CHRONIC STRESS UNDERMINES THE COMPENSATORY SLEEP EFFICIENCY INCREASE IN RESPONSE TO SLEEP RESTRICTION IN ADOLESCENTS

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ABSTRACT

To investigate the effects of real-life stress on the sleep of adolescents, we performed a repeated-measures study on actigraphic sleep estimates and subjective measures during one regular school week, two stressful examination weeks, and a week's holiday. Twenty-four adolescents aged 17.63 ± 0.10 years (mean (M) ± standard error of the mean (SEM)) wore actigraphs and completed diaries on subjective stress, fatigue, sleep quality, number of examinations, and consumption of caffeine and alcohol for four weeks during their final year of secondary school. The resulting almost 500 assessments were analysed using mixed-effect models to estimate the effects of mere school attendance and additional examination stress on sleep estimates and subjective ratings. Total sleep time decreased from 7:38 h ± 12 min during holidays to 6:40 h ± 12 min during a regular school week. This 13% decrease elicited a partial compensation, as indicated by a 3% increase in sleep efficiency and a 6% decrease in the duration of nocturnal awakenings. During examination weeks total sleep time decreased to 6:23 h ± 8 min, but it was now accompanied by a decrease in sleep efficiency and subjective sleep quality and an increase in wake bout duration. In conclusion, school examination stress affects the sleep of adolescents. The compensatory mechanism of more consolidated sleep, as elicited by the sleep restriction associated with mere school attendance, collapsed during two weeks of sustained examination stress.

INTRODUCTION

One of the characteristics of the developmental stage of adolescence is a prominent chronic sleep curtailment. Approximately 10–40% of American high school students experience some degree of sleep deprivation (e.g., Petta, Carskadon, & Dement, 1984). It is not known to what extent this reduction in sleep duration can be compensated for by higher sleep efficiency and more consolidated sleep, and whether shorter but more efficient sleep is equally supportive of daytime function as longer sleep.

Although adolescence is often described as a period of emotional turmoil (Carskadon, Vieira, & Acebo, 1993), the effect of stress on adolescent sleep has received little attention. Stress involves physiological reactions to events that signal increased environmental demands or threats. In this study we investigate whether these reactions could interfere with the compensatory mechanism that normally increases sleep consolidation and efficiency in case of short sleep. Whereas, in normal conditions, short sleep appears to be compensated for partly by more consolidated sleep with a higher sleep efficiency (Levine, Lumley, Roehrs, Zorick, & Roth, 1988; Sadeh, Gruber, & Raviv, 2003), this may not be the case during stressful conditions, which reduce sleep efficiency (Akerstedt, Kecklund, & Axelsson, 2007). It thus seems highly relevant to study a reduction in sleep duration that affects sleep efficiency under normal and stressful conditions. In adolescence, sleep is curtailed by scheduled school times that do not match with the delayed circadian phase they experience as part of the life-long changes in the suprachiasmatic nucleus (Swaab, Van Someren, Zhou, & Hofman, 1996). Within this setting, representative periods of sustained stress are the examination weeks, when multiple examinations are to be taken daily.

Only a few studies have addressed the effects of the real-life stressor of school examinations on the sleep of young adolescents. In 11- to 14-year-olds, a single-day examination did not affect subjective sleep during the three previous days (Horn & Dollinger, 1989). Mesquita and Reimao (2010) reported a correlation between the stress experienced and sleep complaints in a cross-sectional study in older adolescents aged 15–18 years, but did not specifically investigate within-subject changes at examination time. Thus, no inferences on causality could be drawn from this study, as sleep complaints may well have increased their sensitivity to stress. One study showed an effect of examination stress on subjective sleep (Robinson, Alexander, & Gradisar, 2009), but its effect on objective sleep has remained elusive.

