Sleep Medicine 62 (2019) 69–76

Contents lists available at ScienceDirect

Sleep Medicine

journal homepage: www.elsevier.com/locate/sleep

Original Article

Using big data to explore worldwide trends in objective sleep in the transition to adulthood

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ARTICLE INFO

Article history:
Received 12 April 2019
Received in revised form
5 July 2019
Accepted 10 July 2019
Available online 3 August 2019

Keywords:
Adolescence
Wearable
Fitness tracker
Worldwide sleep

ABSTRACT

Background: Development induces changes in sleep, and its duration has been reported to change as a function of aging. Additionally, sleep timing is a marker of pubertal maturation, where during adolescence, the circadian rhythm shifts later. Typically, this is manifested in a later sleep onset in the evening and later awakening in the morning. These changes across development seem to be universal around the world but are unlikely to persist into adulthood.
Methods: This study utilized accelerometer data from 17,355 participants aged 16–30 years (56% female) measured by validated Polar wearables over a 14-day period. We compared sleep duration, chronotype (sleep midpoint) and weekend catch-up (ie, social jetlag) sleep across ages and regions over 242,948 nights.
Results: The data indicate a decline in sleep duration as well as a dramatic shift in sleep onset times throughout adolescence. This continues well into early adulthood and stabilizes nearer age 30. Differences in sleep duration across ages were significant, and ranged from 7:53 h at age 16 to 7:29 h at age 30 in the sample. Additionally, there was a clear difference between females and males throughout adolescence and young adulthood: girls had longer sleep duration and earlier timed sleep in the current study. Differences in sleep were found between regions across the world, and across European areas.
Conclusions: Both sleep duration and sleep timing go through a clear developmental pattern, particularly in early adulthood. Females had an earlier sleep midpoint and obtained more sleep. Regional differences in sleep occurred across the world.

1. Introduction

The transition from childhood to adulthood influences physical, psychological, and social dimensions of human life; moreover, this maturation often leads to dramatic alterations in most sleep measures. Sleep timing is the most evidently affected [1,2] with most adolescents experiencing a shift towards a later circadian preference. This shift is on average between 60 and 120 min in normative development [1], depending on the measurement method. From childhood to the teenage years, sleep duration is likely to shorten from an approximate 10 h to a mean of 8 h [3]. According to recent recommendations [4], adolescents should sleep approximately 8–10 h per night, although only 47% of 11–18-year-olds meet this recommendation [5]. Sex differences in sleep duration typically show that females sleep marginally longer than males (eg, up to 30 min more) [6,7], and there is some evidence that females show greater age related declines in sleep duration [8]. However, further research is warranted regarding sex differences, particularly across adolescence and early adulthood [8].

The reasons behind these developmental changes in sleep are due to both biological and environmental factors relating to puberty onset [9]. Adolescents experience a shift in endogenous melatonin secretion timing as well as several other hormones' (ie, testosterone) secretion levels [10,11]. Furthermore, during

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https://doi.org/10.1016/j.sleep.2019.07.024

adolescence, the development of brain connectivity leads to various behavioural changes [11] (eg, risk-taking) [12]. This is also one reason for the shift in social priorities [13], as well as adolescents' strive for independency, including autonomy over sleep schedules [14,15]. Furthermore, through neural development, adolescents' sleep pressure builds up more slowly, and they are better at resisting it, thus enabling teenagers to be more alert in the evening [16,17].

Normative changes in sleep, as well as the reasons behind these changes seem to be similar around the world, but with some differences relating to region or culture (ie, sleep in Asia tends to be short and late, whereas Europeans seem to have the longest sleep duration) [5,18]. In adolescent and adult populations, the estimated prevalence of problems relating to short sleep is 30% [19] or up to 16% for marked problems in circadian regulation. There is some variation across regions and countries [5] – with a noteworthy higher prevalence of daytime sleepiness in adolescents in Asian countries. These sleep problems appear interrelated, yet at the core, seem to stem from circadian dysregulation. In recent decades, there are worldwide reports of an increasing prevalence of delayed sleep phase in young people (characterized by very late bedtimes and difficulties waking up in the morning at a socially-appropriate time). This manifests in large discrepancies in sleep timing and duration between weekends and weekdays, referred to as social jetlag [20]. As sleep is a central element in optimal daytime functioning, health, and wellbeing, the reliable detection of sleep patterns across development is of key interest.

While the topic has been studied extensively in samples localized to a single country [21–23], studies using 'big data' are sparse, especially those using objective measurements. It is also noteworthy that commercially-available devices may provide ecologically-valid insight into actual sleep behaviour as the devices are typically owned and used as tools for improving one's own wellbeing and performance rather than due to externally motivated reasons (eg, research participation).

