ORIGINAL ARTICLE

Reducing the use of screen electronic devices in the evening is associated with improved sleep and daytime vigilance in adolescents

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Abstract

The use of screen electronic devices in the evening negatively affects sleep. Yet, sleep is known to be essential for brain maturation and a key factor for good academic performance, and thus is particularly critical during childhood and adolescence. Although previous studies reported associations between screen time and sleep impairment, their causal relationship in adolescents remains unclear. Using actigraphy and daily questionnaires in a large sample of students (12 to 19 years old), we assessed screen time in the evening and sleep habits over 1 month. This included a 2 week baseline phase, followed by a 40 min sleep education workshop and a 2 week interventional phase, in which participants were asked to stop using screen devices after 9 pm during school nights. During the interventional phase, we found that the reduction of screen time after 9 pm correlated with earlier sleep onset time and increased total sleep duration. The latter led to improved daytime vigilance. These findings provide evidence that restricting screen use in the evening represents a valid and promising approach for improving sleep duration in adolescents, with potential implications for daytime functioning and health.

Statement of Significance

With the emergence of smartphones and other connected devices, adolescents spend a lot of time on screen electronic devices, especially during the evening. We report that screen time after 9 pm negatively correlates with sleep onset time, sleep duration as well as mood, body weight, and academic performance. Such observable correlations urge for educational strategies to address the chronic lack of sleep observed in today's adolescent populations. Here we also show that limiting screen use after 9 pm improves sleep duration and daytime vigilance in most adolescents. This simple recommendation pertaining to sleep hygiene can be implemented by every household, yielding direct positive effects on sleep, and presumed benefits for health and daytime functioning.

Introduction

Since the early 2000s, the use of screen electronic devices has increased extraordinarily, and is particularly high among today's adolescents who represent the first generation to have lived their entire life with easy access to these devices [1]. With the proliferation of different types of screen devices (e.g. laptops, smartphones, and tablets) and the diversity of activities that they offer (from blogs and social media to video games), adolescents are "over-connected" [2, 3]. Excessive screen time has not only been considered as one form of technological addiction [4, 5], but has also been shown to be associated with poor academic outcome [2] and health problems, such as obesity, insomnia, or depression [6, 7]. Sleep habits during adulthood and adolescence have also changed in the past years [8]. Several studies have reported delayed bedtime, shortened sleep duration, and longer sleep onset latency [9, 10]. In a large sample of Australian teenagers (*N* = 1287), King and colleagues found an association between screen use and sleep disturbances, with bedtime delay being the most prevalent problem [11]. Furthermore, other cross-sectional studies using questionnaires revealed consistent associations between screen time and delayed bedtime leading to shorter sleep duration [12–14]. Interestingly, a parallel has been drawn between the rise in screen use (especially smartphones and tablets) and the increasing prevalence of short sleep duration (<7 hr) during school nights in the past 10 years [8]. The negative impact of screen use on sleep quantity and quality during childhood and adolescence may have detrimental consequences for future adult life [15]. Indeed, chronic sleep restriction at a young age is problematic as it has been associated with a greater risk of developing obesity, hypertension, and mood disturbances, including depression [15–17]. In addition, it is well known that chronic sleep restriction directly affects daytime functioning including attention, learning, and executive functions [18], which, during development, may affect performance at school. Sufficient and good sleep quality have been defined as key contributors to good academic performance [19–21]. Hence, with the continuous expansion of screen devices and their increasing use, especially prior to sleep, it is critical and urgent to find targeted preventive measures to preserve healthy sleep. Recently two studies tested the impact of limiting screen time in the evening: while no effect on sleep was found when limiting screen use after 10 pm in high school athletes [22], limiting smartphone use 1 hr before bedtime improved self-reported measures of sleep in 63 teenagers (14–18 years old) [23]. These findings are promising and suggest a beneficial impact of limiting evening screen time on daytime functioning [21].

Cain and Gradisar proposed three possible mechanisms that may contribute to the influence of screen use on sleep: (1) screen-based activities are time-consuming, and thus compete for time for evening sleep [11, 24]; (2) screen-based activities can increase emotional arousal prior to sleep, affecting bedtime hour but also sleep onset latency [25, 26]; and (3) the light emitted by the screens may be interfering with sleep by delaying hormonal melatonin production [27–29]. Sleep onset delay will consequently shorten sleep duration, as wake up time remains unchanged due to fixed school hours. However, screen use is not the sole contributor in these sleep variations in adolescents. Numerous other factors, such as home environment, emotional status, presleep cognitive, and physical activities, may confound this relationship [30].

In the present prospective interventional study performed in a large sample of adolescents, we tested whether reducing screen time after 9 pm during weekdays is associated with sleep and daytime functioning benefits, using a within-subject design. First, we sought to confirm the relationship between screen use in the evening and sleep parameters, using objective (i.e. actigraphy and melatonin profile) and subjective (i.e. questionnaires and self-report diaries) measures. Second, we hypothesized that a reduction in screen time after 9 pm would advance bedtime hour, which in turn should improve sleep duration and daytime functioning and reduce sleep debt.