Here we report on the effect of two weeks of sustained stress on the sleep of
adolescents in a naturalistic ecologically valid quasi-experimental study. Objective actigraphic sleep estimates and subjectively experienced stress were assessed in adolescents during three periods of the final year of secondary school: one week of regular school activity, two highly stressful school examination weeks, and one week of school holidays. Mixed-effect regression models were applied to estimate within-subject changes in objective sleep due to mere school attendance and examination weeks. We hypothesised that school attendance would shorten sleep duration and lead to a compensatory increase in sleep efficiency, and that examination stress would further shorten total sleep time, but possibly without a compensatory increase in sleep efficiency.

METHODS

Participants
Participants were 28 final-year students of a secondary school located in Amsterdam, the Netherlands. Exclusion criteria were self-reported health problems, use of medication likely to affect sleep or subjective sleeping problems, as indicated by an Athens Insomnia Scale (AIS) score above or equal to the clinical cut-off of 6 (Soldatos, Dikeos, & Paparrigopoulos, 2003) or an outlying value on the School Sleep Habits Survey (SSHS) sleep-wake problems scale and/or sleepiness scale, defined as more than 1.5 times the interquartile range (Wolfson & Carskadon, 1998). The data for two participants were discarded due to the presence of attention deficit hyperactivity disorder and self-reported sleeping problems. The data for two participants were missing: one did not complete the study; the other’s equipment malfunctioned. Of the 24 adolescents included in the analyses, eight of whom were male, the average age was 17.63 ± 0.10 (M ± SEM) years. AIS, SSHS sleep-wake problems and SSHS sleepiness scores were 2.17 ± 0.24, 22.13 ± 0.90 and 14.50 ± 2.70, respectively. The Medical Ethics Committee of the Academic Medical Center of the University of Amsterdam exempted the study from approval, because the protocol did not concern medical research. Nevertheless, the protocol adhered to the ethical principles for medical research involving human participants as stated in the Declaration of Helsinki of the World Medical Association (WMA). Written informed consent was obtained from all children and one of each child’s parents.

Actigraphy
Primary outcome measures were actigraphic sleep estimates obtained from an Actiwatch (Cambridge Neurotechnology, Cambridge, UK) worn continuously on the non-dominant wrist for four weeks and removed only during showering and sports. Sleep parameters were estimated with the accompanying software (Sleep Analysis) according to a validated method (Kushida et al., 2001) using the lights off and rise time times indicated in sleep diaries (see below) to define the first sleep parameter, Time in bed. The following sleep parameters were furthermore estimated actigraphically:

- **Sleep onset latency**: the duration between lights off and sleep onset.
- **Total sleep time**: the time spent asleep between sleep onset and final awakening.
- **Wake after sleep onset**: the time spent awake between sleep onset and final awakening.
- **Sleep efficiency**: the percentage of time in bed spent asleep.
- **Average sleep bout duration**: the average duration of uninterrupted sequences of sleep epochs.
- **Average wake bout duration**: the average duration of uninterrupted sequences of wake epochs.

The first five sleep parameters are the most commonly reported. The average durations of sleep and wake bouts provide measures of sleep continuity versus fragmentation, an often neglected yet important aspect of the functional relevance of sleep for brain function, cognition and emotion (e.g., Carvalho-Bos, Riemersma-Van der Lek, Waterhouse, Reilly, & Van Someren, 2007).

Diaries
Participants kept a diary in which, every morning, they noted the answers to a number of questions. This included three questions on stress, fatigue and subjective sleep quality, rated on five-point scales (1–5), for stress ranging from very relaxed to very stressed, for fatigue from well-rested to very tired and for sleep quality, from very poor to very good. Questions on lights off and rise times were used to calculate time in bed and were used to define the analysis windows in the Actiwatch Sleep Analysis software (see Actigraphy paragraph above). Three more questions concerned the daily number of examinations and alcoholic and caffeinated drinks consumed during the previous day.
Procedure
Participants wore an actigraph and completed daily diaries for a total of four weeks during one autumn. A first 7-day recording took place during a regular school week (the Regular_School period), separated by one week from a second, 14-day recording comprising two examination weeks (the Stress_School period). On average 12.19 ± 1.09 (M ± SEM) examinations were taken, at most two examinations per day. School start-times were 08:30 h and sometimes 09:30 h during the Regular_School period, and 09:00 h in the Stress_School period. Finally, a 7-day recording took place during the holidays (the No_School period).