In the present study, our objective is to explore accelerometer-measured sleep duration and timing in the transition from late adolescence to adulthood, in a large, international sample of young people. First, we anticipate that sleep duration will decrease from adolescence to early adulthood, independent of location. Second, given the dearth of extant research, sex differences in sleep patterns across this critical period will be explored. Third, we expect to find large intercultural differences, with later sleep timing and shorter sleep duration among Asian populations. Additionally, we expect to see a geographic pattern across European countries, whereby those residing in more northern latitudes sleep later and less.

2. Methods

2.1. Participants

Data were collected from 17,355 Polar device users aged 16 to 30 (mean age 25y) who had electronically consented to provide their data for research purposes. Participants self-reported their age, height and weight, country of residence, and habitual exercise level. Polar wrist-worn fitness trackers A370 (84,537 nights [35%]), M430 (144,887 nights [60%]), and M600 (13,516 nights [6%]) were used to measure sleep. Polar anonymized the data completely and created a dataset with variables suitable for answering the abovementioned research questions. To generalize wear time across all individuals, a consecutive 14-day period was chosen between February 2018 and June 2018. This resulted in 242,989 days and nights.

2.2. Sleep

Sleep duration and timing were collected using the Polar A370, M430, and M600 devices, which utilize accelerometers. The devices use a proprietary algorithm to abstract sleep based on characteristics of raw acceleration signals. The sleep measuring technology utilized in A370 and M430 has been validated against polysomnography (PSG) [24], and the technology measuring sleep is similar also in M600. The agreement levels with PSG in these devices are adequate, with excellent sensitivity (the ability of an accelerometer to detect true sleep) (>0.91) and adequate specificity (the ability of an accelerometer to detect true wake) (>0.77) in estimating sleep [24]. Sleep duration (in hrs, calculated from sleep onset to offset), sleep midpoint [starting sleep time + (sleep duration/2)] on both workdays and free days, sleep onset and offset, as well as weekend catch-up sleep were analysed as measures of sleep behaviour. Weekend catch-up sleep (ie, social jetlag [25]) was calculated as the difference in sleep duration between week- and weekend days in the data.

2.3. Geographical regions

The data included measurements from 107 countries. All countries were categorized into regions according to the United Nations Country Grouping (https://www.internetworldstats.com/list1.htm#geo). A detailed description of the countries included in the study and the regional categorisation is available (Table S1, Online only). The following regions were included in our analyses: Africa, Asia, Central and Southern America, Europe, The Middle East, North America and The Caribbean, and Oceania. As the sample was weighted towards European countries (86% from European countries), Europe was further categorized into Northern, Central and Southern Europe. All European countries with the majority of land falling in the latitude of >55°N were considered Northern, all countries with latitude <45°N were considered Southern, while countries that fell in between were considered Central European.

2.4. Statistics

We compared weekday and weekend nights' sleep duration, sleep midpoint, and social jetlag across age groups using ANOVAs. Differences in sleep duration, sleep midpoint, and social jetlag across world regions, and European regions were analysed using ANOVAs. Male and female participants' sleep was additionally compared using *t*-tests. Data were available for 14 nights from all 17,355 participants. Weekday and weekend data were available, but no information regarding whether the measurement days, or mornings were free or scheduled. Thus, comparisons between weekday and weekend data should be interpreted with some caution. Some participants were considered outliers regarding sleep midpoint: 210 (59.5% males) with sleep midpoints that differed more than 3 SDs from the mean were excluded from midpoint analyses. In order to evaluate estimate sizes, we report R^2 for comparisons.

3. Results

The characteristics of the sample are presented in Table 1.

3.1. Age differences

ANOVAs showed significant overall differences in sleep duration and sleep midpoint between participants of different age (p-values<0.0001; $R^2 = 0.02$, $R^2 = 0.02$), as well as in weekend catch-up sleep ($p = 0.002$; $R^2 < 0.01$). The trajectories detailing the mean

Table 1
Characteristics of the sample and differences between female and male participants.

