadian cycles can be ascertained from non-school days, when sleep patterns are minimally shaped by social commitments (Gradisar, Gardner and Dohnt, 2011; Randler *et al.*, 2019). Therefore, we expected sleep deprivation to be rare in our agricultural non-industrial settings and more frequent among urban post-industrial participants. Likewise, we did not expect to find signs of sleep deprivation on free days.

Instead, we found that short sleep quotas during school nights were common in both agricultural societies, with over 75% of adolescents in each group sleeping below 9hrs per day. Furthermore, the proportion of short sleepers in Mexico City and Campeche, the most "traditional" setting in our study, were strikingly similar (94% vs 98%). In addition, a substantial amount of agricultural Maya adolescents in Campeche got short sleep quotas during free days (49%), compared to Totonac (26%) and urban (29%) participants.

Disparities in school workload, access to screen-based devices and sunset times might explain the predominance of short sleep quotas in Mexico City and Campeche on school days. Compared to adolescents from agricultural areas, urban participants underwent greater school workloads, so they were more likely to work late at night and go to sleep later. In addition, urban adolescents had a ready access to screen-based devices, increasing their chances of staying awake longer. Analogously, Maya participants in Campeche experienced longer exposure to daylight due to later sunsets than in Mexico City and Puebla, which could have helped delay their sleep.

Meanwhile, on non-school days waking times were not determined by fixed schedules, gaining importance in the emergence of short sleep quotas. Adolescents who had late bedtimes (possibly due to social/recreational activities paired with absence of parent-set bedtimes) and whose wake-life activities (such as strict training regimes, extra-curricular activities, farming/housework or religious life) prevented them from sleeping until late morning, were more likely to have short sleep quotas. Therefore, our findings in Campeche, where Maya participants had the highest proportion of short sleepers during non-school nights, suggest that adolescent sleep in natural, traditional settings is embedded within social commitments and expectations rather than free from them. Likely, past and present adolescent sleep-wake cycles in other societies (i.e., horticulturalists, hunter-gatherers, pastoralists) have not been free from social expectations either.

It should be noted that sleep deprivation during school nights was significantly less acute in agricultural adolescents, who slept 26-32 minutes longer than urban participants. In contrast, differences in sleep deprivation were minor during free nights, ranging from 4-17 minutes between sites. Disparities in short sleep quotas on school nights might arise from school schedules and commuting times, as Totonac and Maya participants started classes 30 minutes later than urban teenagers and had shorter commutes.

Variability in sleep deprivation could partially explain why the proportion of participants reporting recurrent daytime sleepiness was lower among Totonac and Maya adolescents. However, the perception of drowsiness could also vary depending on the tasks socially sought and reproduced in each site. In this sense, a study by Eide and Showalter (Eide and Showalter, 2012) estimating the “optimal” sleep period to maximize reading and mathematics test performance in U.S.A. students aged 10-19 found that “optimal” sleep quotas changed with age and were dependent on the level of complexity of the task. Therefore, urban participants, who might be more oriented towards academic performance than physical activities, might require more sleep to maintain attention on complex cognitive tasks for longer. Furthermore, subjective feelings of sleepiness may deepen in urban adolescents who perceive academic activities as dull or repetitive (Horne, 2011). Still, these hypotheses are speculative and further studies are required to test them. Additionally, in agreement with the Sleep Continuity Theory (Bonnet, 1986) (stating that a minimum of 10 minutes of interrupted sleep are needed to serve its restorative function), variation in self-rated drowsiness could reflect differences in the participants’ sleep efficiency (i.e., the ratio between the total time spent asleep and the total time in bed). While this matter is beyond the scope of this paper, future research will examine whether sleep efficiency is higher in both non-industrial settings than in Mexico City.

Considering that daily sleep quotas are normally distributed in human populations, it has been pointed out that using cut off values to assess sleep sufficiency is problematic because it assumes optimal sleep is monolithic rather than variable (Horne, 2011; Wolf-Meyer, 2011). Thus, we evaluated sleep curtailment during school days as a complementary approach to check sleep sufficiency (Ohayon *et al.*, 2004; Gradisar, Gardner and Dohnt, 2011). Again, we found that sleep curtailment was pervasive in agricultural adolescents, although significantly less than in Mexico City, where values were between 17-25 min higher than in Puebla and Campeche. As with short sleep, differences in curtailment values are likely due to distinct school workloads, access to screen-based devices, sunset times, earlier school schedules, longer commuting times and the adolescents' likeliness to sleep in during free days. Altogether, our findings undermine the premises of the SJH since they suggest that, given certain socio-cultural and ecological factors, adolescents from non-industrial societies may also express short sleep quotas.

When we examined what specific bio-socio-cultural factors influenced nightly sleep duration in our three samples, we found that advanced puberty had a negative impact on sleep duration during school nights, but not free nights. This effect is most probably related to personhood associated with age than to sexual maturation as older teenagers usually build social bonds outside the household, gain social responsibilities (such as house or farming work) and acquire freedom to set their bedtimes, which in turn results in shortened sleep during school nights. Arguably, such changes are decidedly more marked in agricultural than urban teenagers, which could explain why the effect of advanced puberty was significant in Campeche and Puebla adolescents but not in Mexico City. Results from previous meta-analyses agree with ours inasmuch they note that sleep duration decreases with age on school days but remains the same from pre-puberty to late adolescence on free days (Ohayon *et al.*, 2004; Gradisar, Gardner and Dohnt, 2011).

Along with age, personhood is molded by gender, a cultural variable that previous research has found to have confounding effects on adolescents' sleep duration (Galland *et al.*, 2018). Given that the participants of this study belonged to three distinct cultural groups, we expected to encounter mixed effects of gender on sleep in our samples. Surprisingly, gender consistently influenced sleep duration across all study sites and weekdays, with girls sleeping more than boys. Differences in sleep quotas could be linked to distinct gender access to screen-based devices, involvement in household activities, bedtimes routines, and time investment in getting ready for school. Notably, gender effects were larger on school days, when waking times are fixed, and in agricultural environments, where greater social distinctions between girls and boys might exist. In this sense, our results concur with previous studies indicating that human sleep patterns are heavily shaped by the interaction of gender and socio-economic status (Castrejón *et al.*, 2015; Marczyk Organek *et al.*, 2015). Still, more research is required to clarify whether these findings could also be explained by sexual dimorphism, as some other studies have suggested (Bailey and Silver, 2014).

A third factor affecting participants' sleep was chronotype, a behavioral trait that, unlike gender and sex, has been extensively investigated in relation to adolescent sleep patterns. Specifically, researchers have described a chronotype transition towards eveningness around puberty (Colrain and Baker, 2011) that is considered a marker of adolescent sleep-wake cycles (Touitou, 2013) which is conducive towards sleep deprivation on school days (Touitou, Touitou and Reinberg, 2017). However, we did not find a significant effect of evening chronotype on sleep quotas during school nights, but instead, found a significant positive effect during free nights. The cumulative impact of nocturnal sleep curtailment could partially explain why evening types sleep longer on non-school nights, presumably to recover, even though their sleep is not pointedly reduced on school nights (Blunden and Galland, 2014). Chronotype had the most marked effect on sleep duration in Mexico City, but not in non-industrial locations, where evening chronotypes were less frequent and adolescents were less prone to sleep in during free days. Similar differences in chronotype between urban and rural populations have been previously described in adolescents and adults (Louzada and Menna-Barreto, 2003; Evans *et al.*, 2011; Von Schantz *et al.*, 2015). These findings suggest that differences in social activities affect human chronotype expression and variability.

Daytime napping is another behavioral trait known for shaping nightly sleep quotas (Jakubowski *et al.*, 2016). The propensity of contemporary humans to experience a midafternoon dip in alertness (linked to circadian oscillations of body temperature and performance) is well recognized (Carskadon, 1990; Monk, 2005). Since it has been hypothesized that a napping episode during this period would occur under “natural” conditions but would be inhibited by industrial lifestyles (Monk, 2005; Yetish *et al.*, 2015), we expected to find higher napping rates in agricultural adolescents than post-industrial participants. Additionally, we reasoned we would observe greater nap ratios during school nights, derived from nightly short sleep quotas (Gradisar *et al.*, 2008). None of those predictions was supported by our results. Napping behavior was infrequent in all our study sites and we found no significant differences between weekdays (non-paired t, p = .95), suggesting that napping episodes were opportunistic and did not necessarily reflect participants alleged “sleep debt”. Even so, compared to teenagers in Campeche and Mexico City, participants in Puebla, who slept the most during the night, had the lowest napping rates (probably because they slept the most during the night). This distinction might be why, although napping behavior consistently shortened sleep duration across weekdays, its impact was non-significant in Puebla.

Along with individuals' characteristics and behavioral preferences, the physical and social features of the sleeping environments, such as temperature, lightening and co-sleeping practices, also act as sleep modifiers (Worthman, 2008). For instance, thermal stress, caused by exposure to extreme temperatures, results in difficulty falling asleep and frequent awakenings (David R Samson, Crittenden, *et al.*, 2017). Our results confirmed this, given that higher temperatures in hot weather or in isolated, temperate sleeping environments (Campeche and Mexico City) gave rise to shorter sleep durations but facilitated longer sleep in less shielded, colder sleeping environments (Puebla). Similarly, the effects of light on nightly sleep have been profusely addressed in literature (Roenneberg, Wirz-Justice and Merrow, 2003; Peixoto *et al.*, 2009; Carskadon, 2011; Touitou, 2013; Touitou, Touitou and Reinberg, 2017). In this regard, we presumed that daylight duration and intensity (estimated through clear sky conditions) would predict adolescent sleep duration in "natural" settings, but not in Mexico City, a post-industrial site with buildings designed for buffering external environmental cues. We confirmed that as daylength increased, participants' sleep decreased in Puebla, but we did not find this effect in Campeche. This distinction is most probably related to seasonal differences in agricultural activities. At the time of the study, Totonac participants had more work to do during daylight hours (i.e., maintaining, harvesting, and cleaning their crops) than Maya participants who were engaged in weeding their lands and waiting for the harvest. We also observed that as daylight intensity increased, participants' sleep would decrease in all sites. Daylight at high intensities is recognized for advancing or delaying sleep depending on whether the individual was exposed to morning or evening/night light, respectively (Roenneberg, Wirz-Justice and Merrow, 2003). Although we cannot infer the exact time of participants' exposure to daylight, we can assume that on non-cloudy, rain-free days, adolescents could perform diverse outdoor social and physical activities which would have inhibited sleep propensity and negatively affected sleep duration.

We speculated that the exposure to artificial lights signals during the night would shorten sleep during school days, with a marked effect across sites. Surprisingly, exposure to light at night had mixed effects on sleep quotas depending on its intensity and social context. For example, while standard domestic ambient light at night (<500 Lux) increased sleep duration on school nights, dim ambient light at night (<20 Lux) shortened sleep quotas in Mexico City and increased them in Puebla. Moreover, nocturnal illumination did not affect sleep in Campeche, potentially because of participants' tendency to sleep in dark environments and their limited access to screen-based devices, mobile coverage and the Internet.

Bringing adolescent sleep into its socio-cultural context and emotional dynamics is essential for understanding our contrasting results. Urban and rural participants would commonly report falling asleep under lightened conditions, either because they were watching images on their

TV/mobile/tablet or because those with whom they shared rooms would keep the lights on until late at night. In particular, agricultural Totonac participants in Puebla emphasized that having a light on while sleeping made them feel safe at night, a dangerous period when natural and supernatural characters (e.g., human and non-human predators, sorcerers, evil spirits or dead people) lurk in the shadows. Hence, adolescents whose sleep was exposed to <500 Lux on school nights probably began sleeping before domestic lights went off due to exhaustion (i.e., strong sleep pressure) and the lights' inhibitory effect on arousing emotions, two factors that would promote sleep. On the other hand, lights below 20 Lux mainly coming from electronic media or undesired luminous pollution in Mexico City would presumably elicit arousal among urban participants, shortening their sleep. In contrast, exposure to <20 Lux resulting from the moonlight, streetlights and domestic lights in Puebla would have helped to inhibit arousal among Totonac adolescents, facilitating longer sleep quotas.