Methods

Protocol

The data were collected between November 2014 and May 2015. For organizational reasons, not all the schools participated at the same time. The experimental design of the study included two consecutive 2-week periods (Figure 1), during which participants wore an actimeter and filled out daily questionnaires on sleep and time spent performing screen-based and off-screen activities. The first period (or Phase 1) served as a baseline assessment. During the second period (or Phase 2), participants were instructed to reduce their use of screen devices after 9 pm and any change in the collected variables was examined. Experimenters met with the participants three times (or Visits): right before Phase 1, between the two phases, and after completion of Phase 2. Visit 1 always took place at the participants' school. During Visit 1, we told participants that we would assess their sleep and screen use habits during two periods of 2 weeks each. At that point, participants did not know about the restrictive rule that they would have to follow during Phase 2. We also explained the different measures collected (i.e. actimeter, diaries, and melatonin collection), and that the data would not be communicated to their parents or teachers, and would always remain anonymous. Most importantly, they were repeatedly reminded that that they could leave the project at any time without any consequence. After 2 weeks of habitual screen use, participants came to the laboratory for Visit 2. To explain the instructions for the two following weeks (Phase 2) and increase compliance and motivation, we organized a 40 min interactive workshop including general information on
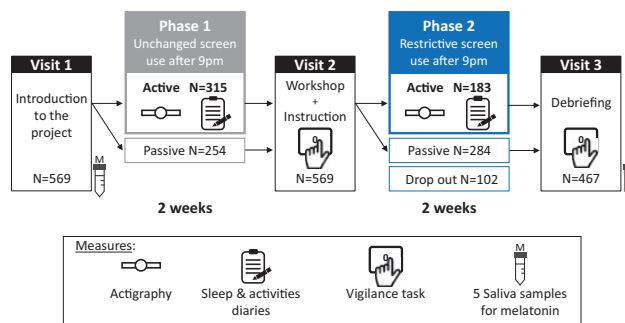
Figure 1. Study design and participants. Distribution of the 569 adolescents across the protocol: 2 × 2 weeks, including baseline period (no change in screen use; Phase 1) and experimental period (restricted use of screen devices after 9 pm; Phase 2), where we collected sleep (actigraphy) and evening activities (diaries) data. Vigilance and saliva samples (for melatonin profiles) were also obtained at baseline and after the intervention.

electroencephalographic recording techniques, sleep stages, sleep disorders, and the importance of sleep on daytime functioning and health. Then, participants filled out several questionnaires (20 min) and performed the Sustained Attention to Response Task (SART; 10 min), after which they visited our neuroimaging platform (EEG, MRI; 20 min). At the end of Visit 2, participants were instructed to stop using screen devices after 9 pm on school evenings, namely, from Sunday to Thursday evenings. Finally, a brainstorming was conducted to help them come up with off-screen activities that they could engage in after 9 pm (e.g. inform and involve the family, play music, and read books; 15 min). Subjects who agreed to participate in Phase 2 symbolically committed (signed a declaration of participation) to follow the restrictive rule. Two weeks later, Visit 3 took place in the schools where all participants filled out several questionnaires and performed the SART. To characterize each participant's melatonin profile and possible changes after Phase 2, salivary samples were collected at home during the night after Visits 1 and 3 (see Melatonin).

The rational for the choice of the simple rule "no screen after 9 pm" was based on several points. First, the National Sleep Foundation [31] recommends sleep duration of 9 h (+/− 1 hr) for teenagers aged between 14 and 17 years old. As school starts at 8 am in Switzerland, adolescents should be in bed at 10 pm maximum in order to have sufficient sleep during school nights. Second, it is recommended to refrain from sleep-interfering activities around 1 hr before going to bed [16], which in the context of the present study would mean 9 pm in order to be in bed at the recommended 10 pm. Third, the project included whole classrooms (as opposed to individual recruitment). Hence, it appeared more feasible to present a common rule for all participants who are highly socially interconnected (rather than asking participants to stop screen use one hour before going to bed, inducing a different timing for each student). Fourth, we also wanted to demonstrate that a simple rule "no screen after 9 pm" could be effective, thus providing an easy rule for adolescents to follow and for parents and healthcare practitioners to recommend.

Finally, the rule was implemented during school nights only for two main reasons. First, because insufficient sleep time generally occurs during school nights, when children and adolescents have to wake up at fixed hours to go to school. Thus, extending sleep duration can only be obtained by advancing bedtime and sleep onset time on school nights. Second, pilot results from continuous screen restriction over 2 weeks (7 days/week) revealed that the restriction was particularly difficult to follow during weekends and was associated with decreased motivation to comply with the restriction (data not reported). We therefore expected less drop-out during Phase 2 if participants were allowed to freely engage in screen-based activities during weekends.

This study was approved by the ethics review board of the Geneva University Hospitals. Adult participants—or the parents of participants under 18 years old—signed the informed consent before taking part in the study. All data collected were kept anonymous using personal identification codes.

Participants

In total, 569 students between 12 and 19 years old (52.5% girls; mean age ± SD: 15.35 ± 2.1), recruited from middle and high schools in Geneva (Switzerland), took part in at least Phase 1 of the study. To obtain reliable estimates of screen use and sleep habits, only participants who filled out all the questionnaires during Visit 2, wore the actimeter, and filled out daily diaries for at least 7 days were analyzed and were called "*Active*" participants for Phase 1. The same criteria were used for Phase 2, with the additional requirement that *Active* participants in Phase 2 also had to be *Active* in Phase 1. Participants who did not meet these criteria were labeled as "*Passive*" and we only analyzed their data from the questionnaires and SART data collected in the classroom and at the laboratory. Note that some participants did not participate to Visit 3 and are referred to as "*Drop-outs*." Accordingly, there were 315 *Active* participants (64.4% girls, mean age ± SD: 15.69 ± 2.12) and 254 *Passive* participants (37.7% girls, mean age ± SD: 14.93 ± 2) for Phase 1. Out of the 315 *Active* participants from Phase 1, 183 participants (65.5% girls; mean age ± SD: 15.74 ± 2.08) agreed to follow the restrictive screen use rule during Phase 2 for at least 7 days. Thus, for Phase 2 (and comparisons between Phases 1 and 2), there were 183 *Active* participants, 284 *Passive* participants (43.3% girls; mean age ± SD: 14.84 ± 1.94), and 102 *Drop-outs* (54.9% girls; mean age ± SD: 16.1 ± 2.19).