Characteristic	All participants Mean/N (%)/SD, min–max	Female participants Mean/N (%)/SD, min–max	Male participants Mean/N (%)/SD, min–max	P
Sex (% female)	17,355 (56.2)	9716 (100)	7639 (0)	
Age	24.87/3.96, 16–30	24.55/3.98, 16–30	25.28/3.88, 16–30	>0.0001
BMI (kg/m^2)	24.67/4.04, 15.3–44.8	24.52/4.46, 15.3–44.8	24.85/3.42, 15.3–40.8	>0.0001
Region				>0.0001
Africa	252 (1.5)	110 (1.1)	142 (1.9)	
Asia	388 (2.2)	180 (1.9)	208 (2.7)	
Central & Southern America	457 (2.6)	217 (2.2)	240 (3.1)	
Europe	14,939 (86.1)	8460 (87.1)	6479 (84.8)	
Northern Europe	7323 (49.0)	4885 (57.7)	2438 (37.6)	
Central Europe	6183 (41.4)	3134 (37.0)	3049 (47.1)	
Southern Europe	1433 (9.6)	441 (5.2)	992 (15.3)	
Middle East	240 (1.4)	115 (1.2)	125 (1.6)	
North America & The Caribbean	980 (5.6)	587 (6.0)	393 (5.1)	
Oceania	99 (0.6)	47 (0.5)	52 (0.7)	
Sleep variables				
Sleep duration, all nights (h)	7.61/0.70, 4.71–11.30	7.76/0.69, 4.92–11.30	7.41/0.65, 4.71–11.08	>0.0001
Sleep duration, weekdays (h)	7.74/0.74, 4.62–11.55	7.74/0.73, 4.68–11.55	7.39/0.71, 4.62–10.93	>0.0001
Sleep duration, weekends (h)	7.82/0.88, 4.52–11.48	7.82/0.87, 4.61–11.41	7.48/0.84, 4.52–11.48	>0.0001
Sleep midpoint, all nights (hh:mm)	3:54/1:12, 0:34–18:14	3:45/1:08, 0:34–17:40	4:04/1:16, 0:56–18:14	>0.0001
Sleep midpoint, weekdays (hh:mm)	3:50/1:14, 0:36–19:51	3:42/1:10, 0:36–16:55	4:00/1:18, 0:40–19:51	>0.0001
Sleep midpoint, weekends (hh:mm)	4:03/1:23, 0:22–23:16	3:54/1:18, 0:28–21:25	4:14/1:27, 0:22–23:16	>0.0001
Social jetlag (h)	0.09/0.80, −3.15–3.83	0.08/0.80, −3.14–3.40	0.10/0.81, −3.15–3.83	0.110

Abbreviations: BMI = body mass index (weight/height x height); SD = standard deviation. *P* refers to significance of difference between sexes (calculated using T-test for continuous variables, χ^2 test for categorical variables).

level values in weekday and weekend sleep duration and timing (midpoint, onset, and offset) according to age are presented in Fig. 1 (panels A–D).

3.2. Sex differences

Differences between male and female participants' mean sleep duration, sleep midpoint, and weekend catch-up sleep are presented in Table 1. There were significant differences in sleep duration with females sleeping longer (MD 21 min, 95% CI % 19.8–22.2 min; p-value<0.0001; $R^2 = 0.06$) and having an earlier sleep midpoint (MD 17 min, 95% CI 14.6–18.4 min; p-value<0.0001; $R^2 = 0.02$). Weekend catch-up sleep did not differ between the sexes. Differences between sexes according to age are presented in Fig. 2.

3.3. Regional differences

Sleep duration and sleep midpoint differences between regions were significant (overall p-values <0.0001), as well as comparisons between the three European regions (p-values <0.0001). The amount of social jetlag was significantly different between world regions (p-values <0.0001) but not for European regions ($p = 0.11$). Fig. 3 (panels A–C) presents the regional differences across the world, and Fig. 4 (panels A–C) across the three European regions. Means, standard deviations, standard errors and 95% confidence intervals according to regions are presented in Table S2 (Online only). The overall differences between regions suggested longest sleep duration in Europe and North America, while the shortest sleep duration was observed in participants from Asia. Regarding sleep midpoint, those in the Middle East had the latest sleep timing while participants in Oceania had the earliest. The amount of social jetlag was greatest among participants from the Middle East, and smallest in African countries. Effect sizes regarding regional differences were small: $R^2 = 0.04$ for sleep duration ($R^2 = 0.03$ for European regions); $R^2 = 0.02$ for midpoint ($R^2 = 0.07$ for European regions), and $R^2 = 0.01$ for social jetlag ($R^2 < 0.01$ for European regions).

4. Discussion

In this study, we investigated the objectively measured sleep of 17,355 adolescents and young adults. The extensive dataset utilized in this study covered 14 consecutive nights from young individuals living in various countries, mostly in Europe. Thus, a strength of this study is the analysis of nearly a quarter of a million nights of objectively-measured sleep data across the globe.