Assisted awakening and social sleep practices provide further evidence of the interrelationship of adolescent sleep and its psycho-socio-cultural context. Even though assisted awakening tended to shorten sleep duration on school nights, an opposite trend was observed in Campeche. It is possible that, as Maya participants were generally awakened by the Sun, dogs barking, roosters or noise of other household members, they would only have needed assistance to wake up when all other awakening cues had failed. This would mean that, contrary to what happened in Mexico City or Puebla, participants who needed assistance for awakening in Campeche ended up waking up later instead of earlier and, thus, sleeping longer. Lastly, social sleep, commonly practiced in agricultural settings, had a marked positive effect on sleep duration in Puebla, while tending to shorten sleep in Mexico City and Campeche. As above, the participants' cognitive-emotional state might underlie the distinct effects of social sleep (Worthman and Brown, 2007). Unlike urban and Maya participants, adolescents in Puebla would have found sleeping with others comforting and reassuring, inhibiting alertness and enabling prolonged sleep quotas.

Taken together, our results suggest that the prevalence of adolescent short sleep quotas is not less in natural, traditional environments than in post-industrial societies. This finding brings into question current assumptions about sufficient sleep and how adolescents slept before the modern era. Contrary to what the SJH suggests, reduced adolescent sleep durations might have been a constant in our species' evolutionary history where individuals weighed the costs of reduced sleep against the benefits to them or their group of economic, social, reproductive or rearing waking-life activities (Yetish *et al.*, 2015; Loftus *et al.*, 2022). Consequently, we advocate further research to delve into the relationship between sleep and health outcomes in natural settings to better understand sleep's role in our evolutionary history.

Additionally, our study highlights the influence of ontogenetic development on the expression of human chronotypes, where a combination of genetic and epigenetic factors (potentially modulated by bio-socio-cultural factors such as photoperiod, temperature, developmental stressors, lifestyle, or parental involvement in offspring sleep) give rise to distinct circadian rhythms from prenatal development to old age (Hudec *et al.*, 2020). Notably, despite the role of circadian rhythms in the maintenance of cognition, behavior and mental wellbeing, the study of epigenetic mechanisms regulating them is recent and mainly focused on non-human models(Stevenson, 2018). Thus, we stress the need to incorporate a developmental approach to the study of infant and adolescent sleep to shed light on the epigenetic regulation of human biological rhythms and its short- and long-term consequences in health.

This research is subject to limitations. Firstly, our sample size was small, limited by convenience sampling in rural and urban settings. Secondly, our study lacked longitudinal data, which is critical for drawing comparisons between different age groups and identifying sleep developmental trajectories. Additionally, we could not incorporate data on seasonal variations in diet and energy expenditure and allocation, which might impact sleep traits. Thirdly, the MERS, employed for assessing the phase preferences of the participants over a 24-hour day, requires individuals to structure time in hours, minutes, and seconds, and not as a function of socio-ecological cues (such as the sunrise, sunset, meal times, non-human animal behavior, radio or TV programming, etcetera). Although most of this study participants were familiar with “modern” uses of time, some were not, which might have reduced the MERS accuracy. Similarly, the PDS, a self-report instrument for evaluating pubertal status, may fail to reflect the precise developmental stage of the adolescents compared to the Tanner stage.

This study provides novel evidence about variation in adolescent sleep quotas through the examination of sleep in one post-industrial and two non-industrial sites in Mexico. We push for further sleep research employing an ecological, cross-cultural perspective to broaden our understanding of human sleep development, variability, health and evolution. Such an approach could help guide future research agendas that translate into more equitable and effective health policies and practices to infant and adolescent wellbeing.

5.4 Methods

Geographical locations and participants

We worked with 163 participants (females=78) from three sites in Mexico, one urban, postindustrial and two rural, non-industrial (Mexico City, n=67, San Juan Ozelonacaxtla, Puebla, n=51, and Xculoc, Campeche, n=45) (Figure 2). Adolescents between 11 and 16 years old (mean age 13.7, SD ± 1.21) recruited from local schools participated in the study over 10 days comprising four non-school days and six school days. The study was conducted in 2019 from February 1st to April 8th, in Mexico City, from May 31st to July 5th, in Campeche, and from September 6th to November 11th, in Puebla. Each site is characterized in Table 7 (day length, precipitation and temperature details in Supplementary Table 1).

Participants and their parents provided written signed consent after obtaining a verbal explanation of the research and reading the study consent form. Consent in Maya and Totonaku was obtained with the support of local assistants fluent in either Highland Totonaku and Spanish or Peninsular Maya and Spanish fluently. The study protocol was approved by the Ethics Committee of the Department of Anthropology at Durham University. All procedures were in accordance with the Declaration of Helsinki, complying with the guidelines established for the execution of health research projects in Mexico by the Mexican General Health Regulation on Health Research Matters and the Mexican Official Standard NOM-012-SSA3-2012.

Instruments

We employed actigraphy devices, sleep diaries, semi-structured interviews, ethnographic observations and two standardized questionnaires to assemble data regarding adolescent sleep. In particular, we measured and characterized participants' sleep variables (see Table 8 for sleep variables definitions), pubertal maturation, daily activities (i.e., schooling and/or working efforts), and environmental factors (i.e., access to electricity and electronic devices, exposure to seasonal thermal and luminous variations, bedding characteristics, solitary or social sleeping practices).

Actigraphy

Unlike polysomnography (PSG), which measures sleep-wake patterns through neuronal activity, actigraphy infers wake and sleep based on the presence or absence of movement (Galland *et al.*, 2018). Although PSG remains the gold standard for quantifying sleep, actigraphy provides a more objective sleep measure than sleep diaries or questionnaires and has proven to be useful at quantifying rest-activity rhythms, sleep timing, duration, nighttime wake-bouts and daytime napping (Peixoto *et al.*, 2009; de la Iglesia *et al.*, 2015; Moreno *et al.*, 2015; Beale *et al.*, 2017; David R. Samson, Crittenden, *et al.*, 2017; Samson, Manus, *et al.*, 2017). This non-invasive method is particularly suitable for field-based studies (Samson *et al.*, 2016; Rattenborg *et al.*, 2017) since it is cheaper than PSG, easy to use in ambulatory populations and causes minimal disruption to sleep (Samson *et al.*, 2016). Additionally, actigraphy devices can capture data continuously over long periods within the subjects' everyday environments and activities (Rattenborg *et al.*, 2017; Galland *et al.*, 2018).

A total of 147 participants wore a Motionlogger Micro Watch unit (Ambulatory Monitoring Inc., US) on their non-dominant wrist during 10 continuous days for 24 hours to estimate sleep characteristics and ambient light. The actigraphs were set for 1-min epochs in the Zero Crossing Mode (ZCM). Participants were asked to mark the start of any sleep event during the study using the event logger button. As two teenagers did not have valid actigraphy data due to watch malfunctions, our final sample was reduced to 145 participants (Mexico City, n=50; Puebla, n=51; Campeche, n=44), with 72 being females.

We assembled 1405 sleep observations, of which 618 were non-school nights and 787 school nights. The actigraphy records were analyzed with the ActionW 2.7 software employing the Sadeh algorithm to characterize the sleep-wake behaviour of adolescents. As recommended, we used sleep diaries to further validate the accuracy of sleep scores generated by the software (Short *et al.*, 2012; de la Iglesia *et al.*, 2015). When encountering a nap episode, missing data (caused by a watch malfunction or off-wrist period) or additional information regarding the participant's sleep-wake behaviour derived from sleep diary, the analyst edited the scores manually. This approach allowed us to identify “false” sleep-like or wake-like entries (Samson *et al.*, 2016).

Sleep diaries and questionnaires

Sleep-wake behaviour and drowsiness during the day were captured using a customized, simplified version of the Paediatric Daytime Sleepiness Scale (PDSS) and the Consensus Sleep Diary (Carney, Buysse, Ancoli-israel, *et al.* 2012). Sleep diaries employed colours, images and scales to encourage completion by adolescents with limited literacy. All participants were asked to complete their 10-day sleep diary before and after each nightly sleep.

To obtain information about the adolescents' chronotype and pubertal maturation, every participant responded to two standardized questionnaires: the Morningness-Eveningness Reduced Scale (MERS) (Adan & Almirall 1990) and the Pubertal Development Scale (PDS) (Robertson, Skinner, Love, *et al.* 1992). Both questionnaires were verbally explained to participants and any questions answered. Together with sleep diaries, data from MERS helped us further validate the accuracy of actigraphy measurements and overcome technical hurdles, such as watch removal periods. The PDS, a non-invasive, self-report instrument was used to assess pubertal status.

Interviews and ethnographic observations

We used semi-structured interviews (lasting 45 minutes on average) to capture information about the sleeping environment of every participant. Specifically, questions were aimed at learning about: 1) the participants' ongoing sleep-wake patterns and sleep quality, 2) the cultural ideas and practices norming sleep, 3) the characteristics and cultural settings in which adolescents slept, and 4) participant access to electricity and/or electronic devices. Interviews were based on the work of Grandner *et al.* (2014) and included items from the Pittsburgh Sleep Quality Index (PSQI) (Jiménez-Genchi, Monteverde-Maldonado, Nenclares-Portocarrero, *et al.* 2008; Grandner, Jackson, Gooneratne, *et al.* 2014). Ethnographic observations were made in and outside the schools to further explore the social roles, peer relationships, attitudes towards sleep and daily lives of adolescents. A field diary was employed to record observations, daily activities, notes about interviews, casual conversations and comments concerning research development.

Meteorological and solar variables

Geographical coordinates for the three sites were utilized with the NASA Langley Research Center (LaRc) POWER Project (https://power.larc.nasa.gov/) to attain daily data on surface pressure, precipitation, humidity, sky insolation incident, temperature, and the Insolation Clearness Index. Additionally, based on the methods provided in Iqbal (1983), daily data on the times of sunrise, sunset and day length were obtained using solar geometry (Iqbal 1983).

Data analyses

To examine whether adolescents in non-industrialized societies experience sleep deprivation, we focused on the variation of participants' sleep duration (i.e., the interval between one goes to bed to sleep, and the time one gets out of bed) and total sleep duration (i.e., the total amount of time spent in bed per day, including daytime naps). In particular, we employed two of the most utilized approaches to evaluate sleep sufficiency: 1) to assess if participants slept a minimum of 9 hours per night as recommended by USA advisory bodies (Institute of Medicine, 2006; Pereira, Louzada and

Moreno, 2010; Worthman and Brown, 2013), and 2) to evaluate sleep curtailment during school days measured as the difference in adolescents' total sleep duration (TSD) mean values between school nights and free nights (Wolfson and Carskadon, 1998; Carskadon, 2011; Gradisar, Gardner and Dohnt, 2011). The first approach is based on the findings of two seminal studies investigating the effect of different sleep durations on adolescent daytime sleepiness (Carskadon *et al.*, 1980; Mercer, Merritt and Cowell, 1998); the latter is supported by two meta-analyses reporting that TSD decreases with age only when recordings take place on school nights, remaining constant and sufficient on free nights from pre to late adolescence (Ohayon *et al.*, 2004; Gradisar, Gardner and Dohnt, 2011). It is noteworthy that these studies were performed on urban populations, predominantly from rich, industrialized countries.

Descriptive statistics characterized daytime napping, sleep timing and sleep duration in our sample population. Then, we utilized paired t-tests to look for significant differences in the adolescents' sleep duration values between school and free nights, and to assess whether the participants' sleep duration and TSD values had significant differences on school and non-school nights. Next, we ran two ANOVAs to check if there were significant differences in sleep duration and TSD values between our three sites. We subtracted each participant's TSD mean during school days from their TSD mean during free days to gauge sleep curtailment on school days, and used an ANOVA to determine if the resultant values differed significantly between the three sites. All tests were two-tailed. Finally, we ran Benjamini-Hochberg post hoc tests to determine specific differences between sites.