To ensure that the results of the intervention were not influenced by a selection bias, *Active* subjects who participated to both phases (N = 183) were compared with those who were only *Active* during Phase 1 (N = 132). Age, gender breakdown, sleep parameters, and duration of evening activities during Phase 1 did not differ between these groups, suggesting that the data obtained during Phase 2 (and comparisons between Phases 1 and 2) were not confounded by a selection bias. To investigate the effect of age on the relation between screen use and sleep, we further separated participants into four age groups: 12–13, 14–15, 16–17, and 18–19 years old. Descriptive data (age and gender) about these four groups for Phases 1 and 2 can be found in Supplementary Table S1.

Measures

Sleep and evening activities diaries

Every day, participants provided information about their sleep and their evening activities on screen devices and off-screen (either on paper version or via internet, see Supplementary Figure S1). For sleep, they reported their light off time, time to fall asleep (i.e. sleep latency), wake-up time (as time of morning awakening), out of bed time, and the number of nocturnal awakenings. They also evaluated their sleep quality and morning mood using a 5-star rating system (from 1: very bad sleep to 5 stars: very good sleep, and from 1: very bad mood to 5 stars: very good mood). For evening activities, they reported the time spent (in minutes) on different screen-based activities and off-screen activities after 9 pm (from 9 pm until sleep onset). Screen-based activities included times spent on social media (e.g. Facebook, WhatsApp, SMS, and Snapchat), watching TV, watching videos (not on TV), playing games, and computer activities (e.g. email, reading blogs, and online homework). Off-screen activities comprised times spent on homework (not using a computer), sports, and reading. For each evening (after 9 pm) and each participant, we computed the total time spent on screen-based activities and offline activities separately, as the sum of the reported use (in minutes) of all activities from the corresponding category (screen-based or offline; see above). We then also computed the

average time spent on screen-based and offline activities, separately for school nights and weekend nights. "School nights" referred to the evenings and nights preceding school days (i.e. Sunday to Thursday). "Weekend nights" were the evenings and nights before weekend days (i.e. Friday and Saturday) where participants had no wake-up time constraint related to school.

Actigraphy

Participants wore an Actimeter GT3X+ (Actigraph, Pensacola, FL) on their nondominant wrist nonstop for the two successive periods of 2 weeks (Phases 1 and 2). This device contains a triaxial accelerometer with a dynamic range of ± 8 G, a sampling rate of 30 Hz and data are stored in a raw nonfiltered format in G's directly into a nonvolatile flash memory. Mean actigraphic data during 60 s epochs were scored as sleep or wake using an automatic detection algorithm (AARA—http://orbi.ulg.ac.be/handle/2268/173392). Then, we reviewed each night manually by comparing the sleep onset times indicated by the analyses of the actimetry data with those reported by the participants in the diaries (i.e. reported light off time + sleep latency). In case of a mismatch greater than 1 hr between objective and subjective sleep onset times, all measurements from the corresponding evening (screen/off-screen activities) and night (sleep) were excluded from further analysis. In case of a mismatch of less than 1 hr, two rules applied: either objective sleep onset time was detected before subjective sleep onset time, in which case we used the first sleep bout detected by actimetry occurring after light off time (reported by the participants); or objective sleep onset time was later than subjective sleep onset time and no correction was applied (i.e. sleep onset time from the actimetry was used as such). A similar rule was applied to subjective (reported by the participant) and objective (actigraphy) morning wake-up times: we excluded all the data from any night where a 1 hr mismatch between subjective and objective wake-up times was observed. When the mismatch was less than 1 hr, two rules applied: the objective wake-up time was detected after subjective wake-up time, in which case the subjective wake-up time was used; in the converse situation, actimetry measures were used without correction. Note that according to these rules only 6.4% of the nights were excluded for further analyses.

Hence, we obtained the following sleep variables during school nights and weekend nights: light off time (from the diary; time at which participants turned off the light), sleep onset time (detected by actigraphy and diary), wake-up time (detected by actigraphy and diary); out-of-bed time (from the diary), time in bed (TiB; period between light off time and out-of-bed time), total sleep period (TSP; period between sleep onset time and wake-up time), total sleep time (TST; TSP minus wake period after sleep onset time), and sleep efficiency (SE in %: TST/TiB*100).

Questionnaires

All participants (N = 569; including *Active* and *Passive* participants) filled out two sets of questionnaires: one at the end of Phase 1 and one at the end of Phase 2. Besides questionnaires about their age, gender, height, weight, health status, consumption habits, evening activities habits, and academic performance, participants also answered the Chronic Sleep Reduction Questionnaire (CSRQ) [32] translated from Dutch, which contains questions about sleepiness, irritation, and loss of energy during the day. They also responded to the Kessler Psychological Distress Scale (K6) [33] that quantifies nonspecific psychological distress including anxiety, depression, and despair.

Sustained Attention to Response Task

Participants performed the SART on tablet computers at the end of each phase. Due to technical problems with tablets early in the study, we included data from 454 (out of 569) participants in the final analyses. The SART is a variant of the GO/NO GO task, which measures sustained attention and vigilance performance [34]. The task required participants to tap the screen as quickly as possible in response to frequently presented GO stimuli and to withhold responses to infrequently presented NO GO stimulus (the digit 3). Participants were shown a random series of digits from 0 to 9 presented one at a time, each for 250 ms. A fixation cross was presented for 900 ms after each digit. A total of 250 single digits were presented in a pseudo-random order excluding the immediate succession of the same number, with every digit appearing 25 times. The duration of the task was 4.3 min. We analyzed the number of commission errors (responding when the "3" appeared—maximum 25 errors) and the number of omissions (not responding to a "GO" signal—maximum 225 errors) and we computed the SART error score that represents the sum of omission and commission errors (maximum 250 errors) [35]. We calculated mean reaction times (RTs) for correct responses, and also the 75th percentile (slowest) of the distribution of the RTs, which has been shown to best reflect deterioration of psychomotor vigilance and wake instability due to augmented sleep pressure [18, 36]. Indeed, the slowest RTs have been shown to be more sensitive to sleep deprivation than faster RTs [37].