Data Analysis
On average, 2.83 ± 0.46 (M ± SEM) days of excessive (>3 units) alcohol consumption were excluded per individual. For all variables, outliers (z-transformed values > 2.58) were excluded to prevent leverage in the subsequent analyses. Mixed-effect models (MLwiN, Centre for Multilevel Modelling, Institute of Education, London, UK) were used to estimate the effects of mere school attendance and additional examination stress. The mixed-effect model approach takes into account the multi-level interdependency of data points, missing data on different days, and time-varying covariates such as weekend days versus weekdays. The model used to evaluate the effect of mere school attendance and additional examination stress on any outcome measure, \( y_{ij} \), is defined as:

\[
y_{ij} = \beta_0 + \beta_1 x \text{school attendance}_i + \beta_2 x \text{examination stress}_i + \epsilon_{ij},
\]

where level \( i \) represents the repeated measures 1–28 and level \( j \) represents participant numbers 1–24. School attendance and examination stress were included in the model as dichotomous dummy variables. The school attendance factor encoded days during the No_School week as 0 and days during both the Regular_School and the Stress_School weeks as 1. The examination stress factor encoded days during the No_School week as 0 and days during both the Regular_School and the Stress_School weeks as 1. A z-test was used to obtain the significance of the effect sizes.

Results

Sleep Estimates
Due to the occasional missing of a night’s sleep and to nights excluded because of alcohol consumption, the actigraphic estimates of sleep parameters were based on 5.29 ± 0.19 (M ± SEM) nights per participant in the Regular_School period; 12.68 ± 0.19 nights in the Stress_School period; and 4.36 ± 0.19 nights in the No_School period. Table 1 shows the effects of mere school attendance and additional examination stress.

School attendance reduced time in bed by 90.1 ± 14.6 min (\( p < .001 \)), reduced total sleep time by 57.5 ± 12.1 min (\( p < .001 \)), reduced wake after sleep onset by 23.9 ± 4.7 min (\( p < .001 \)), increased sleep efficiency by 2.2 ± 0.7% (\( p = .002 \)) and induced an almost significant reduction (\( p = .05 \)) of the average wake bout duration by 0.15 ± 0.08 min, but did not affect sleep onset latency or the average sleep bout duration. Examination stress additionally reduced total sleep time by 17.5 ± 8.2 min (\( p = .03 \)), reduced sleep efficiency by 1.5 ± 0.5% (\( p = .002 \)) and increased the average wake bout duration by 0.13 ± 0.05 min (\( p = .01 \)), but did not affect time in bed, sleep onset latency, wake after sleep onset, or the average sleep bout duration.

In accordance with previous findings (Levine et al., 1988; Sadeh et al., 2003), an extended model revealed sleep efficiency to be negatively associated with time in bed (\( p = .003 \)), whilst the positive effect of school attendance (\( p = .02 \)) and negative effect of examination stress (\( p = .001 \)) remained significant.

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Extended regression models that included dummy-coded weekend nights versus weekday nights indicated that the weekend nights were characterised by 98.0 ± 9.8 min longer time in bed (\( p < .0001 \)) and 78.2 ± 8.1 min longer total sleep time (\( p < .0001 \)). Inclusion of the weekend versus weekday variable in the model did not result in a noteworthy change of the estimated effect, or significance, for any of the significant effects of school attendance or examination stress on the outcomes mentioned above. Extended regression models indicated that the more examinations taken on a particular day, the less time in bed (\( p < .0001 \)) and the less total sleep time (\( p < .0001 \)), supporting the validity of the sleep and stress estimates. Extended regression models that evaluated whether actigraphic sleep
estimates showed a day-by-day change over the entire Stress_School period showed a progressive worsening of sleep bout duration, deceasing on average by 0.21 ± 0.10 min, or 1.5% per day (p = .04), as well as a progressive worsening of wake bout duration, increasing on average by 0.017 ± 0.008 min, or 0.7% per day (p = .02). Inclusion of the days-since-start-of-the-examinations regressor in the model did not result in a noteworthy change of the estimated effect, or significance, for any of the significant effects of school attendance or examination stress on the outcomes mentioned above.