To investigate the influence of sexual maturation, natural and artificial light, and social sleep practices on adolescents' sleep duration values on school nights and free nights, we fitted two multilevel models with the *lme4* R-package (Bates *et al.*, 2015). We incorporated "subject" and "site" as random effects to control for repeated measurements of individuals who are nested within three distinct sites. Furthermore, we fitted three site-specific models to unravel the specific influences of our predictor variables on the adolescents' sleep duration in each site. In these models, we incorporated "subject" and "condition" (i.e., school nights and free nights) as random effects to control for repeated measurements of individuals who are nested within two different conditions.

All our models tested pubertal maturation (typified as pre/early, mid-, and advanced puberty), chronotype (scored as morning, neither and evening type), gender, daytime napping, nightly light exposure (the percentage lux count epochs in relation to the participant's sleep duration), nightly exposure to screen-based devices (NESDI-index of the number of devices being handled after 8 pm), day length, clear sky conditions (assessed via the Insolation Clearness Index, with values close to 1 under clear, sunny conditions and to 0 under cloudy conditions), minimum temperature, assisted awakening (the usage of an external agent, alarm or person, to wake up), and social sleep practices (the practice of room-sharing or bed-sharing) as predictor variables (resulting full models available in Supplemental Tables 3-4). When fitting and selecting our final models, we employed the *MuMin* R-package (Barton, 2020) using the Akaike Information Criteria (AIC) and the Bayesian Information Criterion (BIC). The residuals of all the best-fitted models were normally distributed. All statistical analyses were conducted with significance levels set at 0.05 using R software version 3.6.3. Our statistical inferences were established on confidence intervals and p-values.

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Figures and tables

Sleep ecology	%	Mexico City	Puebla	Campeche
Access to screen-based devices †	Mobile phones	94	67	57
	Tablets	54	35	9
	Computers	94	18	9
	TV	100	96	98
Darkness/Light	Dark	76	39	68
	External illumination ††	18	24	16
	Indoors light	6	37	16
Social sleep	Solitary sleep	72	33	11
	Social sleep	28	67	89
Materiality of sleep	Sleeping surface	Bed	Bed or traditional wooden surface	Hammock
	Housing materials	Concrete, steel, and bricks	Concrete, steel, bricks, rocks, wood, and cardboard	Concrete, steel, bricks, raw earth, palm, wood and cardboard
School demands	School Day Start	7:30 hrs	8:00 hrs	8:00 hrs
	Commuting times	5-50 minutes*	5-10 minutes**	5-10 minutes**

† Unlike urban participants, most Totonac and Maya adolescents from Puebla and Campeche did not personally own screen-based devices but borrowed them from a family member. Consequently, their access to such devices was more restricted than participants from Mexico City.

†† Streetlights or moonlight are considered as external sources of night lighting.

*By walk, car, public transport, or school bus

**By walk

Table 1. Micro- and Macro-ecological characteristics of participants' sleep by sites. Data are represented as percentages relative to each sample group.

Weeknight	Site	Start time	End Time	Sleep duration	Nap ratio
School days	Mexico City	-96.21 (54.58)	372.47 (27.12)	471.01 (57.94)	17.23 (22.04)
	Puebla	-88.95 (65.94)	416.35 (28.45)	508.41 (65.36)	13.07 (18.05)
	Campeche	-71.04 (47.33)	416.61 (29.56)	488.66 (50.18)	20.12 (27.43)
Free nights	Mexico City	-29.52 (82.11)	525.95 (93.61)	556.47 (91.39)	14.78 (19.78)
	Puebla	-86.78 (73.3)	481.51 (74.99)	571.06 (88.16)	13.56 (19.79)
	Campeche	-54.75 (80.01)	479.63 (65.58)	535.39 (89.16)	18.75 (26.85)

Table 2. Values for sleep timing, duration and daytime napping by sites. Data are represented in minutes as mean (standard deviation).

Site	%	Sleep curtailment	Total sleep duration		
			School day	*Free day*	*Significance*
Mexico City	96	-95.9 (59.72) †	478.06 (57.83)	561.99 (92.56)	t=-6.5, p < .001
Puebla	87	-79.12 (46.89) *	518.5 (69.44)	580.23 (84.91)	t=-8.1, p < .001
Campeche	88	-70.48 (44.63) *	497.4 (51.19)	550.29 (89.38)	t=-9.4, p < .001
Significance		F=3.76, p = 0.03	F=20.52, p < .001	F=6.8, p = .001	

'†' reference group

Significance codes: '***' ≤ 0.001 '**' ≤ 0.01 '*' ≤ 0.05 '·' < 0.1

Table 3. Comparison of total sleep duration and sleep curtailment values between post-industrial (Mexico City), Totonac (Puebla) and Maya (Campeche) adolescent populations. Data are represented in minutes as mean (standard deviation). Sleep curtailment can be expressed as a negative value when TSD is shorter during school days compared to free nights, a 0 value when equal, and a positive value when greater.

Site	A) Short sleep				B) Drowsiness	
	%	*School night*	%	*Free night*	% ≤ 1 time per week	% ≥ 1 times per week
Mexico City	94	459.42 (39.3) †	29	493.5 (37.15) †	20	80
Puebla	78	490.98 (33.69) ***	26	506.25 (24.63) *	55	45
Campeche	98	485.8 (33.2) ***	49	489.19 (40.46)	42	58
Significance		F=9.51, p < 0.001		F=2.82, p = 0.07		

'†' reference group

Significance codes: '***' ≤ 0.001 '**' ≤ 0.01 '*' ≤0.05 '·' < 0.1

Table 4. A) Prevalence and comparison of short sleep quotas on school nights and free nights among the three study sites. Data are represented in minutes as mean (standard deviation). B) Self-rated prevalence of daytime drowsiness on school days over a 1-month time interval.

All-site final models		**School nights**				**Free nights**		
Predictor	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*
Mid puberty	-10.11	(-30.22 – 10.00)	0.325	595				
Advanced puberty	-26.49	(-45.01 – -7.98)	**0.005**	595				
Gender †	29.35	(12.83 – 45.88)	**<0.001**	595	20.35	(1.79 – 38.90)	**0.032**	577
Nap before big sleep	-22.05	(-34.22 – -9.88)	**<0.001**	595	-23.68	(-42.78 – -4.58)	**0.015**	577
Nightly exposure to light (<500 lux)	256.22	(141.97 – 370.47)	**<0.001**	595				
Clear sky conditions	-38.76	(-73.68 – -3.84)	**0.03**	595	-0.03	(-0.08 – 0.02)	0.22	577
Assisted awakening	-12.53	(-27.54 – 2.47)	0.102	595				
Intermediate type					15.5	(-4.96 – 35.97)	0.138	577
Evening type					40.35	(6.56 – 74.14)	**0.019**	577
Sites (Intercept)								
Mexico City	-10.02				-0.09			
Puebla	13.51				0.78			
Campeche	-3.49				-0.69			

† Boys are the reference category for gender; the estimates are for girls

Table 5. Bio-socio-cultural predictors of sleep duration variation on school nights and free nights across locations. Negative coefficients indicate decreased sleep durations, while positive coefficients higher sleep durations.

Site-specific final models		**Mexico City**				**Puebla-Totonac**				**Campeche-Maya**		
Predictor	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*
Gender	21.28	3.22 – 39.33	**0.021**	403	37.05	14.34 – 59.77	**0.001**	404	55.32	23.24 – 87.41	**0.001**	347
Intermediate type	19.64	-1.02 – 40.31	0.062	403								
Evening type	38.62	13.01 – 64.24	**0.003**	403								
Nap before big sleep	-28.62	-48.44 – -8.81	**0.005**	403					-28.98	-46.78 – -11.18	**0.001**	347
Nightly exposure to light (<20 lux)	-1.82	-3.30 – -0.35	**0.015**	403	21.71	5.98 – 37.44	**0.007**	404				
Nightly exposure to light (< 500lux)	33.6	8.70 – 58.50	**0.008**	403	195.51	27.71 – 363.30	**0.022**	404				
Clear sky conditions	-110.45	-207.02 – -13.88	**0.025**	403	-0.04	-0.08 – -0.00	**0.043**	404	-59.03	-109.34 – -8.71	**0.021**	347
Minimum temperature	-6.05	-12.83 – 0.74	0.081	403	8.31	3.88 – 12.73	**<0.001**	404	-15.94	-23.47 – -8.41	**<0.001**	347
Assisted awakening	-30.89	-61.75 – -0.02	**0.05**	403					16.42	-2.04 – 34.87	0.081	347
Mid puberty					4.03	-29.99 – 38.05	0.816	404	-9.75	-35.99 – 16.49	0.467	347
Advanced puberty					-28.95	-58.30 – 0.40	0.053	404	-44.5	-76.91 – -12.10	**0.007**	347
Day length (min)					-0.98	-1.57 – -0.39	**0.001**	404				
Room sharing					23.79	0.35 – 47.24	**0.047**	404				
Bed sharing					23.98	0.54 – 47.43	**0.045**	404				
Night type (Intercept)												
School night	-28.42042				-31.20166				-28.16103			
Free night	28.42				31.20166				28.16103			

† Boys are the reference category for gender; the estimates are for girls

Table 6. Bio-socio-cultural predictors of sleep duration values for each study location across weeknights.