Melatonin

Five saliva samples were collected twice in order to assess individual melatonin profiles before Phase 1 and after Phase 2 (Figure 1). Collection was performed at home by the participants using the saliva cotton oral Swab (SOS; Sarstedt, Numbrech, Germany) method. Participants were asked to collect saliva every hour, starting 4 hr before their usual light off time and finishing with the last one collected 1 hr after their usual light off time. They were instructed to avoid eating 1 hr before the first extraction and between the five saliva samples. They were also asked to avoid drinking alcohol and energy drinks after 3 pm, and also to avoid too much sweet (e.g. chocolate, banana) or sour (e.g. lemon) food during the last meal. They were asked to place the tubes with the saliva samples in their fridge and to bring them to their school the next morning, where the tubes were collected by one experimenter. Salivary samples were centrifuged briefly to collect the supernatant at the bottom of the tube (only when there were at least four samples for one evening) and the preprocessed samples were then kept at minus 80℃ until assays were performed. Using the protocol advised by the manufacturer, the quantitative determination of melatonin in saliva was then obtained using enzyme-linked immunosorbent assay (ELISA) kits (Direct Saliva Melatonin ELISA; Bühlmann Laboratories, Allschwil, Switzerland). Hour of Dim Light Melatonin Onset (HDLMO) was calculated using the hockey-stick method [38–40]. We were able to successfully analyze melatonin profile for 70 *Active* participants for Phase 1, whereas only 13 *Active* participants had melatonin profiles for both Phases 1 and 2.

Statistical analyses

Statistical analyses were performed using IBM SPSS Statistics for Windows (Version 23.0. Armonk, NY: IBM Corp). Using multivariate linear regressions, we examined associations between time spent on screen-based activities or off-screen activities after 9 pm and several sleep parameters such as sleep onset time and TSP. Repeated measures analyses of variance (ANOVA)

with post hoc pairwise *t*-tests were used to specify main and interaction effects due to the instruction. Thus, most ANOVAs included a repeated measure factor Phase (Phase 1, Phase 2) as within-subject factor. Depending on the effects tested, some ANOVAs also included the between-subjects factors Age Group (12–13, 14–15, 16–17, and 18–19 years old) or Types of Night (School, Weekend nights). Degrees of freedom were corrected according to the Greenhouse–Geisser method, when appropriate. The level of significance was set to a *p*-value of <0.05. To further examine the impact of the different types of screen-based activities performed after 9 pm on sleep duration during Phase 1 (see Supplementary Results), we used a Structural Equation Modeling (SEM) approach (multivariate path analysis in SPSS AMOS Version 23.0. Armonk, NY: IBM Corp).

Results

Phase 1

The intervention explicitly targeted screen-based activities during the evenings preceding school days (called school evenings, including Sundays to Thursdays). We therefore first focused on the school evenings and nights measurements. During Phase 1, 96.8% of the *Active* participants (*N* = 315) reported spending on average (±SEM) 79 (±3) min on screen devices after 9 pm on school evenings (Figure 2A, grey plot). An ANOVA on screen time after 9 pm with Age Group as between-subjects factor revealed a main effect of Age Group [$F(3,311)$ = 12.81; $p < .0001$] as older teenagers spent more time on screen devices than younger ones (Figure 2B, grey plot).

Sleep duration (total sleep period; time between sleep onset time and wake-up time) for school nights decreased with age [ANOVA on sleep duration with Age Group as between-subjects factor; $F(3,311)$ = 27.05; $p < .0001$; Figure 2D, grey plot], whereas sleep onset time was progressively delayed with age [ANOVA on sleep onset with Age Group as between-subjects factor; $F(3,311)$ = 19.84; $p < .0001$]. On average (±SEM), adolescents slept 7 hr 33 min (±3 min) during school nights (Figure 2C, grey plot). For weekend nights, we observed that adolescents slept longer (8 hr 40 ± 4 min) suggesting a possible sleep debt accumulated during the week. An ANOVA on sleep duration with Type of Night (school nights, weekend nights) as within-subjects factor and Age Group as between-subjects factor revealed a significant main effect of Type of Night [$F(1,298)$ = 305.59; $p < .0001$], which reflects an extended period of sleep during the weekends. We also found a main effect of Age Group [$F(3,298)$ = 24.9; $p < .0001$] as sleep duration differ between age group, although sleep rebound was present across all age groups (all *t*-test $p < .001$). Further results on activities after 9 pm and sleep habits during Phase 1 are reported in Supplementary Results.