In summary, school attendance reduced time in bed by 16% and total sleep time by 13%, whilst it increased sleep efficiency by 3%. Examination stress did not additionally change time in bed, but did reduce total sleep time further by another 4%; examination stress also attenuated sleep efficiency by 2% relative to the No_School period (5% relative to the Regular_School period), and increased the average duration of wake bouts by 5% relative to the No_School period (11% relative to the Regular_School period).

**Stress, Fatigue, Sleep Quality and Caffeine Consumption**

Table 1 shows the differential effects of mere school attendance and additional examination stress on the subjectively experienced stress, fatigue and sleep quality ratings. School attendance increased stress by 0.85 ± 0.12 points (p = .001) and fatigue by 0.95 ± 0.13 points (p = .001), without affecting sleep quality. Examination stress additionally increased stress by 0.80 ± 0.08 points (p = .001) and reduced sleep quality by 0.28 ± 0.08 points (p = .001), without affecting fatigue.

Whereas mere school attendance did not change the number of caffeinated drinks per day, examination stress induced a marginally significant (p = .05) increase of 0.20 ± 0.10 drinks consumed per day. Caffeine consumption was not significantly related to any of the actigraphic sleep estimates (13 < p < .65), or to subjective stress (p = .13) or sleep quality (p = .49), but was positively related to fatigue (p = .04). Extended regression models show that participants experienced less stress (0.38 ± 0.09 points or 40%, p < .001) and less fatigue (0.47 ± 0.09 or 31%, p < .001) during weekend days compared to weekdays. Moreover, they rated the quality of their sleep higher for weekend nights compared to weekday nights (0.42 ± 0.08 points or 12%, p < .001). Caffeine use did not differ between weekend days and weekdays (p = .34). Inclusion of the weekend versus weekday variable in the model did not result in a noteworthy change of the estimated effect, or significance, for any of the significant effects of school attendance or examination stress on the subjective outcomes mentioned above. Extended regression models indicated that the more examinations taken on a particular day, the lower the subjective sleep quality (p = .03) and the more subjectively experienced stress (p < .0001) and fatigue (p < .0001), supporting the validity of the subjective ratings. Extended regression models that evaluated whether diary measures showed a day-by-day change over the Stress_School period revealed a progressive worsening of fatigue by 0.02 ± 0.01 points per day (p < .05). Inclusion of the days-since-start-of-the-examinations regressor in the model did not result in a noteworthy change of the estimated effect, or significance, for any of the significant effects of school attendance or examination stress on the subjective measures mentioned above.

In summary, school attendance increased the subjectively experienced stress by

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<th><strong>TABLE 1</strong> Mixed-Effect Model Outcomes</th>
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<td><strong>Characteristics</strong></td>
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<td><strong>Sleep parameter estimates</strong></td>
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<td>Time in bed (min)</td>
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<td>Sleep onset latency (min)</td>
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<td><strong>Subjective ratings (1-5)</strong></td>
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**Note.** Mixed-effect regression estimates of the mean (M) baseline values ± standard errors of the mean (SEM), and the additive within-subject effects of school attendance and examination stress. All effect estimates include p-values of significance and % difference relative to the baseline. Within-subject effect estimates account for between-subject differences in the number of available days in each period, which would not be the case if raw period means would be provided. Significant effects are highlighted in bold font.
100% and fatigue by 68%, and examination stress increased the subjectively experienced stress by another 94%, increased caffeine consumption by 18% and attenuated subjective sleep quality by 8%.