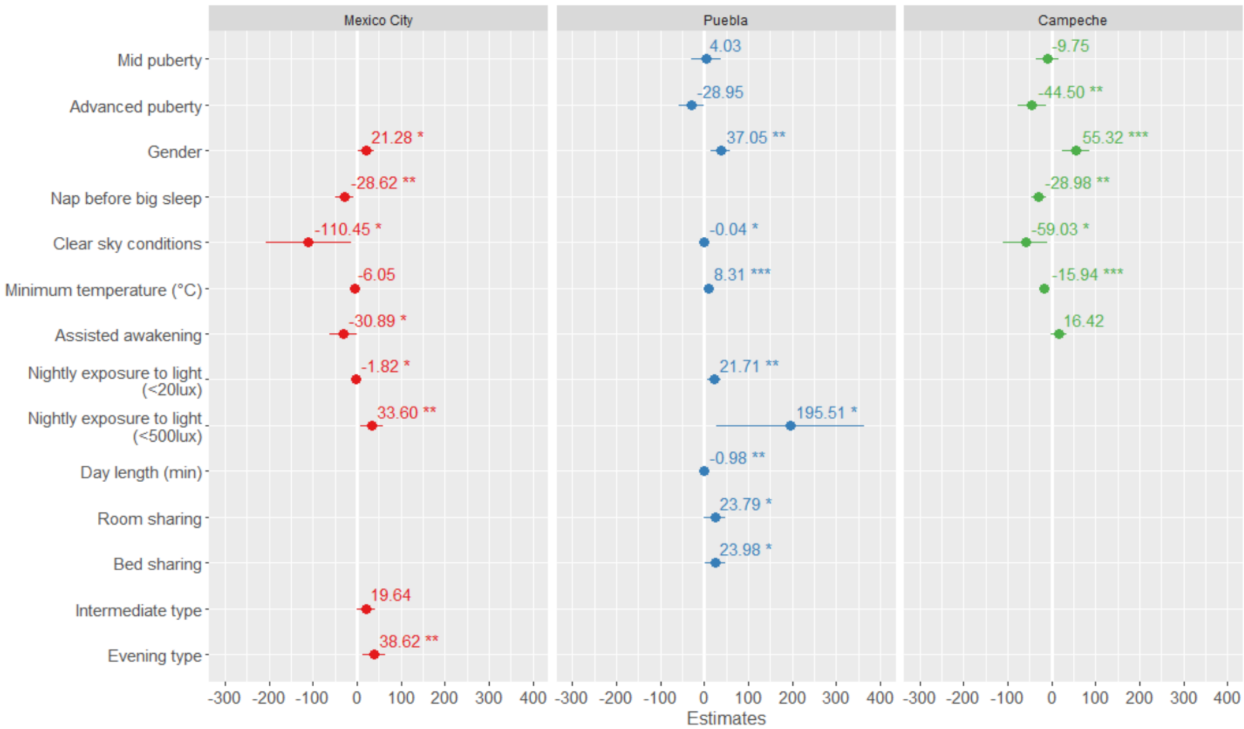

Figure 1. Effect sizes for site-specific models

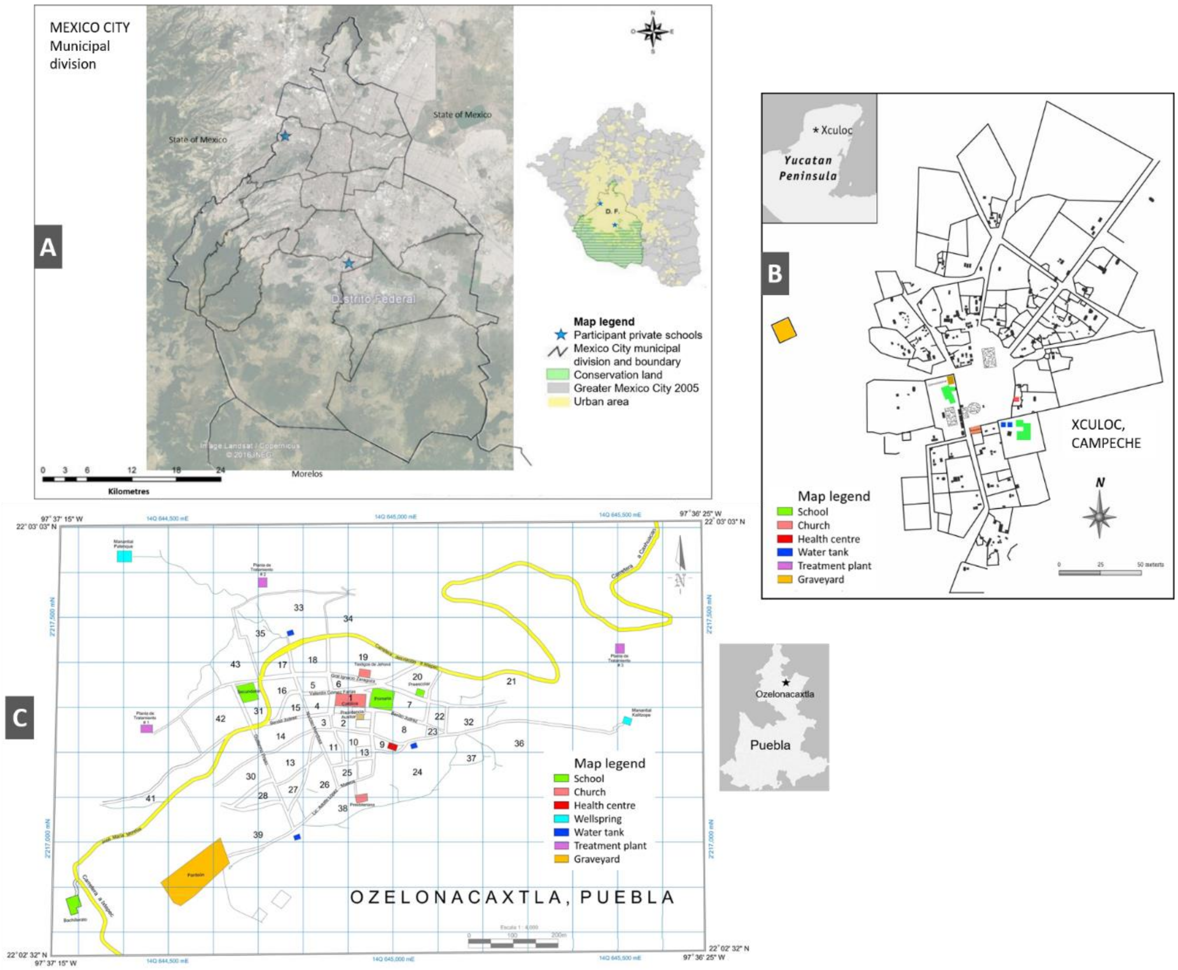

Figure 2. Study locations. Maps edited by Andrea Silva-Caballero based on: A) INEGI, Municipal geostatistical framework, 2016, B) Karen Kramer and Russell Graves, 2017, C) Google Earth and Ludovico Núñez, 2019.

Table 7. Characterization of the study sites

Study site	Geographic location	Economy	Inhabitants and ethnic composition	Main language
Mexico City (South and Northeast urban areas)	19.42847, -99.12766 The city is located in a highlands plateau, 2,303 m above sea-level.	Metropolis with a predominantly service-based economy. Participants belonged to relatively affluent and educated families whose occupations comprised trades (such as driver, shopkeeper or merchant) to professions (accountant, engineer, teacher, doctor, dentist, among others).	~8.9 million inhabitants Mexico City has an admix ethnic background composition, 89% identifying as "mestizos", 9% belonging to an indigenous group and 2% as Afro-descendants.	Spanish
San Juan Ozelonacaxtla, Huehuetla, Puebla	20.183333, -89.833333 The village lies 834 m above sea-level at the intersection of two mountain systems.	Agricultural Totonac community. By the end of the 1980s electricity and running water were introduced, followed by better roads, schools and a local health centre. Because regional orographic characteristics prevented the adoption of mechanized agriculture, traditional farming techniques have prevailed. Household economies mainly depended on agriculture (typically growing coffee, pepper and corn) and animal breeding (chicken, ducks, pigs and cattle), but also trades (such as shopkeeper or baker) and remittances from migrant family members working in Mexico City or Puebla de Zaragoza in construction or domestic work. Generally, children and adolescents with migrant parents stayed in the community under the care of close relatives.	~1,368 inhabitants Population in San Juan Ozelonacaxtla identify as Totonac, Mexico's tenth largest ethnic group.	Highland Totonaku
Xculoc, Hopelchen, Campeche	20.046944, -97.613611 The village is located in the Yucatan Peninsula plain, 69 m above sea level.	Small agricultural Maya community undergoing demographic and economic transitions with the recent introduction of running water, electricity, new farming techniques for intensive agriculture, schools and roads. Still, the site remains isolated from public transport. Household economies largely depended on subsistence agriculture and crop sales (such as peanuts, corn and squash), animal breeding (ducks, chicken and sheep), apiculture, construction labor, or work in in neighboring village restaurants.	~835 inhabitants Population in Xculoc identify as "Mayeros" or Maya, Mexico's second largest ethnic group.	Peninsular Maya

Sleep measure	Definition
Sleep duration	The interval between the participant goes to bed to sleep, and the time she/he gets out of bed. We scored a period of inactivity in our actigraphy data as time in bed if it exceeded 210 minutes.
Total sleep duration	The total amount of time spent in bed per day, including daytime naps.
Sleep onset and sleep end	The clock time when the time in bed starts and when the final morning awakening takes place, respectively. Reported as minutes before or after midnight. It can be expressed as a negative value prior to midnight, a 0 value when midnight, and a positive value past midnight.
Sleep deprivation	Sleep of shorter duration than the basal need per night of 9-10 hours in early adolescence. The extent of sleep debt is conventionally calculated through the subtraction of the Total sleep duration (TSD) on Workdays from the TSD on Free days.
Nap	Period of sleep typically occurring during daylight outside a main big sleep bout. We scored a period of inactivity in our actigraphy data as a nap episode if it fell within the threshold of 15 to 210 minutes and occurred at least an hour distance from a main big sleep.
Nap ratio	The proportion of actigraphy-assessed nap days, calculated as the total number of days with at least one observed nap divided by the number of days with actigraphy data.

Table 8. Definitions of sleep measurements

Supplementary information

Supplementary Table 1. Day length, precipitation and temperature in Mexico City, Campeche and Puebla

Site	Month	Sunrise	Sunset	Day Length	Precipitation (mm/day)	Maximum Temp (ºC)	Minimum Temp (ºC)	Average Temp (ºC)	Insolation Clearness Index
Mexico City	February	07:09:06	18:31:37	11:22:31	0.17	24.97	8.21	15.64	0.65
	March	06:48:32	18:42:47	11:54:14	0.21	27.23	9.1	17.42	0.68
	April	07:11:10	19:38:30	12:27:19	0.3	28.27	9.97	18.44	0.64
	Average	07:07:26	19:10:59	12:03:32	0.23	27.18	9.22	17.40	0.67
Xculoc, Bolonchen, Campeche	May	06:27:08	19:24:25	12:57:16	2.63	37.33	24.98	30.65	0.61
	Jun	06:23:32	19:35:32	13:12:00	7.48	34.74	24.64	29.21	0.56
	July	06:31:59	19:37:50	13:05:50	5.2	33.47	23.62	28.11	0.62
	Average	06:31:51	19:45:27	13:13:35	5.13	35.57	24.68	29.65	0.60
SJO, Huehuetla, Puebla	September	07:21:02	19:30:10	12:09:07	4.19	28.56	22.67	18.28	0.51
	October	07:28:49	19:03:41	11:34:52	8	25.39	20.65	16.99	0.5
	November	06:49:31	17:54:12	11:04:41	2.04	22.83	17.65	13.78	0.47
	Average	07:18:07	19:02:04	11:43:57	4.83	25.88	16.54	20.55	0.51

Supplemental Table 2. Resulting full models for school nights and free nights

All-site full models	School nights				Free nights			
Predictor	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*
Mid puberty	-9.6	(-29.80 – 10.61)	0.352	593	-5.85	(-35.22 – 23.51)	0.696	573
Advanced puberty	-26.74	(-45.16 – -8.32)	**0.004**	593	-17.95	(-44.48 – 8.58)	0.185	573
Gender †	30.48	(13.75 – 47.20)	**<0.001**	593	26.46	(2.90 – 50.02)	**0.028**	573
Intermediate chronotype	-4.42	(-18.87 – 10.03)	0.549	593	11.67	(-9.12 – 32.47)	0.271	573
Evening chronotype	-13.95	(-38.50 – 10.59)	0.265	593	39.55	(5.73 – 73.37)	**0.022**	573
Nap before big sleep	-22.08	(-34.24 – -9.91)	**<0.001**	593	-22.52	(-41.63 – -3.41)	**0.021**	573
Nightly exposure to light (<500 lux)	254.54	(140.25 – 368.82)	**<0.001**	593	6.41	(-7.79 – 20.60)	0.376	573
Clear sky conditions	-38.88	(-73.79 – -3.98)	**0.029**	593	-0.03	(-0.08 – 0.02)	0.248	573
Assisted awakening	-12.31	(-27.26 – 2.64)	0.107	593	11.96	(-13.24 – 37.16)	0.352	573
Sites (Intercept)								
Mexico City	-9.00				-0.14			
Puebla	13.48				7.58			
Campeche	-4.47				-7.49			