We found that total screen time after 9 pm correlated negatively with sleep duration (R^2 = 0.23; $p < .001$; Figure 3A). By contrast, total time spent doing off-screen activities did not significantly affect sleep duration (R^2 = 0.001; p = .54; Figure 3B). Note that because wake-up time was constrained by early morning school schedules, the impact of screen time on sleep duration was primarily attributable to a later sleep onset time. Indeed, there was a significant correlation between screen time after 9 pm and sleep onset time (R^2 = 0.35; $p < .001$). Finally, there was a significant correlation between screen time after 9 pm and melatonin profiles (Hour of Dim Light Melatonin Onset, HDLMO; see Methods; R^2 = 0.239; p = .001; Figure 3, A and B), suggesting a possible partial impact of exposure to screen light on the circadian regulation of sleep.
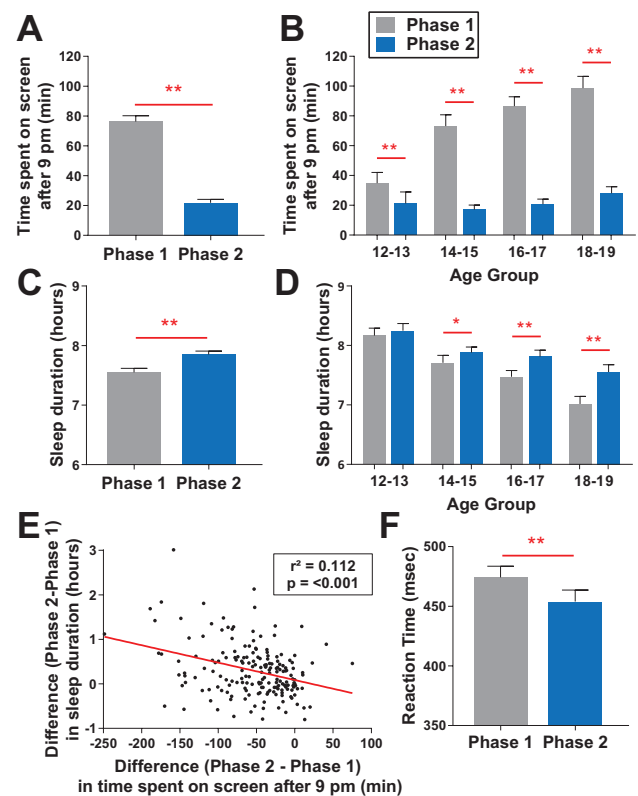

Figure 2. Phases 1 and 2—Association between restrictive use of screen devices after 9 pm and sleep and vigilance. (A) Mean (±SEM) time spent on screen-based activities after 9 pm during school nights for Phase 1 (grey) and Phase 2 (blue). (B) Mean (±SEM) time spent on screen-based activities after 9 pm during school nights per age group for Phase 1 and Phase 2. (C) Mean (±SEM) sleep duration during school nights for Phase 1 and Phase 2. (D) Mean (±SEM) sleep duration during school nights per age group for Phase 1 and Phase 2. (E) Scatter plot showing a significant correlation ($p < .001$) between the difference in time spent on screen-based activities after 9 pm (Phase 2 minus Phase 1) and the difference in sleep duration (Phase 2 minus Phase1) during school nights. (F) Mean (±SEM) reaction time (slowest 75th percentile) during the vigilance task (SART) performed at the end of Phase 1 (grey) and Phase 2 (blue). Asterisks represent significance (*p*) of 2-tailed paired *t*-tests between Phase 1 and Phase 2: **<0.001; *<0.05.

Regarding waking performance, extensive screen time in the evening correlated with lower grades at school (R^2 = 0.064; $p < .001$), increased psychological distress (K6; R^2 = 0.014; p = .033), increased daytime fatigue (CSRQ; R^2 = 0.033; p = .001), and higher body mass index (BMI) score (R^2 = 0.046; $p < .001$). However, no correlation was observed between screen time and performance on the SART (Sustained Attention to Response Task), an objective measure of vigilance ($p > .05$ for all SART measures; see Methods). Note that sleep duration did not correlate with school performance, nor psychological distress, but correlated negatively with daytime fatigue (CSRQ; R^2 = 0.065; $p < .001$), BMI score (R^2 = 0.073; $p < .001$), and daily mood rating (R^2 = 0.016; p = .024).

Comparisons between Phase 1 and Phase 2

Effects of the intervention on off- and on-screen activities after 9 pm

On average, *Active* participants (*N* = 183) reduced their time spent on screen devices by 71.3% after 9 pm on school evenings (mean ± SEM;

SCREEN-BASED ACTIVITIES AFTER 9 PM

A

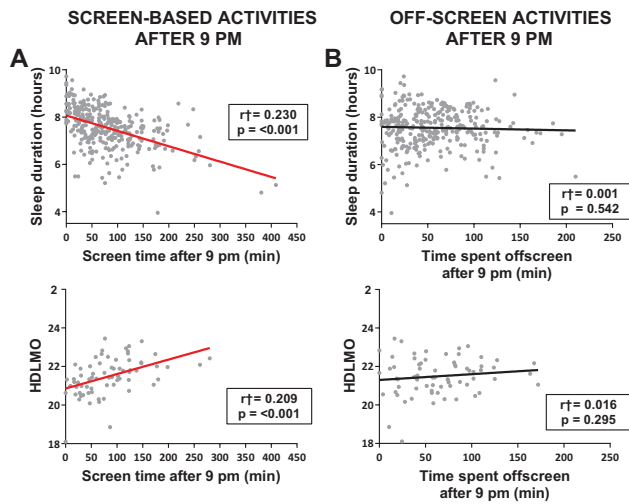## OFF-SCREEN ACTIVITIES AFTER 9 PM

B

Figure 3. Phase 1—Activities performed after 9 pm are associated with sleep during school nights. (A) Scatter plots showing significant correlation ($p < .001$) between screen time after 9 pm and sleep duration (N = 315; top), and hour of dim light melatonin onset (HDLMO; N = 70; bottom) during school nights. (B) Scatter plots showing no correlation ($p > .5$) between the time spent on off-screen activities after 9 pm and sleep duration (N = 315; top), and HDLMO (N = 70; bottom) during school nights.