**DISCUSSION**

The current study is, to the best of our knowledge, the first to examine the causal effect of a 2-week period of chronic real-life stress on adolescent sleep. Actigraphic sleep estimates and subjectively reported stress, fatigue, sleep quality, and intake of caffeine were assessed during regular school attendance, two stressful weeks of final-year secondary school examinations, and holidays. This approach allowed us to discern the effects of mere school attendance and the additional effects of examination stress. Compliance with long-term actigraphy was good: on average, fewer than three (10%) out of 28 days per participant were missing.

Mere school attendance reduced time in bed and total sleep time by 1.5 and 1 h, respectively, which triggered a compensatory increase in sleep efficiency and a near significant decrease in the average duration of wake bouts. The suggestion of partial compensation is supported by the finding that school attendance did not affect subjective sleep quality. Studies on the effect of sleep restriction on cognition in adolescents support the presence of compensatory mechanisms. In adolescents, neither a single night nor four nights of sleep restriction affect declarative memory consolidation or cortisol (Kopasz, Loessl, Valerius, et al., 2010; Voderholzer, et al., 2012; Voderholzer, et al., 2011). Reviewing previous studies, Kopasz et al. (2010) concluded that adolescents appear able to maintain cognitive performance by compensating in case of brief periods of sleep restriction, and suggested that impairments might show only if there is an interaction with stressors such as socioeconomic burden. Also, Buckhalt et al. (2007) suggested that an accumulation of stressors, including low social economic status (SES), may be necessary to affect sleep efficiency and cognitive performance.

Indeed, the present study supports this suggestion, in part, by demonstrating that compensatory mechanisms collapsed only when the sleep restriction induced by school attendance was accompanied by subjectively verified chronic stress, as indicated by an increase in the duration of wake bouts and a decrease in sleep efficiency. This worsening occurred despite a further reduction in total sleep time, which under non-stressed conditions would be expected to induce a compensatory decrease in the duration of wake bouts and an increase in sleep efficiency (Levine, et al., 1988; Sadeh, et al., 2003). The increase in wake bout duration suggests a shift from brief arousal-related movements towards more prolonged periods of movement associated with true wakefulness (Gimeno, Sagales, Miguel, & Ballarin, 1998). Although examination stress shortened total sleep time by only 17.5 min, on average, it may have been the worsened sleep efficiency and longer wake bout duration that led to the subjectively experienced reduction in sleep quality.

In young adults, burnout due to chronic exposure to stress is associated with an increased number of microarousals during sleep (Soderstrom, Ekstedt, Akerstedt, Nilsson, & Axelsson, 2004). Interference with sleep continuity, even in the absence of changes in sleep duration, might also be particularly detrimental for brain function and cognition (Bonnet & Arand, 2003), also in children (Sadeh, Gruber, & Raviv, 2002). It would be interesting for future studies to evaluate how individual differences in the sleep response to stress may lead to differences in the effect of stress on cognitive performance: in medical school students aged 19–31 years, the perceived stress and sleep problems that were elicited by examinations were most pronounced in those with worse grades (Ahrberg, Dresler, Niedermayer, Steiger, & Genzel, 2012).

The actigraphically estimated total sleep time was somewhat short. During the holidays the participants achieved 7:38 h ± 12 min of sleep (M ± SEM), which was reduced by 58 ± 12 min during the regular school week and reduced by a further 18 ± 8 min during stressful school examination weeks. Given the suggested optimum amount of approximately 9 h of sleep for adolescents (Carskadon, et al., 1980), our findings suggest that adolescents may expose themselves to chronic sleep restriction that may not be compensated for sufficiently by the small increase in sleep efficiency it elicits. Indeed, 63–87% of healthy adolescents report that they do not get enough sleep (Mercer, Merritt, & Cowell, 1998; Wolfson & Carskadon, 1998). Actigraphic estimates of sleep efficiency were also surprisingly low, given a commonly applied cutoff of 85% for disturbed sleep. Low actigraphic estimates of sleep efficiency in healthy adolescents have been reported previously. Using the same actigraph in 94 children aged 13–14 years, Gaina et al. (2005) reported sleep efficiency estimates of 82.2% in girls and 80.8% in boys during school-free days, and Palermo et al. (2008) reported a sleep efficiency of 81.8% in 20 children with an average age of 15 years. Low sleep efficiency is compatible with the primary conclusion of an extensive review on the association between sleep and academic performance, that students suffer from poor sleep quality (Curcio, Ferrara, & De Gennaro, 2006). On the other hand, a sleep efficiency as low as reported here has been observed only in the first night of
polysomnographic recordings of adolescents (Voderholzer, et al., 2011), and may be specific to actigraphy.