We conclude that, as expected, the sleep duration of young people shortens across adolescent development and into young adulthood. Our findings are consistent with meta-analytical data examining normative developmental changes in sleep patterns [6] and findings from a recent study using large-scale data from wearable devices to examine sleep patterns in users (15–80 years of age) across East Asia and Oceania [26]. In contrast to previous research, the current study provides a comprehensive snapshot of age and sex differences in sleep duration during the critical transitional period from late adolescence to early adulthood. With the exception of the 16-year old group, near-linear declines in sleep durations occurred for both sexes, with females obtaining a meaningful 21 min of extra sleep across this developmental period. Previous studies using adolescent and adult samples have found somewhat similar sex differences in sleep duration (eg, 11–29 mins [7], 6–28 mins [6]). In adults, it is possible that some of this effect is accounted for by differences in family structure and carer responsibilities [7,27]. However, the mechanisms underlying sex differences in children's and adolescents' sleep remains unclear [6]. One possible explanation is related to the earlier onset and offset of puberty in females, as data from the US National Longitudinal Study of Adolescent Health suggests. An earlier shift in chronotype may partially account for the longer sleep duration of females in our sample, in that young women reach their maximum in lateness earlier. Roenneberg and colleagues [20] were able to show that this was around 19.5 years, whereas young men continue to delay their bedtime until around the age of 21 years. Similarly to Ong and colleagues, sex differences in social jetlag were not observed in the present study [26].

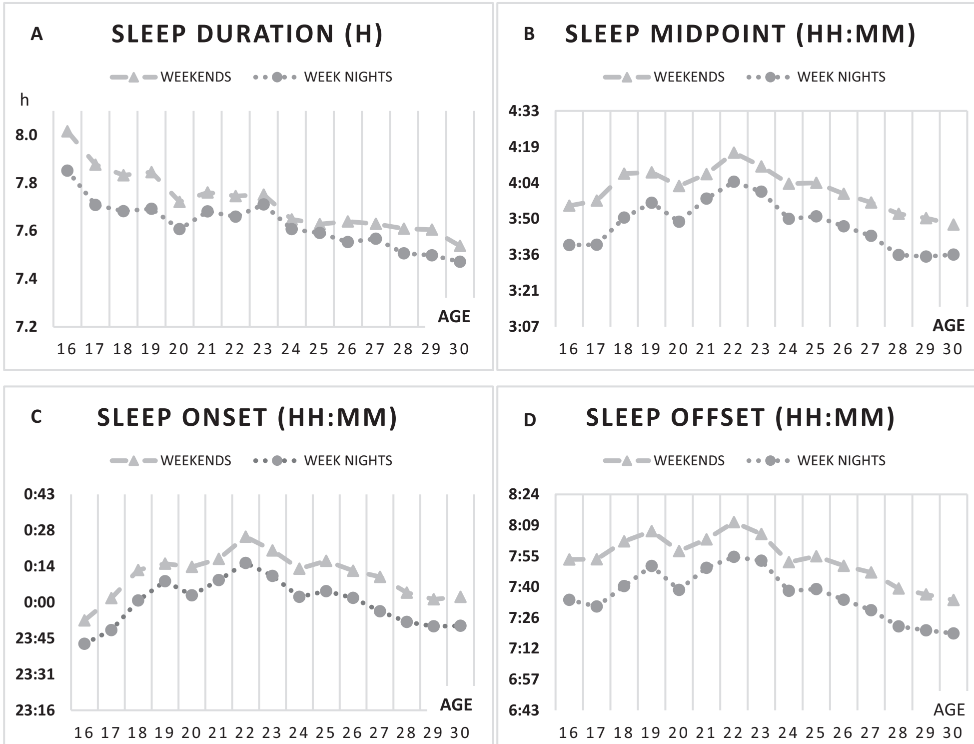

Fig. 1. Sleep duration (Panel A), sleep midpoint (Panel B), sleep onset (Panel C), and sleep offset (Panel D) at different ages.

Previous studies (especially in adolescent groups) suggest significantly longer weekend sleep than weekday sleep [28], but this was not evident in the current research. As the data utilized in this study did not contain information about the actual morning commitments of the participants, it is possible that the differences between weekdays and weekends do not reflect true individual preferences in sleep. It is, however, noteworthy that the sleep patterns in people interested in their health may also be more stable over the week.

In addition to the shortening of sleep duration as a function of development, sleep timing showed a non-linear curve, with a peak in delayed sleep timing around the age of 22 years for both genders. After, sleep timing gradually shifts to an early phase up until almost 30 years of age, and then plateaus. Overall, this non-linear trajectory is similar to previous self-reported data [20], showing a peak around 20–21 years of age, and a gradual decline thereafter without a plateau. These slight differences may be due to the nature of the measurement (self-report vs accelerometers), and/or differences in cohorts or the range of populations sampled. Whilst adolescence is a sensitive period in relation to circadian regulation, where sleep timing usually shifts later [20] these findings suggest, at least from a sleep timing perspective the transition from adolescence to adulthood may occur in the early 20s.