† Boys are the reference category for gender; the estimates are for girls

Supplemental Table 3. Resulting full models for Mexico City, Puebla and Campeche

Site-specific full models	**Mexico City**				**Puebla-Totonac**				**Campeche-Maya**			
Predictor	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*	*Estimates*	*Confidence interval*	*p*	*df*
Mid puberty	0.6	-27.31 – 28.52	0.966	395	6.23	-29.76 – 42.22	0.734	398	-4.73	-32.84 – 23.37	0.741	337
Advanced puberty	9.38	-16.60 – 35.36	0.479	395	-28.07	-57.87 – 1.74	0.065	398	-39.65	-73.92 – -5.38	**0.023**	337
Gender †	11.35	-11.11 – 33.82	0.322	395	35.58	12.10 – 59.06	**0.003**	398	44.02	9.48 – 78.55	**0.012**	337
Intermediate chronotype	28.52	6.19 – 50.85	**0.012**	395	-4.31	-27.43 – 18.81	0.715	398	-8.67	-31.37 – 14.03	0.454	337
Evening chronotype	49.42	22.26 – 76.59	**<0.001**	395	-39.09	-88.73 – 10.54	0.123	398	-0.79	-74.27 – 72.69	0.983	337
Nap before big sleep	-27.9	-47.68 – -8.12	**0.006**	395	-11.4	-31.26 – 8.46	0.261	398	-26.24	-44.36 – -8.12	**0.005**	337
NESDi (1)	-7.15	-31.59 – 17.29	0.566	395	12.61	-14.76 – 39.98	**0.367**	398	-10.91	-35.83 – 14.01	0.391	337
NESDi (2)	-21.6	-51.09 – 7.89	0.151	395	12.04	-14.83 – 38.91	0.38	398	-10.96	-37.60 – 15.67	0.42	337
NESDi (3+)	-38.27	-76.21 – -0.34	**0.048**	395	N/A	N/A	N/A	N/A	-42.23	-95.41 – 10.95	0.12	337
Nightly exposure to light (<20 lux)	-1.71	-3.18 – -0.24	**0.023**	395	21.19	5.43 – 36.94	**0.008**	398	-0.28	-2.26 – 1.70	0.785	337
Nightly exposure to light (<500 lux)	35.92	10.99 – 60.85	**0.005**	395	186.86	18.75 – 354.97	**0.029**	398	1.62	-10.62 – 13.87	0.795	337
Day length (min)	0.28	-0.18 – 0.75	0.229	395	-0.94	-1.53 – -0.35	**0.002**	398	1.05	-3.82 – 5.93	0.672	337
Clear sky conditions	-109.96	-206.71 – -13.21	**0.026**	395	-0.04	-0.08 – -0.00	**0.039**	398	-64.59	-119.01 – -10.17	**0.02**	337
Minimum temperature	-7.13	-14.14 – -0.13	**0.046**	395	8.14	3.69 – 12.58	**<0.001**	398	-15.2	-22.86 – -7.53	**<0.001**	337
Room sharing	-19.43	-39.84 – 0.99	0.062	395	25.05	2.08 – 48.01	**0.033**	398	-22.22	-54.04 – 9.59	0.171	337
Bed sharing	-1.65	-47.40 – 44.09	0.944	395	18.04	-6.71 – 42.79	0.153	398	-45.45	-86.57 – -4.32	**0.03**	337
Assisted awakening	-26.16	-57.33 – 5.00	0.1	395	-16.73	-40.90 – 7.43	0.175	398	20.26	1.91 – 38.62	**0.03**	337
Night type (Intercept)												
School night	-30.01				-25.76				-28.39			
Free night	30.01				25.76				28.39			

6. CONCLUSIONS

The results presented above contribute to improved understanding of "normal" sleep patterns and development in non-industrial populations and were specifically aimed at answering the research questions presented in Chapter 1 and reiterated below:

i) Do early adolescents in non-industrialized and in industrialized societies go through a phase delay expressed in later sleep onset and awakening times?

ii) Do adolescents in non-industrialized and in industrialized societies experience sleep deprivation?

iii) How might characteristics such as working/schooling, access to electric light and electronic devices, daily exposure to natural light, and the practice of social sleep alter the timing and duration of adolescent sleep?

Chapter 4 tested the hypothesis that advanced puberty would be associated with an adolescent sleep phase delay in industrial and non-industrial settings. Meanwhile, Chapter 5 tested the hypothesis that sleep deprivation would be rare in non-industrial settings and more frequent in industrial environments. Three further hypotheses guided the analysis of bio-socio-cultural influences on sleep in both chapters, namely that: 1) school schedules, access to electric light and electronic devices, and social sleep would be associated with later sleep onsets and shorter sleep durations during school days, 2) daily exposure to natural light would be associated with earlier sleep onsets and longer sleep durations during school days, and 3) sleep duration would be significantly affected by environmental factors on school days but not on free days.

Altogether, this research provided evidence that suggest the shift in adolescent sleep timing associated with sexual maturation is contextual rather than universal. This would indicate that the set of socio-cultural and bio-physical features within which individuals are embedded create different developmental niches where growing teenagers express and develop their sleeping behaviours (Harkness & Super 1994; Worthman & Melby 2002). Furthermore, by highlighting the influence of ontogenetic development on the expression of human chronotypes, the studies here point to the interaction of genetic and epigenetic factors giving rise to variations in circadian rhythms across the lifespan (Hudec, Dankova, Solc, *et al.* 2020) (Figure 13).

In addition, the results presented in this thesis challenge current frameworks characterizing adolescent "natural" sleep, highlighting that under certain socio-cultural and ecological factors, adolescents living in non-industrial environments may also express short sleep quotas. Not only does this finding brings into question existing assumptions about sufficient sleep for adolescents, but also about how they slept before the modern era. It is likely that reduced adolescent sleep quotas were present in our species' evolutionary history and are not a modern feature (Yetish, Kaplan, Gurven, *et al.* 2015; Loftus, Harel, Nuñez, *et al.* 2022).

Chapters 4 and 5 also revealed that although sleep duration among adolescents was more responsive to environmental factors on school days, sleep timing was not. Additionally, some bio-socio-cultural factors had contradictory effects on sleep measurements. For instance, depending on its psycho-socio-cultural context, nightly exposure to dim light and social sleep could act to inhibit or excite alertness, thereby promoting or hindering adolescent sleep. Lastly, contrary to what had been hypothesized, daily exposure to natural light was associated with earlier sleep offset and shorter sleep durations only in Campeche.

Even though existing studies indicate that changes in adolescent sleep have a biological basis (i.e., "diluted" melatonin secretion, reduced circadian photosensitivity, neural pruning, and a less robust build-up and decay of sleep pressure) (Carskadon 2011; Touitou, Touitou & Reinberg 2017; Hummer & Lee 2016), the results of this study suggest that their expression is dependent on other ecological factors. Changes towards plastic adolescent sleep-wake cycles may arise from life-history trade-offs related to the switchover to investments in reproduction (Stearns & Koella 1986). In addition, under the Interdependence hypothesis (proposing that highly social species individuals rely on one another for several aspects of their fitness), changes in adolescent sleep may constitute ontogenetic adaptations favouring social coordination throughout the day (Tomasello & Gonzalez-Cabrera 2017). In ancestral human environments, individuals with circadian and homeostatic plasticity would have been able to adapt to changeable social and living conditions, engage in cooperative rearing activities and collaborative forms of subsistence (e.g., gathering, hunting, farming, livestock raising), and perform sentinel behaviours, thus, benefitting individual and group fitness (Hrdy 2007; Hawkes 2014; Tomasello & Gonzalez-Cabrera 2017).

In sum, this research focused on the development of human sleep (or ontogeny) using a comparative ecological perspective and addressed sleep variability mechanisms (or causation) at an ecological level. The results of this work will have important implications for the field of comparative developmental ecology and contribute to unravelling the natural history of sleep (Worthman & Melby 2002). A broader understanding of sleep mechanisms, development, adaptive significance and evolutionary history can help deliver a stronger foundation for studying and assessing sleep needs and dysfunctions (Worthman & Melby 2002; Nesse 2019). This could help inform health recommendations and policies, setting the foundations for tailoring interventions based on individual and community needs. Detaching from one-size-fits-all approaches is crucial for translating research into more equitable and effective health practices and interventions to human wellbeing.

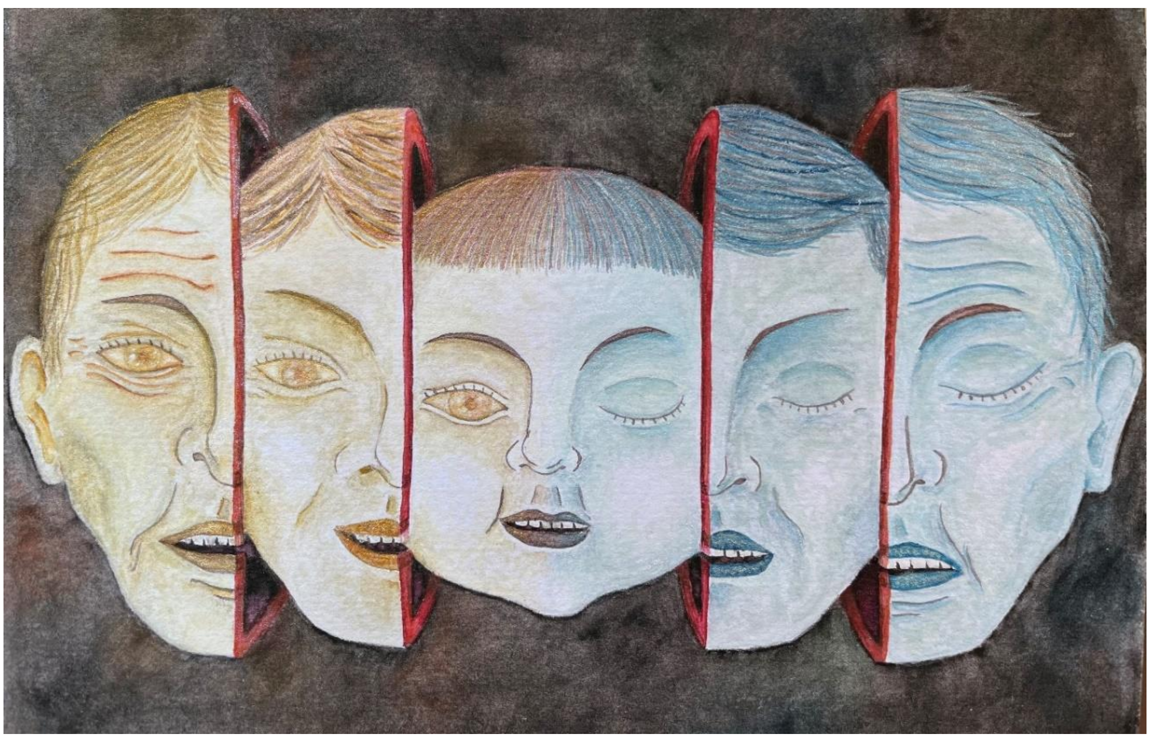

Figure 13. Pictorial representation of the ontogenetic development of human sleep-wake cycles. Artist: Andrea Silva-Caballero, 2021 (Watercolour on paper)

6.1 Strengths and limitations

Strengths

This study has several strengths. First, compared to sleep diaries or sleep questionnaires dependent on individual subjective recall, actigraphy provides a more reliable estimation of sleep measurements. Additionally, the continuous wear protocol of actigraphy watches for 24-hour across 10 days and not just during nighttime hours made it possible to characterize sleep-wake rhythms in adolescents throughout the week. Furthermore, sleep data scoring was achieved using the automated algorithm cross-checked with sleep diaries and semi-structured interviews. This increases the likelihood of correctly identifying sleep and nap episodes and ensures they are not mistaken for sedentary time or watch removal intervals.

Secondly, semi-structured interviews and ethnographic observations were employed with the specific aim of amassing high-quality data regarding participants' social contexts, sleep practices and sleeping environments. Personal interaction helped build rapport with the participants, facilitating their engagement with the study and placing them as co-creators of knowledge. Moreover, positioning adolescents' experiences at the centre of the conversation, provided important contextual information about sleep and wake activities that are often ignored when research relies solely on quantitative data. Similarly, employing an ecological framework allowed the effects of different norms and practices on sleep outcomes (such as keeping a light on while sleeping) to be considered rather than ignoring them.

Thirdly, the diverse ethnic and socioeconomic backgrounds of the participants are the main strength of this study. Generally, the results of sleep studies in naturalistic settings are difficult to compare with those of urban or lab environments due to different protocols and methodologies. However, because of this study design, comparisons were possible. Having representations across different human environments and not solely in WEIRD samples is essential for decolonizing science and, in this specific case, sleep research.