A number of possible limitations of the present study may be discussed. First, it should be noted that the study is quasi-experimental. Second, the order of the periods of a regular school week, stressful examination weeks, and holidays was fixed so that, strictly speaking, history effects cannot be excluded. To address this possibility, we ran ancillary analyses that showed no effect of time-in-study on any outcome (.24 < p < .96, average p = .55), arguing against confounding by an order effect. A third possible limitation is the use of actigraphy rather than polysomnography (PSG) to estimate sleep. On the other hand, by making it feasible to assess multiple-night averages, actigraphy can yield robust sleep parameter estimates in the presence of day-to-day variability (Van Someren, 2007). Indeed, the availability of 14 nights during a stressful period enabled us to demonstrate a progressive worsening of the duration of sleep bouts (becoming shorter) and wake bouts (becoming longer). A previous study could not demonstrate an effect of a single school examination on self-reported sleep in 11- to 14-year-old children (Horn & Dollinger, 1989), suggesting that it may be essential to study more chronic stressors, for which purpose actigraphy is well suited. A fourth possible limitation is that the subjective assessment of stress may have been influenced by expectation bias. Future investigations may include objective stress parameters like cortisol, shown previously to be feasible in a sleep restriction study in adolescents (Voderholzer, et al., 2012). However, expectation bias cannot be reasonably expected to have led to the significant effects observed in the primary outcomes of actigraphically-estimated sleep. A final possible limitation of the present study is that the generalisability may be restricted. Measurements were performed at a single school with a prestigious profile, attended predominantly by Caucasian adolescents from families with above-average SES. To what extent the reported effects hold for adolescents within a different range of intellectual abilities or SES remains to be addressed in future studies. However, it is not unlikely that the effects of examination stress on sleep in adolescents of lower SES may be even more severe. As mentioned above, sleep and cognitive performance may suffer most in case of an accumulation of stressors, including low SES (Buckhalt, et al., 2007).

The possible limitations thus seem counterbalanced by advantages and advances in our study on the effects of stress on sleep in adolescents. A further strength of the current study is the large number of repeated measurements. Other methodological strengths are the use of actigraphy to obtain objective estimates of sleep parameters and the assessment of two weeks of chronic real-life stress in a naturalistic environment. One notable finding of the current study is that the sleep restriction induced by school attendance per se appears to activate compensatory mechanisms that result in more consolidated sleep. The most important finding of the present work may be that when stress increases during examination weeks, the hypothesised compensatory mechanisms collapse and sleep becomes less consolidated.

Given the importance of sleep for cognitive and emotional functioning in school-age children and adolescents (Astill, Van der Heijden, Van IJzendoorn, & Van Someren, 2012; Kopasz, Loessl, Hornyak, et al., 2010), our study may have implications for the way in which examinations are administered in the present educational system. It could prove advantageous to provide stress-management techniques in preparation of examination weeks. Taking our findings one step further, clustering examinations on consecutive days for an extended period of time may not be the best way to test knowledge. The stress induced by this schedule affects sleep and this disturbed sleep, in turn, may affect daytime cognitive and emotional functioning. It would seem worthwhile to investigate the effect of objective and subjective ratings on examination performance and whether coping style or personality influence how stress affects sleep in adolescents. Coping style was shown to be an important moderator of the effect of stress on sleep in undergraduate students (Sadeh, Keinan, & Daon, 2004). Alternative methods of testing adolescents—for instance, by spreading the examinations out more—might limit stressfulness and improve performance and well-being.

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Chapter 3

II EXPERIMENTAL WORK