In the current study, we also found noticeable differences between regions. Similar to previous meta-analyses and studies involving wearable devices, young adults in Asia had the shortest sleep duration (6 hr 30 min), whereas those in Oceania (7 hr 14 min) and Europe (7 hr 7 min) had the longest [5,6,26,29]. Young adults in Central and Southern America and The Middle East also reported short sleep (6 hr 40 min). This mimics previous findings in Middle Eastern young adults, who frequently reported an average of 7 hr sleep or less on school nights. Later bedtimes without an accompanying rise time delay leads to Asians obtaining less sleep than those in European and Oceanic regions [26,29]. Likewise, mid-sleep point was also later in Asia (4:05am) compared to Oceania, Africa and North America, although Middle Eastern young adults had the latest (4:38am). Greater emphasis on work and academic performance in Asian countries compared to Western countries [26,29] could explain the later sleep mid-point and shorter sleep duration. Additionally, in the present study similar catch up sleep was seen in Asian regions compared to Europe, Oceania, and Northern America. Furthermore, country-specific differences in school and work starting hours may explain some of the variation in rise times, especially in the younger participants included in this study. Importantly, these sociocultural aspects are likely to influence rise times over and above the individuals' biologically determined sleep patterns in adolescence and young adulthood. This is likely to mask some of the more pronounced effects of age on sleep patterns which have been previously reported in the adolescent literature [20,30].

Notably, the present study collected international data, spanning multiple longitudes, latitudes, day lengths and timing of day length, although this data were not measured. Despite sunlight being a strong zeitgeber, indoor light exposure is more prevalent, thus influencing sleep to a greater extent [18]. Furthermore, behavioural practices such as sleep hygiene, and culture exhibit larger influence over sleep than photoperiod [29,31]. Focusing just on Europe, we found those living in southern regions of Europe to obtain less sleep than those residing in northern regions. On the one hand, greater day length has shown to be a small yet significant contributor to more sleep in young people [31], yet on the other hand, cultural factors likely exert stronger effects on bedtimes, and thus sleep duration.

While this dataset contained only a limited amount of measurements from other regions, our findings nevertheless support findings from a previous meta-analytic study on adolescents' sleep patterns around the world [5].