Fourthly, the mixed methods approach used in this study allowed accounting for seasonal or time-period differences (e.g., variations in temperature, day length, and agricultural or school workloads) in qualitative and quantitative terms. Firstly, ethnographic records helped with an understanding of adolescents' farming/working and school efforts during the study at each site. Secondly, the multilevel technique allowed controlling for the effects of seasonal ecological variables, with the variable "site" as a random effect accounting for seasonal and site-specific differences and with the inclusion of particular environmental variables (e.g., sunrise times, sunset times, day length, clear sky conditions, and minimum temperature) as predictor variables.

Limitations

First, being a cross-sectional study reliant on convenience sampling in rural and urban settings, the sample size was small and longitudinal data, which are critical for identifying sleep developmental trajectories with accuracy, were not attainable. In addition, the study could not account for seasonal variations in diet and energy expenditure and allocation, which might impact sleep-wake patterns.

Secondly, although salivary biomarkers of melatonin and cortisol are preferred over usage of sleep midpoints to evaluate sleep phasing (Moreno, Vasconcelos, Marqueze, *et al.* 2015), because of limited time, human resources and budget, this methodology was not feasible. Similarly, although Tanner stages may provide a more precise assessment of pubertal status than the PDS, the latter instrument is less invasive and easier to apply by a single researcher (Koopman-Verhoeff, Gredvig-Ardito, Barker, *et al.* 2020). Additionally, sleep diaries and standardized sleep questionnaires require individuals to structure time in hours, minutes, and seconds, and not as a function of socio-ecological cues (such as sunrise, sunset, non-human animal behaviour, meal times, radio or TV programming, etcetera). Even though most of the participants were familiar with “modern” uses of time, some were not, which might have reduced accuracy of these instruments.

Thirdly, it was not possible to distinguish between the different light sources to which participants were exposed while sleeping. Although it is reasonable to assume that illumination registered by the actigraphy watches ranging from 20 to 499 Lux came from household electrical lightning, illumination below 20 Lux could have come from various light sources, including electronics, streetlights, the moon, and house lights. Knowing the type of light sources illuminating participants' sleep could have improved data analysis.

6.2 Future directions

Unfortunately, it was impossible to analyse all the sleep data assembled during fieldwork due to time constraints. On the bright side, this offers a clear path for future research. For instance, this thesis did not specifically address adolescent sleep quality and efficiency. Along with sleep duration, these traits are used to evaluate sleep sufficiency (Blunden & Galland 2014). Therefore, future analyses will compare sleep quality and efficiency in industrial and non-industrial contexts and will explore how adolescent sleep ecology might be shaping these measurements. Another future study will visually characterize and compare circadian activity patterns using functional linear modelling (Wang, Xian, Licis, *et al.* 2011; Samson, Crittenden, Mabulla, *et al.* 2017b). This method, which has proven useful for conducting intra- and intergroup comparisons of sleep-wake patterns, will serve as a complementary approach to delve into sleep differences due to gender and/or pubertal development.

Addressing the psycho-socio-cultural lives of sleep by analysing the qualitative data amassed during fieldwork constitutes a third future research direction. Biomedical and folk knowledge about sleep also framed adolescent sleep practices in each site. This is a topic that deserves further attention and could help translate research into more effective community-based health interventions to enhance adolescent wellbeing.

Given that developmental sleep research has largely focused on WEIRD populations, the instruments it uses are not necessarily adequate for cross-cultural research. Consequently, future research should be directed towards the comparison of actigraphy, sleep diaries and standardized questionnaires completed by adolescents in this study, and should reflect on the main challenges encountered when implementing data collection tools in each population. This work could offer recommendations for the study of behavioural sleep in traditional populations with the overarching aim of stimulating future cross-cultural research.

Finally, although differences in adolescent sleep ecologies in the three study settings allow interesting analyses of the ecological variables impacting sleep, all differ from the presumed Pleistocene environments where human sleep behaviour evolved. For instance, even though sleep was more entrained to sunlight and sleep sociality in both rural sites, teenagers led a sedentary way of life, attended school, and had access to electricity. Therefore, to deepen our understanding of human sleep behaviour and development, future work on adolescent sleep ecology should focus on populations with no formal schooling, electricity access, and/or a nomadic way of life.

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APPENDICES

Appendix 1: Sleep diary

¡Buenas noches! (Español) ¡Ma'alob áaka'ab! (Maya) ¡Tzi'sua! (Totonaco)	Ejemplo 07 / Enero / 2019 (día) (mes) (año)	Viernes __/__/__	Sábado __/__/__	Domingo __/__/__	Lunes __/__/__	Martes __/__/__	Miércoles __/__/__	Jueves __/__/__	Viernes __/__/__	Sábado __/__/__	Domingo __/__/__
1. Tacha el número de veces que hayas tomado una **siesta** o dormitado en el día.	☐ 0 ☐ 1 ☑ 2 ☐ 3 ☐ 4 ☐ 5 veces o más	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 veces o más	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 veces o más	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 veces o más	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 veces o más	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 veces o más	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 veces o más	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 veces o más	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 veces o más	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 veces o más	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 veces o más
2. En total, **¿cuánto tiempo** calculas haber dormido en el día?	1 hora, 15 minutos										
3. ¿Cuáles de estas **bebidas** tomaste el día de hoy?	☐ Café ☑ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___	☐ Café ☐ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___	☐ Café ☐ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___	☐ Café ☐ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___	☐ Café ☐ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___	☐ Café ☐ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___	☐ Café ☐ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___	☐ Café ☐ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___	☐ Café ☐ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___	☐ Café ☐ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___	☐ Café ☐ Té ☐ Refresco ☐ Bebidas energéticas ☐ Otra ___
4. ¿Cuánto **tiempo** pasaste **al aire libre a la luz del día** (sin un techo sobre tu cabeza)?	2 horas, 25 minutos										
5. Comentarios	Tengo gripa										

¡Buenos días! (Español) ¡Ma'alob ki'in! (Maya) ¡Cui'ni'! (Totonaco)	Ejemplo 08/ Enero / 2019 (día) (mes) (año)	Sábado __/__/__	Domingo __/__/__	Lunes __/__/__	Martes __/__/__	Miércoles __/__/__	Jueves __/__/__	Viernes __/__/__	Sábado __/__/__	Domingo __/__/__	Lunes __/__/__
6. ¿Al quedarte dormido, te acostaste con la intención de dormir?	☑ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No
Si la respuesta es SÍ, ¿a qué hora te acostaste para dormir?	10:35 p.m.										
7. ¿A qué hora te quedaste dormido?	10:38 p. m.										
8. ¿Cuánto tiempo tardaste en dormir?	3 minutos										
9. ¿Despertaste en la noche?	☑ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No	☐ Sí ☐ No
10. ¿Cuántas veces despertaste?	3 veces										
11. En total, ¿cuánto tiempo calculas haber pasado despierto?	15 minutos										
12. ¿A qué hora terminaste de dormir?	7:00 a. m.										
13. ¿A qué hora te levantaste para empezar tus actividades del día?	7:10 a. m.										
14. ¿Qué tan descansado te sentiste al despertar?	☐ Nada descansado(a) ☐ Poco ☑ Algo ☐ Bastante ☐ Muy descansado(a)	☐ Nada descansado(a) ☐ Poco ☐ Algo ☐ Bastante ☐ Muy descansado(a)	☐ Nada descansado(a) ☐ Poco ☐ Algo ☐ Bastante ☐ Muy descansado(a)	☐ Nada descansado(a) ☐ Poco ☐ Algo ☐ Bastante ☐ Muy descansado(a)	☐ Nada descansado(a) ☐ Poco ☐ Algo ☐ Bastante ☐ Muy descansado(a)	☐ Nada descansado(a) ☐ Poco ☐ Algo ☐ Bastante ☐ Muy descansado(a)	☐ Nada descansado(a) ☐ Poco ☐ Algo ☐ Bastante ☐ Muy descansado(a)	☐ Nada descansado(a) ☐ Poco ☐ Algo ☐ Bastante ☐ Muy descansado(a)	☐ Nada descansado(a) ☐ Poco ☐ Algo ☐ Bastante ☐ Muy descansado(a)	☐ Nada descansado(a) ☐ Poco ☐ Algo ☐ Bastante ☐ Muy descansado(a)	☐ Nada descansado(a) ☐ Poco ☐ Algo ☐ Bastante ☐ Muy descansado(a)
15. ¿Cómo calificarías la calidad de tu dormir?	☐ Muy mala ☐ Mala ☐ Mediana ☑ Buena ☐ Muy buena	☐ Muy mala ☐ Mala ☐ Mediana ☐ Buena ☐ Muy buena	☐ Muy mala ☐ Mala ☐ Mediana ☐ Buena ☐ Muy buena	☐ Muy mala ☐ Mala ☐ Mediana ☐ Buena ☐ Muy buena	☐ Muy mala ☐ Mala ☐ Mediana ☐ Buena ☐ Muy buena	☐ Muy mala ☐ Mala ☐ Mediana ☐ Buena ☐ Muy buena	☐ Muy mala ☐ Mala ☐ Mediana ☐ Buena ☐ Muy buena	☐ Muy mala ☐ Mala ☐ Mediana ☐ Buena ☐ Muy buena	☐ Muy mala ☐ Mala ☐ Mediana ☐ Buena ☐ Muy buena	☐ Muy mala ☐ Mala ☐ Mediana ☐ Buena ☐ Muy buena	☐ Muy mala ☐ Mala ☐ Mediana ☐ Buena ☐ Muy buena
16. Comentarios	Había un mosquito en mi cuarto										

Appendix 2: Interview guide

The next table comprises the guide and sample questions for the fieldwork semi-structured interviews. The interviews covered the following topics:

1. Personal data
2. Household group composition
3. Household characteristics
4. Access to screen-based devices
5. Sleep environment
6. Sleep practices
7. Sleep experience and knowledge

1. Personal data	
1.1 Identifier	
1.2 Age	
1.3 Sex	Fem / Masc
1.4 Height	**How tall are you now?** _______________ meters
1.5 Weight	**How much do you weigh now?** ____________kg
1.6 Education (grade)	
1.7 Parental status	With offspring / Without offspring Num. Ages.
1.8 Activities	School Language / music / remedial courses Domestic chores Work outside the house Which one? __________________________ Other_________________________________
	Free days M - Tue - W - Th - F - Sat -Sun - None
1.9 Leisure activities	**How do you spend your free time?** Sports Reading Watching TV Social network Meeting friends Dancing Playing music Other ______________________________
1.10 Pubertal Development Status (PDS)	1. Growth sprout 2. Body hair 3. Pimples 4. Breasts growth (Women) 5a. & 5b. Menarche (Women) 6. Voice changes (Men) 7. Facial hair growth (Men)

2. Household group composition	
2.1 Household group size	**How many people currently live in your house?** Num. ________________
2.2 Household group composition	**Do you live with your parents?** Mom / Dad / Both Grandparents Uncles / Aunts
	Do you have siblings? How old are they? Yes / No Ages.
	What do they do for a living? Parents. Siblings. Others.
2.3 Domestic animals	**Do you keep any animals in or around the house?** Yes / No **Which ones are allowed to enter the house?** __________________________

3. Household characteristics	
3.1 Type of tenure	Own Rented Lent
3.2 Intradomiciliary services	Water Light Drainage Telephone
3.3 Construction material	Sheet of cardboard, wood or other Mixed Masonry
3.4 Number of rooms	

4. Access to screen-based devices	
4.1 Mobile phone	**Do you own a mobile phone?** Yes / No **If so, when do you use it?** 4 pm - 8 pm 8 pm - 12 am 12 am - 4 am 4 am - 8 am

4.2 TV	**Do you have a TV at home?** Yes / No **If so, do you watch it?** Yes / No **At what times do you watch it?** 4 pm - 8 pm 8 pm - 12 am 12 am - 4 am 4 am - 8 am
4.3 Tablet and/or computer	**Do you have a Tablet or a computer in your house?** Yes / No **Do you use them?** Yes / No **If so, when do you use them?** 4 pm - 8 pm 8 pm - 12 am 12 am - 4 am 4 am - 8 am