Phase 1: 76.15 ± 3.57 min, Phase 2: 21.49 ± 2.15 min; Figure 2A). An ANOVA on screen time after 9 pm using Phase (Phase 1, Phase 2) as within-subjects factor and Age Group as a between-subjects factor revealed a significant main effect of Phase [$F(1,179)$ = 220.73; $p < .0001$] due to the reduction in screen time during Phase 2. This effect is present in each age group (post hoc *t*-test, all $p < .001$). We also observed a main effect of Age Group [$F(3,179)$ = 7.95; $p < .0001$] and a Phase by Age interaction [$F(3,179)$ = 12.44; $p < .001$] as older adolescents (14–19 years old) exhibited larger screen time during baseline and therefore exhibited greater reduction during Phase 2 (Figure 2B). A second ANOVA on Phase and Types of Screen Activity (Social media, Watching TV, Watching Video, Games, and Computer Use) similarly revealed a main effect of Phase [$F(1,182)$ = 190.1; $p < .0001$] and Types of Screen Activity [$F(4,728)$ = 34.5; $p < .0001$] as all types of screen-based activities were reduced. There was also a Phase by Types of Screen Activity interaction [$F(4,728)$ = 25.8; $p < .0001$] explained by the large reduction in social media, watching TV, and videos which were the most used activities during baseline (see Supplementary Results). We used similar analyses to check the impact of the intervention on off-screen activities after 9 pm. ANOVA using Phase and Age Group showed no main effect of Phase [$F(1,179)$ = 1.23; $p = .26$], a main effect of Age Group [$F(3,179)$ = 3.08; $p = .028$], but no Phase by Age interaction [$F(3,179)$ = 0.85; $p = .46$], suggesting stable time dedicated to off-screen activities between phases for each Age group. Moreover, when looking at the time spent on the different types of off-screen activities, we found a main effect of Types of Off-Screen Activity [$F(2,364)$ = 207.4; $p < .001$] due to large amount of time doing homework in both phases and a Phase by Types of Off-screen interaction [$F(2,364)$ = 19.9; $p < .001$] that was driven by a significant increase in the time spent reading (mean ± SEM; Phase 1: 5.43 ± 0.45 min, Phase 2: 14.18 ± 1.30 min; *t*-test $p < .001$) during Phase 2.

The restrictive use of screen beneficially affects sleep parameters

Active participants (N = 183) during Phases 1 and 2 went to bed earlier on school nights (mean ± SEM; Phase 1: 23 hr 28 ± 4 min, Phase 2: 23 hr 07 ± 3 min; *t*-test $p < .001$) and consequently increased their sleep duration (mean ± SEM; Phase 1: 7 hr 33 ± 3 min, Phase 2: 7 hr 50 ± 3 min; *t*-test $p < .001$; Figure 2C) by 17 min (±2 min) during Phase 2. Note that their wake-up time and out-of-bed hours did not change between Phase 1 and Phase 2 (see Supplementary Table S2). An ANOVA on sleep duration (TSP) using Phase as within-subjects factor and Age Group as a between-subjects factor revealed a significant main effect of Phase [$F(1,179)$ = 44.03; $p < .001$], Age Group [$F(3,179)$ = 11.14; $p < .001$], and a Phase by Age Group interaction [$F(3,179)$ = 5.23; $p = .002$] due to significant increase in sleep duration between phases for adolescents between 14 and 19 years old ($p < .05$; Figure 2D). Similar results were found for TiB and TST (all $p < .001$; see Supplementary Table S2). Moreover, note that same ANOVA on sleep onset time and light off time revealed similar significant results (all $p < .0001$), demonstrating earlier bedtime during Phase 2 (see Supplemental Table S2). The relationship between decreased screen time in the evening and subsequent increased in sleep was further supported by significant correlations between the difference (between Phases 1 and 2) in screen time and the difference in sleep onset time ($R^2 = 0.133$; $p < .001$), as well as the difference in sleep duration ($R^2 = 0.112$; $p < .001$; Figure 2E). In summary, the better participants complied with the instructions regarding screen use, the earlier they went to bed and the more they slept. Moreover, in order to assess whether the reduction of screen use may be associated with a beneficial impact on sleep debt (i.e. rebound of sleep during weekend nights) observed during Phase 1, we performed an ANOVA on sleep duration (TSP) using Phase and Type of Night (school nights, weekend nights) as within-subject factors. We found significant main effect of Phase [$F(1,169)$ = 8.94; $p = .003$] and Type of Night [$F(1,169)$ = 187.45; $p < .001$] as they slept more during school nights in Phase 2 (see Supplementary Table S2). We also found a significant Phase by Type of Night interaction [$F(1,169)$ = 10.57; $p = .0014$], reflecting smaller difference between school nights TSP and weekend nights TSP (rebound) during Phase 2. Post hoc *t*-tests revealed that the sleep rebound during the weekend nights significantly decreased (mean ± SEM; Phase 1: +1 hr 08 ± 4 min, Phase 2: +49 ± 5 min; *t*-test $p = .003$) and correlated with the increase in sleep duration during school night ($R^2 = 0.11$; $p < .001$). In Phase 2, while participants were not instructed to comply with the screen curfew after 9 pm during the weekends, they reported spending less screen time on the weekend nights (mean ± SEM; Phase 1: 122.77 ± 6.63 min, Phase 2: 102.23 ± 5.79 min; *t*-test $p < .001$). However, unlike what we observed for school nights, this decrease in screen time did not correlate with changes in sleep parameters during weekends (all $p > .05$). We also tested whether Gender or the Season during which the intervention was conducted could affect the observed results but we found no significant interaction with Gender or Season for any of the reported analyses (all $p > .05$). Note that all ANOVA analyses using School Grade as between-subject factor yielded similar results as using an Age Group factor. Finally, there was no significant change in melatonin profiles between Phases (*t*-test $p = .59$). Note however that we could obtain reliable melatonin profiles for both Phase 1 and Phase 2 from only 13 participants.