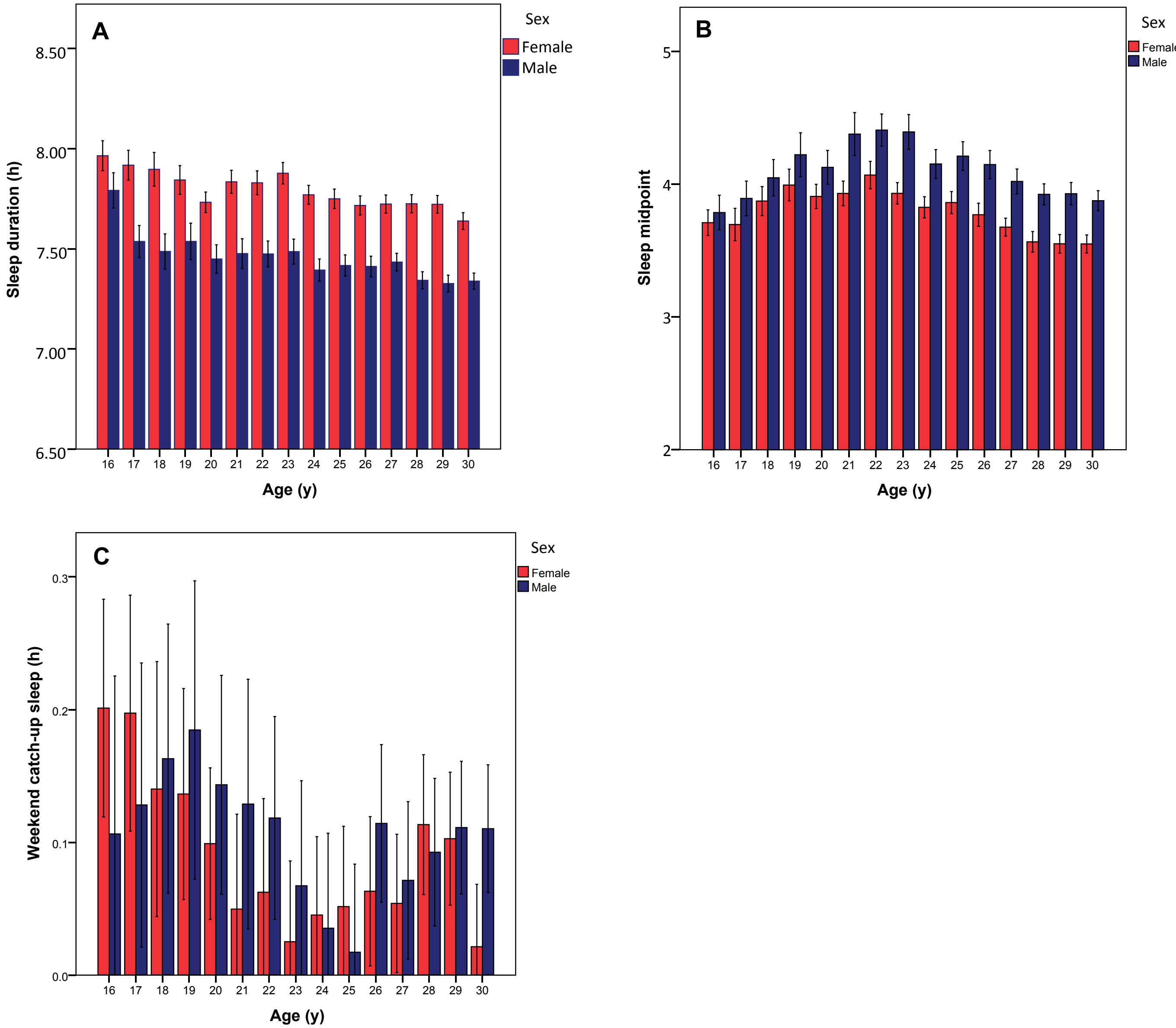

Fig. 2. Differences in sleep duration (Panel A), sleep midpoint (Panel B), and weekend catch-up (social jetlag) (Panel C) sleep between females and males at different ages.

4.1. Strengths and limitations

Our data included over 17,000 Polar device users who allowed their sleep data to be utilized for research purposes. These data were thus a reliable sample of actual wearable users who owned their devices, were used to the functionalities, and were interested in self-measurement of sleep. The measurements consisted of 14 days and nights, with no missing data, providing an excellent representation of the user's typical sleep behaviour.

One limitation in our sample was the greater weighting of European participants, and the age distribution (ie, 20-year-olds were over-represented in this sample). Moreover, we did not have any information regarding the participants' daytime duties or schedules, thus our weekday-weekend comparisons (eg, social jetlag) may not be fully representative. That is, the calculation of the midpoint of sleep on weekend days (ie, chronotype) requires knowledge of whether the individual slept until their natural wake time (ie, were not woken early due to an alarm, another person, or a morning obligation). However, our findings mirror previous studies regarding sleep timing during development [2,22,32], so it is likely that measurement error in this sample was minimized.

Daytime napping data were not available for the current study, which can be seen as a limitation. Naps are a common element of sleep behaviour in some regions and cultures, with the prevalence ranging from 12% (Japan) to over 40% (Brazil) among adults [33]. While short naps early in the day are unlikely to influence homeostatic pressure for sleep, longer periods of rest during the day might play a role in night-time sleep. However, a recent review [34] on sleep hygiene suggests that napping does not usually influence nocturnal sleep, and thus, its effects on sleep patterns in this study are likely to be marginal.

One potential limitation is selection bias: it is likely that the users of consumer-targeted wearables do not fully represent others. The participants included in the current study are likely to lead