5. Sleep environment	
5.1 Bedding	**Where do you normally sleep?** Mattress Hammock Floor Other_________________________________
	Do you use something to cover yourself during your sleep? Duvet Sheet Blanket Other_________________________________
	Do you use a pillow when sleeping? Yes / No **If NO, do you use some other support to rest your head when sleeping?** Yes / No Which one? ______________________________ E.g. Cushion, clothes, other
	Do you sleep indoors or outdoors? Indoors / Outdoors
	Do you find this place comfortable? Yes / No **Do you find it safe?** Yes / No

	During the night, **is the place you sleep in lightened or dark?** Lightened / Dark **Is it noisy or quiet?** Noisy / Quiet
5.2 Social sleep	**Do you share the place you sleep with others?** Yes / No **If YES**: Same room / Same bedding **With whom?** ____________________
	While you sleep, **are there any animals allowed to sleep in the same place?** Yes / No Which ones? ____________________

6. Sleep practices	
6.1 Sleep duration	During the past month, **how much time do you think you have slept during the night and how much during the day? (4. PSQI)** A. On weekends Night: ____________ Day: ____________ B. On weekdays Night: ____________ Day: ____________
6.2 Sleep timing	During the past month, **at what time have you usually gone to sleep? (1. PSQI)** A. On weekends ________________ B. On weekdays ________________ **how long has it taken you to fall asleep each night? (2. PSQI)** A. On weekends ________________ B. On weekdays ________________ **do your parents and/or siblings go to sleep at the same time?** Yes / No If NO, **at what time do they usually sleep?** ________________ **Do you usually decide when to go to sleep?** Yes / No **Who usually decides it?** ____________________

<table>
<tr>
<td>6.3 Awakening and sleep inertia</td>
<td colspan="5">During the past month,

at what time have you usually gotten up in the morning? (3. PSQI)
A. On weekends ______________________
B. On week days

how difficult have you found waking up and getting out of bed during week days?
Difficult / Slightly / Not difficult at all

Normally, how do you wake up?
You need an alarm to wake up
Your need someone to wake you up
You wake up spontaneously (without help)
Other____________________________________</td>
</tr>
<tr>
<td>6.4 Drowsiness</td>
<td>During the past month, how often have you had trouble staying awake while doing some activity (watching TV, traveling by car, eating, reading, etc.)? (8. PSQI)

What would you do if you were feeling sleepy during the day?
Take a nap
Sleep more or better
Increase caffeine
Increase exercise
Other_______________________________</td>
<td>None during the past month</td>
<td>Less than once a week</td>
<td>Once or twice a week</td>
<td>Three or mor times a week</td>
</tr>
<tr>
<td>6.5 Insomnia</td>
<td>During the last month, how often have you had trouble sleeping because you (5. PSQI):

A. Cannot get to sleep within the first 60 minutes
B. Wake up in the middle of the night or early morning
C. Other reason(s) (please describe)

How often have you taken medicine (prescribed or "over the counter") to help you sleep? (7. PSQI)

What would you do if you were having trouble sleeping tonight?
Eat/drink anything
Eat/drink specific food/beverages:_________
Other_______________________________</td>
<td>None during the past month</td>
<td>Less than once a week</td>
<td>Once or twice a week</td>
<td>Three or mor times a week</td>
</tr>
</table>

	During the last month, **how often have you had**	None during the past month	Daily/ almost daily	1-3 times a week	Once o twice a month
6.6 Stimulants consumption	drunk alcohol smoked tobacco drunk coffee drunk energy drinks (red bull or similar) other stimulant(s):___________________				
6.7 Reduced questionnaire of morn/even	(Adan & Almirall, 1990) Topics: 1. Preferred time to get up 2. Sense of rest 3. Preferred time to sleep 4. Time for better performance 5. Chronotype self-evaluation				

7. Sleep experience and knowledge	
7.1 Sleep and health	**Do you think sleep is important for your health?** Yes / No **Why?**
	In your opinion, how can people ensure their sleep is healthy? **Is sleep duration important?** Yes / No **What is its importance?** **Should sleep happen at a certain time or times?** Yes / No **At what time(s) should it happen?** **Why is that timing important for sleep?**

<table>
<tr><td>7.5 Biomedical knowledge about sleep</td><td colspan="5">Have you heard any of the next statements?

Not enough sleep…

-affects your health
-makes you feel tired
-causes weight gain
-affects your mood
-affects your ability to remember things or concentrate
-affects your performance at school/work (result: you get lower marks)</td></tr>
<tr><td></td><td colspan="5">Where have you heard them from?
From your parents, grandparents, brothers or uncles
From your neighbours
From your friends
At school
From a doctor
From television, radio or the Internet
From the newspaper or a book</td></tr>
<tr><td>7.3 Sleep and function</td><td colspan="5">In your experience, does sleep has any benefits? Yes / No
Which one(s)?</td></tr>
<tr><td></td><td colspan="5">In your experience, are there any consequences of not getting enough sleep? Yes / No
Which ones?

How can you tell that you have not slept enough?</td></tr>
<tr><td>7.4 Pittsburgh Sleep Quality Assessment</td><td>During the past month,
how would you rate your sleep quality overall (6. PSQI)?

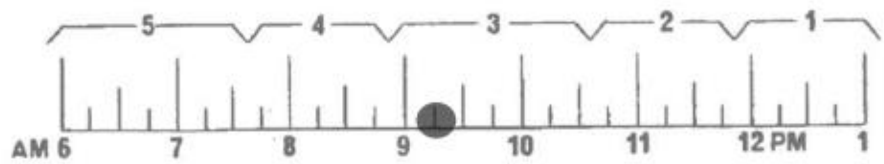
Very good
Fairly good
Fairly bad
Very bad

how much of a problem has it been for you to keep up enthusiasm to get things done (9.PSQI)?</td><td>None during the past month</td><td>Less than once a week</td><td>Once or twice a week</td><td>Three or more times a week</td></tr>
</table>

Appendix 3: Morningness-Eveningness Reduced Scale and Pubertal Development Scale

EJEMPLO - MERS

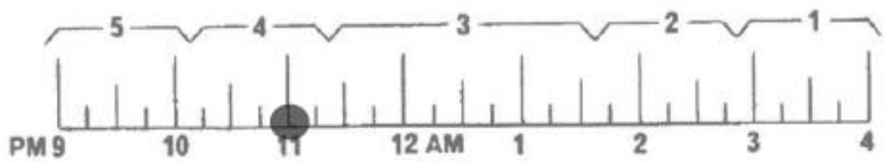
1. Considerando únicamente tus propias preferencias, ¿a qué hora te levantarías si fueras completamente libre para planear tu día?



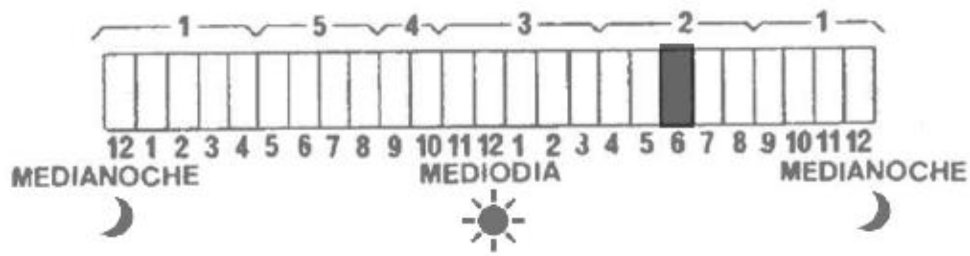
2. Normalmente, durante la primera media hora después de despertarte por la mañana te sientes....

Muy cansado.................... 1
Bastante cansado............ 2
Bastante descansado...... 3
Muy descansado............... 4

3. ¿A qué hora de la noche sueles sentirte cansado y con ganas de dormir?



4. ¿A qué hora del día sueles sentirte más alerta y con más energía?



5. Suele hablarse de personas de tipo "matutino" (gente madrugadora) y "vespertinas" (gente más nocturna). ¿Con cuál de estos dos tipos te identificas más?

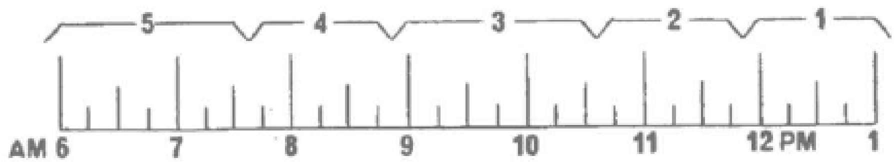
Soy...

Claramente "matutino" (madrugador)........... 6
Más "matutino" que "vespertino"................. 4
Más "vespertino" que "matutino"................. 2
Claramente "vespertino" (nocturno).............. 0

Identificador____________

6.7 Cuestionario Matutinidad-Vespertinidad (Adan & Almirall, 1990)

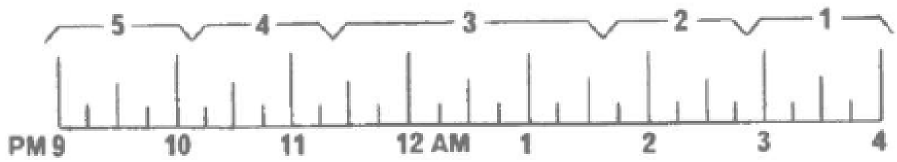
1. Considerando únicamente tus propias preferencias, ¿a qué hora te levantarías si fueras completamente libre para planear tu día?



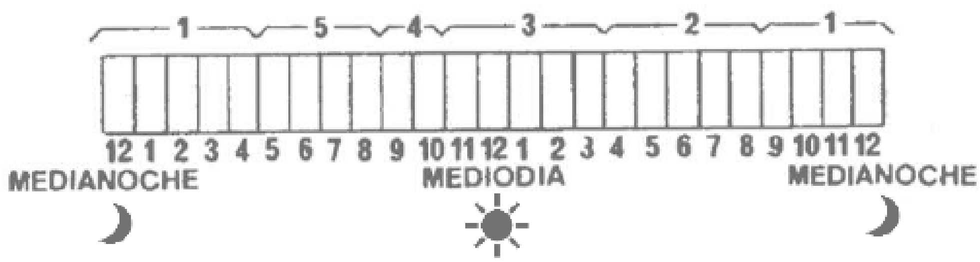
2. Normalmente, durante la primera media hora después de despertarte por la mañana te sientes....

Muy cansado.................... ☐ 1
Bastante cansado............ ☐ 2
Bastante descansado...... ☐ 3
Muy descansado.............. ☐ 4

3. ¿A qué hora de la noche sueles sentirte cansado y con ganas de dormir?



4. ¿A qué hora del día sueles sentirte más alerta y con más energía?



5. Suele hablarse de personas de tipo "matutino" (gente madrugadora) y "vespertinas" (gente más nocturna). ¿Con cuál de estos dos tipos te identificas más?

Soy...

Claramente "matutino" (madrugador)........... ☐ 6
Más "matutino" que "vespertino".................. ☐ 4
Más "vespertino" que "matutino".................. ☐ 2
Claramente "vespertino" (nocturno).............. ☐ 0

La puntuación directa global del cuestionario, sumatorio de la puntuación de los 5 ítems que lo componen, puede ser considerada en 5 intervalos que determinan los tipos resultantes:

	PUNTUACIÓN
Tipo claramente matutino	22.25 (CM)
Tipo moderadamente matutino	18-21 (MM)
Ningún tipo	12-17 (NT)
Tipo moderadamente vespertino	8-11 (MV)
Tipo claramente vespertino	4-7 (CV)

After adding the scores of the 5 items composing the questionnaire, the global score can be considered in 5 intervals that determine the resulting types:

	TOTAL SCORE
Definite morning type	22.25 (DM)
Moderate morning type	18-21 (MM)
Neither type	12-17 (NT)
Moderate evening type	8-11 (MV)
Definite evening type	4-7 (DV)

Participante______________

Escala de Desarrollo Puberal (EDP) – Formato para Mujeres

Introducción

Las siguientes preguntas tratan sobre cambios que pueden estar ocurriendo en tu cuerpo. Es normal que estos cambios le suceden a la gente joven a diferentes edades. Dos de los cambios más notorios son un crecimiento rápido gracias al cual nos volvemos más altos en poco tiempo, y la aparición de vello o pelo en partes del cuerpo en donde antes no existía (como puede ser debajo de los brazos, en las axilas).