Restrictive use of screen during the evening affects daytime vigilance

Active participants of Phase 2 who performed the SART task during Visit 2 (after Phase 1) and Visit 3 (after Phase 2, N = 177; Figure 1) exhibited faster RTs on the slowest responses (75th percentile) in Phase 2 compared with Phase 1 (mean ± SEM;

Phase 1: 474.21 ± 9.31 ms, Phase 2: 453.92 ± 9.6 ms; P =.003; Figure 2F). To account for possible learning effects, we compared the results from those participants to the *Passive* participants who also performed the SART in both Phases (N = 253) with an ANOVA on slowest RTs, using Phase as within-subjects factor and Participation Group (*Active*, *Passive*) as a between-subjects factor, and observed a significant main effect of Phase ($F(1,444)$ = 8.75; P =.003) but no effect of Group ($F(1,444)$ = .042; P =.83) nor Phase by Participation Group interaction ($F(1,444)$ = .82; P =.36). Critically, note that a *t*-test comparing Phases revealed no significant improvement in the slowest RTs in the *Passive* group (P =.13) in contrast to what we observed for the Active participants. Similar ANOVAs on the number of commission errors (press on NOGO), number of omission errors (no press on GO) and the SART error score (see Methods) with Phase as within-subject factor and Participation Group as between-subject factor revealed no main effects or interaction for any measures (all *p* > .05; see Supplementary Table S3). Regarding others' waking variables, we found no significant association between the reduction of screen use and participants' self-reported daily mood between Phase 1 and Phase 2 (*t*-test *p* = .094). However, we found a decrease in daytime fatigue (CSRQ) score between phases in both *Active* and *Passive* participants. ANOVA using Phase as within-subjects factor and Participation Group as between-subjects factor revealed a main effect of Phase [$F(1,444)$ = 56.42; *p* < .001], no effect of Participation Group [$F(1,443)$ = 0.91; *p* = .34] and a Phase by Participation Group interaction [$F(1,1)$ = 4.86; *p* = .028] due to larger decrease in CSRQ score in *Active* participants, reflecting less fatigue after Phase 2.

Discussion

Over the past decade, excessive screen use and insufficient sleep in adolescents have dramatically increased and have been associated with various consequences on daytime performance and long-term difficulties [11, 16, 41, 42]. However, to the best of our knowledge, no study to date has investigated the potential impact of a restrictive exposure to screen in the evening on objective measures of sleep and wake performance in a large sample of adolescents. Here we tested whether a simple recommendation—"no exposure to screens after 9 pm during two weeks"—was associated with beneficial consequences on sleep and performance in adolescents. Using subjective and objective measures of sleep on 183 adolescents (aged between 12 and 19 years old), we first show that decreasing screen time in the evenings preceding school days was associated with advanced light off time, sleep onset time and increased sleep duration, especially in older adolescents (14–19 years old). Secondly, we report improved daytime vigilance after reduced screen time in the evening. Together, these data provide unprecedented scientific evidence from a large population of adolescents that reducing screen time in the evening is associated with benefits on sleep and daytime vigilance.

Screen use in the evening delays sleep onset time and shortens sleep duration

Previous studies using questionnaires in children and adolescents have suggested a relationship between screen time in the evening and sleep habits [12, 13, 42, 43]. Here, using objective (i.e. actigraphy and melatonin profile) and subjective (i.e. daily diaries) measures, we confirm that time spent on screen devices after 9 pm correlates with later sleep onset time, and consequently shorter total sleep duration, as wake up time does not change during school-days. Moreover, we provide further experimental support for this relationship by demonstrating that decreasing screen time in the evening is associated with advanced sleep onset time and increased sleep duration. Why does screen use affect sleep? Screen use is time consuming, and may thus simply compete with sleep time, especially when wake-up time is constrained as this is the case for adolescents during school days [41]. Yet, in our study, adolescents devoted a substantial amount of time doing off-screen activities, but only time spent on screen-based activities significantly correlated with sleep parameters, thus not corroborating the claim of screen time merely replacing sleep time (see also below). Screen use also often implies activities that are known to increase stress and emotional arousal levels (e.g. social media and video games) [25, 44], which can affect bedtime hour as well as sleep initiation [45]. Finally, screen use may also influence sleep through the high spectral radiance blue-light emitted by the screen devices, which was shown to directly interfere with the circadian regulation by the suprachiasmatic nucleus via the retino-hypothalamic pathway [46]. Exposure to screen use thus delays the evening rise of the sleep-promoting hormone melatonin, leading to an increase in alertness and reduced sleepiness [27–29, 47, 48]. Our results are in line with both latter hypotheses since all activities on screen devices (i.e. PC and smartphones) contributed significantly to the modulation of sleep duration, except watching TV. Moreover, sufficient distance between screen and eyes might indeed prevent sleep disruption due to the blue-light emitted by the screen [8]. We could not detect a significant change in melatonin profile as a function of the intervention but note that this analysis was conducted on a very restricted number of participants (N = 13) and should be considered as preliminary.