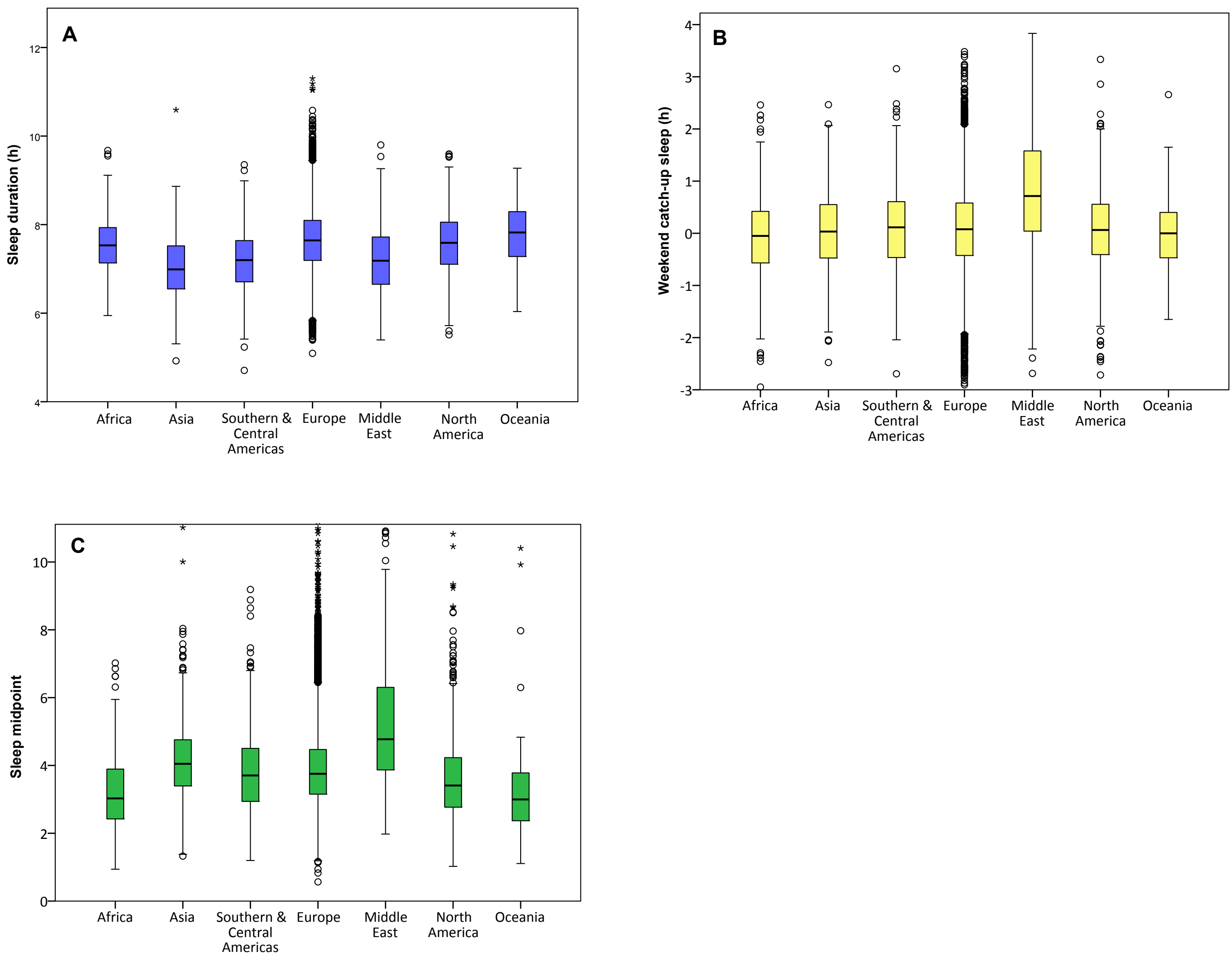

Fig. 3. Sleep duration (Panel A), weekend catchup sleep (or social jetlag) (Panel B), and sleep midpoint (Panel C), according to different world region.

healthy lifestyles, and to strive for optimal performance. Thus, to some extent, sleep patterns may reflect health choices rather than individual rhythms in this study population. However, the amount of measured people and nights in this study covers a substantial range both age-wise and geographically. This implies that measuring sleep and activity by using wearables may already be considered a norm in many cultures and populations.

4.2. Implications

Wearable devices are increasingly common among many user groups, and are not only limited to health enthusiasts. Despite the availability and popularity of consumer sleep technologies (CSTs), the clinical utility of such devices has been hindered by a paucity of research establishing their validity [35]. Consequently, the American Academy of Sleep Medicine does not currently recommended CSTs for standalone use in the diagnosis and treatment of sleep disorders [36]. The Polar devices (ie, A370, M430, M600) used in the present study have recently been validated against polysomnography [24], while our results provide additional evidence from a large ecologically valid sample. Hence, an accumulating body of evidence suggests that validated wearables could perform a valuable clinical role as an adjunct therapeutic component that enhances patient outcomes. For example, in clinical practice, these devices could potentially provide a more affordable, convenient and innovative sleep assessment tool compared to traditional sleep technologies, such as actigraphy [37]. Furthermore, these devices could also be used to compliment the formal clinical treatment of sleep disorders such as circadian rhythm disorders. Real time data feedback on the duration and timing of a user's sleep pattern could be used to generate actionable suggestions tailored to the individual about what they can do to improve their sleep, between appointments with a clinician. That is, if a user's sleep problem were characterised by mis-timing of the circadian rhythm, suggestions would be based on chronotherapy (ie, bright light therapy, evening melatonin). Although promising, further research is needed to determine the effectiveness of these devices as adjunct clinical tools.