Los cambios en tu cuerpo pueden estar relacionados con tus hábitos de sueño, por lo que es importante que te esfuerces en responder con cuidado las siguientes preguntas. Si no entiendes una pregunta o no sabes la respuesta, tacha la opción "No lo sé".

Pregunta	Opciones de respuesta	Puntaje
1. Dirías que tu crecimiento en altura:		
	☐ Aún no ha comenzado a aumentar rápidamente	1
	☐ Apenas ha comenzado	2
	☐ Está definitivamente en marcha	3
	☐ Parece haberse completado	4
	☐ No lo sé	5
2. ¿Qué pasa con el crecimiento de tu vello corporal? Dirías que el crecimiento de vello o pelo en nuevas partes de tu cuerpo:		
	☐ Aún no ha comenzado	1
	☐ Apenas ha comenzado	2
	☐ Está definitivamente en marcha	3
	☐ Parece haberse completado	4
	☐ No lo sé	5
3. ¿Has notado algún cambio en tu piel, especialmente granitos o espinillas?		
	☐ Aún no ha comenzado	1
	☐ Apenas ha comenzado	2
	☐ Está definitivamente en marcha	3
	☐ Parece haberse completado	4
	☐ No lo sé	5
4. ¿Has notado que tus senos han comenzado a crecer?		
	☐ Aún no han comenzado a crecer	1
	☐ Apenas hnn comenzado a crecer	2
	☐ Su crecimiento está definitivamente en marcha	3
	☐ Su crecimiento parece haberse completado	4
	☐ No lo sé	5
5a. ¿Has comenzado a menstruar (comenzaste a tener tu periodo)?		
	☐ Sí	4
	☐ No	1
5b. Si repondiste "Sí" a la pregunta anterior, ¿qué edad tenías cuando tuviste tu primer periodo?		
	Edad en años: ______________________	

Participante____________

Escala de Desarrollo Puberal (EDP) – Formato para Hombres

Introducción

Las siguientes preguntas tratan sobre cambios que pueden estar ocurriendo en tu cuerpo. Es normal que estos cambios le suceden a la gente joven a diferentes edades. Dos de los cambios más notorios son un crecimiento rápido gracias al cual nos volvemos más altos en poco tiempo, y la aparición de vello o pelo en partes del cuerpo en donde antes no existía (como puede ser debajo de los brazos, en las axilas).

Los cambios en tu cuerpo pueden estar relacionados con tus hábitos de sueño, por lo que es importante que te esfuerces en responder con cuidado las siguientes preguntas. Si no entiendes una pregunta o no sabes la respuesta, tacha la opción "No lo sé".

Pregunta	**Opciones de respuesta**	**Puntaje**
1. Dirías que tu crecimiento en altura:		
	☐ Aún no ha comenzado a aumentar rápidamente	1
	☐ Apenas ha comenzado	2
	☐ Está definitivamente en marcha	3
	☐ Parece haberse completado	4
	☐ No lo sé	5
2. ¿Qué pasa con el crecimiento de tu vello corporal? Dirías que el crecimiento de vello o pelo en nuevas partes de tu cuerpo:		
	☐ Aún no ha comenzado	1
	☐ Apenas ha comenzado	2
	☐ Está definitivamente en marcha	3
	☐ Parece haberse completado	4
	☐ No lo sé	5
3. ¿Has notado algún cambio en tu piel, especialmente granitos o espinillas?		
	☐ Aún no ha comenzado	1
	☐ Apenas ha comenzado	2
	☐ Está definitivamente en marcha	3
	☐ Parece haberse completado	4
	☐ No lo sé	5
4. ¿Has notado que tu voz se haya vuelto más grave?		
	☐ Mi voz aún no ha comenzado a cambiar	1
	☐ Mi voz apenas ha comenzado a cambiar	2
	☐ Los cambios en mi voz están definitivamente en marcha	3
	☐ Los cambios en mi voz parecen haberse completado	4
	☐ No lo sé	5
5. ¿Te ha comenzado a crecer vello o pelo en la cara?		
	☐ No me ha comenzado a crecer vello en la cara	1
	☐ Apenas me ha comenzado a crecer vello en la cara	2
	☐ Definitivamente me ha comenzado a crecer vello en la cara	3
	☐ El crecimiento de vello en mi cara parece haberse completado	4
	☐ No lo sé	5

Algoritmos de puntuación

Para las preguntas 1 a 4 contenidas en los formatos para mujeres y hombres, las opciones de respuesta fueron:

> Aún no ha comenzado (1 punto)
> Apenas ha comenzado (2 puntos)
> Definitivamente ha comenzado (3 puntos)
> Parece haberse completado (4 puntos)
> No lo sé (ausente)
> **Sí** en la pregunta sobre menstruación = 4 puntos; No = 1 punto

El puntaje se promedia entre el número total de preguntas para obtener la puntuación de la Escala de Desarrollo Puberal (EDP).

Los puntajes para cada *categoría de pubertad* se calculan con base en los criterios de Crockett (1988, sin publicar) mediante la suma de los valores de escala establecidos anteriormente.

Calcule los puntajes de *categoría de pubertad* para **Hombres** (use el crecimiento del vello corporal, el cambio de voz y el crecimiento del vello facial) de la siguiente manera:

> Prepuberal = 3
> Pubertad temprana= 4 o 5 (sin respuestas de 3-puntos)
> Pubertad media= 6, 7, ó 8 (sin respuestas de 4-puntos)
> Pubertad avanzada = 9-11
> Post-pubertad = 12

Calcule los puntajes de *categoría de pubertad* para **Mujeres** (use el crecimiento del vello corporal, el desarrollo de los senos y la menarca) de la siguiente manera:

> Prepuberal = 2 y ausencia de menarca
> Pubertad temprana = 3 y ausencia de menarca
> Pubertad media = > 3 y ausencia de menarca
> Pubertad avanzada = <= 7 y menarca
> Post-pubertad = 8 y menarca

Appendix 4: Information sheet and Consent form

Mexico, ___ / ___________ / 2019

PARTICIPANT INFORMATION SHEET

Project title: *Changes in sleep: sleep habits among adolescents in rural and urban societies*

Researcher: MSc Andrea Silva-Caballero
Department: Anthropology Department, Durham University, United Kingdom

Contact details Dawson Building, South Road, Durham, United Kingdom, DH1 3LE

andrea.silva-caballero2@durham.ac.uk

Supervisors names: Dr. Gillian Bentley g.r.bentley@durham.ac.uk

Dr. Helen Ball h.l.ball@durham.ac.uk

Your son/daughter and yourself are invited to take part in a study that I am conducting as part of my PhD Thesis Project at Durham University, UK.

This study has received ethical approval from the Anthropology Department Ethics Committee of Durham University. The study is possible thanks to the funding of the Mexican National Council of Science and Technology- CONACyT.

Before you decide whether to agree to take part it is important for you to understand the purpose of the research and what is involved as a participant. Please read the following information carefully. Please get in contact if there is anything that is not clear or if you would like more information.

What is the purpose of the study?

This project aims to increase our understanding of the human sleep by studying how adolescents sleep. Specifically:

- How the way we sleep changes as we grow up
- How much time teenagers spend sleeping each day
- How could this time be linked to family, school and social commitments
- The importance that teens place on sleep

The results of the study should:

1) Retrieve and account for the knowledge that adolescents and their families have about sleep.
2) Offer a perspective through which adolescents and their families can know more about their sleep.

The role of you and your son/daughter's in the study

Your participation in the project involves answering one interview with an approximate duration of 20 minutes. The interview will be scheduled according to your time availability.

In addition, your son/daughter will be asked to use a wristwatch that measures sleep and daily physical activity, and to complete a brief sleep diary before going to sleep and after waking up. He/she should use the wristwatch and fill in the diary for 10 days over two weeks: three days during the week and the whole weekend. Your son/daughter will be required to use the watch 24 hours a day during this stage of the research.

Do I have to take part?

Your participation is completely voluntary. If during the investigation you or your son/daughter feel uncomfortable for any reason, you are entirely free to omit questions you do not want to answer or to withdraw at any time you wish without explanation.

Will our data be kept confidential?

All the data you provide will be kept confidential and your participation will be anonymous. You will be assigned an anonymous number for data collection that will have no connection to your name or identity. This guarantees that, if the results of the research are published, your data cannot be identified individually.

All research data and records needed to validate the research findings will be stored for 10 years after the publication of the results. Anonymized data will be archived electronically and may be shared with others for legitimate research purposes. After the 10 years period, the records will be destroyed.

What will happen to the results of the project?

The project in which you and your child are invited to take part will come to an end in January 2022. The information obtained during the study will be used to write up a PhD thesis that will be submitted to Durham University. It can also be used in scientific and/or dissemination publications, reports and presentations.

Durham University is committed to sharing the results of its world-class research for public benefit. As part of this commitment the University has established an online repository for all Durham University Higher Degree theses which provides access to the full text of freely available theses. Since the study in which you are invited to participate will be written up as a thesis, you will have online access in the University archives as of July 2022.

Likewise, in September 2022 a physical copy of the PhD thesis will be provided to the secondary school from which participants will be recruited. The text will be translated into Spanish to ease its reading and understanding.

Who is the researcher in charge of the project?

The project in which you have been invited to take part in being led by Andrea Silva Caballero. Her contact information is provided at the beginning of this information sheet.

Andrea Silva is an anthropologist who has specialized in paediatric health issues and has worked in summer science dissemination courses for children and adolescents, where she has offered workshops on the human brain and human emotions.

Who do I contact if I have any questions or concerns about this study?

If you or your son/daughter have any further questions or concerns about this study, please speak to the researcher or their supervisors. If you remain unhappy or wish to make a formal complaint, please submit a complaint via the University's Complaints Process (https://www.dur.ac.uk/academicsupport.office/appeals/)

Thank you for reading this information and considering taking part in this study.

Consent form

Project title: *Changes in sleep: sleep habits among adolescents in rural and urban societies*

Researcher: MSc Andrea Silva-Caballero
Department: Anthropology Department, Durham University, United Kingdom

Contact details: South Road, Durham, United Kingdom, DH1 3LE

andrea.silva-caballero2@durham.ac.uk

Supervisors names: Dr. Gillian Bentley g.r.bentley@durham.ac.uk

Dr. Helen Ball h.l.ball@durham.ac.uk

This form is to confirm that you understand what the purposes of the project, what is involved and that you are happy to take part. Please initial each box to indicate your agreement:

I confirm that I have read and understand the information sheet dated____________ for the above project. (dd/mm/yy)	
I have had sufficient time to consider the information and ask any questions I might have.	
I am satisfied with the answers I have been given.	
I understand who will have access to personal data provided, how the data will be stored and what will happen to the data at the end of the project.	
I understand that anonymised versions of my data may be archived and shared with others for legitimate research purposes.	
I understand that my words may be quoted in publications, reports, presentations, web pages, and other research outputs. *Please choose one of the following two options:* ○ **I agree** to my real name being used in the above ○ **I do not agree** to my real name being used in the above	
I agree to take part in the above project.	
I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason.	

Participant's Signature_______________________________________ Date______________

(NAME IN BLOCK LETTERS) ____

Researcher's Signature______________________________ Date______________

(NAME IN BLOCK LETTERS) ____