Controlling screen use in the evening as an effective strategy to improve sleep and daytime functioning in adolescents

In the present study, our sample of adolescents slept less (mean ± SEM; 7 hr 33 ± 3 min during school nights) than the 10 hr (+/− 1 h) for school age (6–13 years) and 9 hr (+/− 1 hr) for teenager (14–17 years) recommended by the National Sleep Foundation [31], indicating a state of chronic sleep deprivation during the week [49], as further evidenced by a rebound of sleep (i.e. extended sleep duration) during weekend nights (See Supplementary Results). Our data show that short sleep duration correlated with higher daytime fatigue, psychological distress, and low mood rating [20]. Moreover, chronic sleep restriction at such a young age can put adolescents at risk for the development of sleep and health disorders, such as depression, diabetes, or obesity [15, 50, 51]. For example, in our sample, both short sleep duration and extensive time on screen device in the evening correlated with higher BMI. These alarming observations call for the development of strategies to extend sleep duration in adolescents. An efficient strategy would be to act on both bedtime and wake-up time, by changing school starting time [52, 53], as well as pre-sleep behavior, screen use being a likely efficient target. In 2015, Harris and colleagues [22] reported that a restrictive use of screen devices after 10 pm in a sample of high school athletes (N = 44) did not improve

sleep habits, mood, or physical and cognitive performance. As suggested by these researchers, it is plausible that preventing screen use after 10 pm was not effective because the tested population had early habitual bedtimes already. By contrast, in our study, we found that reducing screen time after 9 pm (i.e. following the recommendation) was associated with decreased sleep onset time, increased sleep duration, and daytime vigilance. These results are in line with the study conducted by Bartel and colleagues [23] who reported that stopping mobile phone use 1 hr before usual bedtime (mean mobile stop time: 20:59 ± 14 min) was associated with increased self-reported sleep duration in 63 adolescents between 14–18 years old. Converging with our results on a general population of adolescents, a previous study showed that the extension in sleep duration by gradually advancing bedtime in teenagers exhibiting symptoms of chronic sleep reduction (*N* = 28) led to earlier sleep onset and longer sleep duration, with favorable repercussions on cognitive performance [21]. Recently Lo and colleagues showed that a 45 min delay in school start time in a large population of adolescents resulted in short- (after 1 month) and long-term (after 9 months) benefits in sleep, associated with improved daytime alertness and well-being. More specifically, teenagers increased their sleep duration by 10 min during school nights. Similar to our findings, the increase in sleep duration is small relative to the total sleep time of one night but is sufficient to improve daytime functioning [53]. Within the *Active* participants, all age groups decreased their screen time during Phase 2, with associated beneficial consequences on sleep for all groups except the youngest group (12–13 years old). This observation might be explained by the low use of screen devices in the evening and earlier light off time in younger participants during Phase 1, thus leaving less room for changes in screen time and the potential effects on sleep during Phase 2 (Figure 2, B and D). Parental supervision might therefore play a more significant role in this age group, thus limiting the impact of the intervention. Indeed, it has been shown that parental monitoring of bedtime during weeknights decreases with age and can be nearly absent for older teenagers (from 17 years old) [54]. However, we did not measure parental control in our sample.

Limitations

A first limitation of the present investigation and previous studies on screen use relates to the fact that on- and off-screen activities were measured through questionnaires, scales, or self-reports that rely on the participant's own perception and willingness to communicate information. It would thus be necessary in the future to find ethically valid and objective strategies to obtain these data, such as using applications that would measure all activities directly from the electronic devices [23]. However, because our main results come from within-subject comparisons between Phase 1 and Phase 2, the impact of such potential distortion in the data is limited. A second limitation concerns the relatively simple format of the diary reporting evening activities. In the diary, participants indicated each evening how much time in total they spent on each category of activities (between 9 pm and sleep onset), but they were not required to continuously record their activities (e.g. every 15 min). We therefore cannot test for the impact of the exact timing of screen use in the evening, namely, whether at the beginning of the evening or just before sleep onset, and cannot account for task switching or multitasking in the analyses (see Supplementary Figure S1). A third limitation is the small number of participants for whom we could extract the melatonin profiles during Phase 2. Limited power may have negatively affected the detection of potential differences between both phases and prevented the

inspection of further links with other variables. These results should therefore be considered as preliminary. Lastly, using a wait list control group might have controlled for the use of repeated measurements in time, but was not possible for ethical reasons, because our study was part of a youth awareness program. Additionally, although this was not a main goal of the present study, we were not able to distinguish the respective influence of the intervention alone ("no screen after 9 pm") and of the sleep education session (40 min of interactive discussion on EEG recordings, sleep stages, sleep disorders, and importance of sleep on daytime functioning and health; see Methods). Indeed, participants from the Passive group followed the workshop, but then did not wear the actimeter and/or fill the diaries. Their data were only used to control for possible learning effects between phases for the SART data. Some studies revealed that school-based sleep education alone can positively influence sleep parameters [55, 56]. For example, a school-based sleep education program (6 × 2 hr) given over 6 weeks to children aged between 7 and 11 years old accompanied with an information session given to the environment supporting the children (family, school staff) can extend sleep duration and sleep efficiency in children [55]. However, this is unfortunately not a systematic finding because the format and delivery regime of such educational programs was found to highly influence the sleep outcomes [57, 58]. In the present study, participants only received a 40 min sleep education session, but it is possible that this short sleep education delivered immediately before Phase 2 increased the motivation to participate to Phase 2 and stop screen activities after 9 pm.

Furthermore, we could not collect data about the psychosocial environment, economic status, or parental monitoring, all factors that may also modulate the impact of an intervention such as the one we used here.

Our findings have several implications. First, the data from Phase 1 (before the intervention) confirmed with objective and subjective measures that time on screen after 9 pm correlated negatively with sleep duration during school nights. Second, we found that it is possible to extend sleep in adolescents by imposing a restriction on their screen time after 9 pm, with beneficial consequences on daytime vigilance. The present study represents a necessary step towards the development of strategies to prevent chronic sleep restriction related to screen use, which has recently emerged as a major health issue in adolescents.

Supplementary material

Supplementary material is available at *SLEEP* online.

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