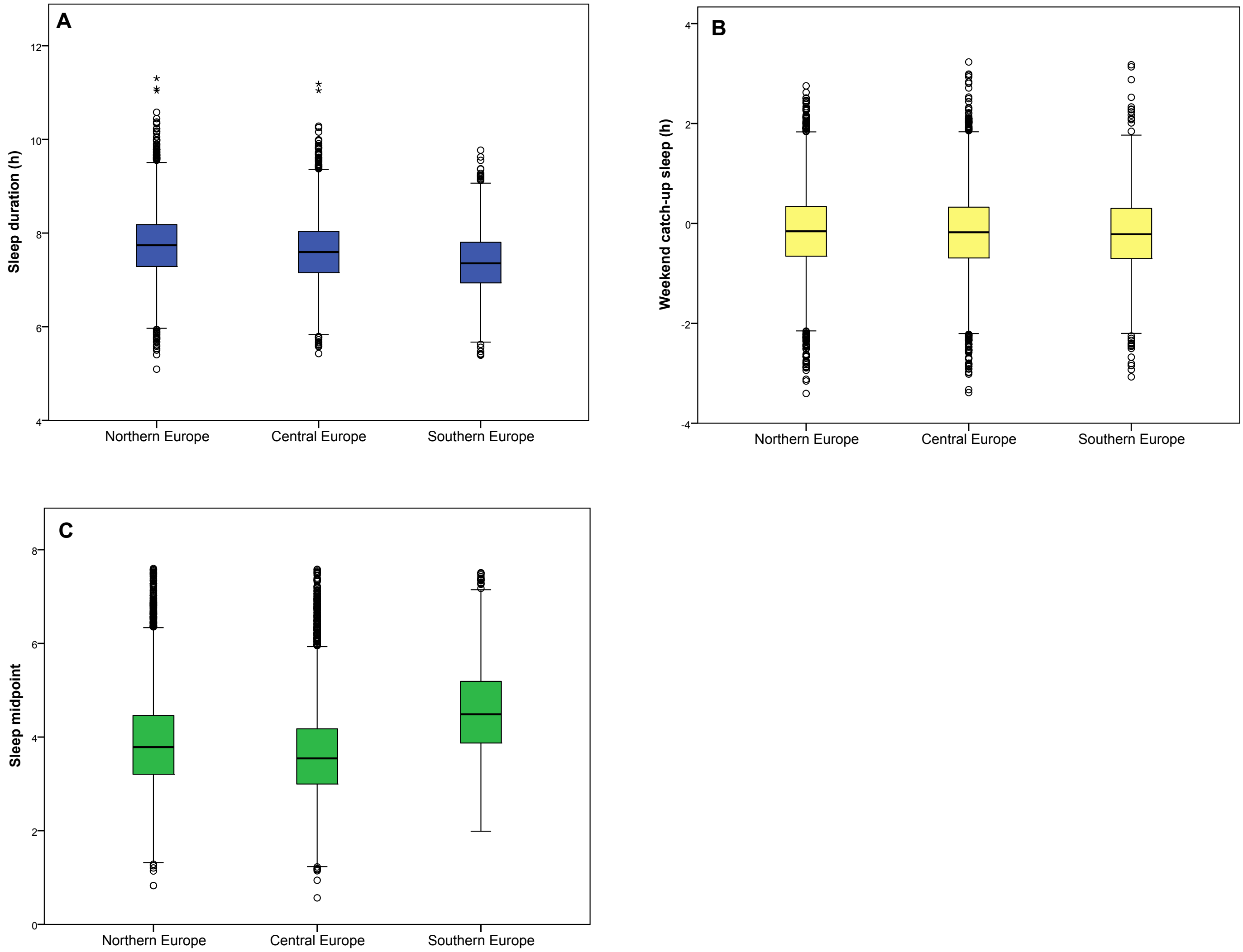

Fig. 4. Sleep duration (Panel A), weekend catch-up sleep (or social jetlag) (Panel B), and sleep midpoint (Panel C), according to different European regions.

5. Conclusions

Our study utilized a dataset with 17,355 participants who had used their own wearable device to measure sleep for a total of 242,989 nights. We found an age-dependent trend in sleep duration and timing. The most notable association was in sleep timing, with adolescence being a period for later-timed sleep, especially among males. We also found significant differences between regions worldwide, with less sleep occurring for those in the Middle East and Asia. In addition, we found shorter sleep duration and a later sleep timing occurring in Southern regions within Europe. These findings suggest that cultural factors likely impinge upon the sleep opportunity of young people in various regions throughout Europe and around the world.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

The ICMJE Uniform Disclosure Form for Potential Conflicts of Interest associated with this article can be viewed by clicking on the following link: https://doi.org/10.1016/j.sleep.2019.07.024.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sleep.2019.07.024.

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