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The Effects of Acute Sleep Restriction on Adolescents' Pedestrian Safety in a Virtual Environment

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ABSTRACT

Purpose: Over 8,000 American adolescents ages 14–15 years require medical attention owing to pedestrian injury annually. Cognitive factors contributing to pedestrian safety include reaction time, impulsivity, risk taking, attention, and decision making. These characteristics are also influenced by sleep restriction. Experts recommend that adolescents obtain 8.5 hours of uninterrupted sleep each night, but most American adolescents do not. Inadequate sleep may place adolescents at risk for pedestrian injury.
Methods: Using a within-subjects design, 55 14- and 15-year-olds engaged in a virtual reality pedestrian environment under two conditions, scheduled a week apart: sleep-restricted (4 hours' sleep the previous night) and adequate sleep (8.5 hours). Sleep was assessed using actigraphy and pedestrian behavior via four outcome measures: time to initiate crossing, time before contact with vehicle while crossing, virtual hits or close calls and attention to traffic (looks left and right).
Results: While acutely sleep restricted, adolescents took more time to initiate pedestrian crossings, crossed with less time before contact with vehicles, experienced more virtual hits or close calls, and looked left and right more often compared with when adequately rested. Results were maintained after controlling for age, gender, ethnicity, and average total sleep duration before each condition.
Conclusions: Adolescent pedestrian behavior in the simulated virtual environment was markedly different, and generally more risky, when acutely sleep restricted compared with adequately rested. Inadequate sleep may influence cognitive functioning to the extent that pedestrian safety is jeopardized among adolescents capable of crossing streets safely when rested. Policy decisions might be educated by these results.

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IMPLICATIONS AND CONTRIBUTION

The results have implications in at least three areas. They may 1) confirm the benefit for pediatricians to address sleep health during preventative counseling discussions with adolescents and parents; 2) inform policy makers to delay school start times, providing safer travel to school; and 3) influence parents to enforce appropriate bedtimes.

Unintentional pedestrian injury is the sixth leading cause of death in United States (US) adolescents ages 14–15 years, injuring 8,133 and killing 105 adolescents in 2008 [1]. Safe pedestrian behavior depends on advanced cognitive and self-regulatory skills, including attention, reaction time, decision making, risk taking, and impulsivity [2–5]. These skills diminish with sleep restriction, which suggests that tired adolescents may behave in dangerous ways while crossing streets.

To function well, experts currently suggest that the typical teenager requires at least 8.5 hours of uninterrupted sleep nightly [6], although the recommended time is controversial and has changed over the years [7,8] and there is individual variation in the amount of sleep each person needs [9]. Adolescents in the US have been found to require more sleep than younger children [9,10], and they reportedly obtain an average of 7.5 hours on school nights, leading to chronic sleep restriction patterns [11]. American adolescents obtain inadequate sleep for multiple

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biological, cultural, and psychosocial reasons. Inadequate sleep on school nights likely results from the change in circadian rhythm during adolescence, which causes them to fall asleep later, with a biological need to sleep later to obtain adequate sleep [12–14], but adolescents are required to awaken early due to early school start times [13]. Other factors affecting acute adolescent sleep deprivation include decreased supervision by parents, adolescents' desire for independence, increased academic demands, involvement in social and extracurricular activities, and response to peer pressure [12–14]. Chronically sleep deprived individuals demonstrate increased impulsivity and risk taking, slower reaction times, decreased attention, and impaired decision making [15–18]. Citing these cognitive influences on functioning, scientists have reported increased unintentional injury risk among children with chronically inadequate sleep or sleep disturbance [19–21].

Whereas many adolescents experience chronic sleep deprivation over days or weeks [22], others have highly inadequate sleep on single occasions, causing acute sleep restriction. Although there is little documented research on this area, because 4% of adolescents report sleeping for $\leq$5 hours each night on a regular basis [23], it is plausible that the number of adolescents who obtain this little sleep on single occasions is higher. Adolescents experience acute sleep restriction for various psychosocial and cultural reasons, including evening social events (e.g., a late-night football game or high school dance) and academic deadlines (e.g., staying up late to prepare for an exam). Cognitive consequences of acute sleep restriction are not understood as well by researchers as are those of chronic sleep deprivation, although some evidence links acute sleep restriction with decreased attention [24] and increased unintentional injury risk [25,26].

This study used a within-subjects experimental design to study associations between acute sleep restriction and adolescent pedestrian behavior. A total of 55 14- and 15-year-olds engaged in a pedestrian environment on mornings after an adequate night's sleep (8.5 hours' sleep) and an acutely sleep restricted night (4 hours' sleep). The hypothesis was that adolescents would exhibit riskier pedestrian behavior when sleep restricted.

Method

Participants

A total of 55 14- to 15-year-olds participated. They were recruited through community sources, including a laboratory database of names of local families interested in participating in research, and through distribution of information and permission slips at middle schools in the Birmingham, Alabama area. The sample was 58% female, 53% African-American, and 47% Caucasian, and had an average age of 14.89 years (standard deviation [SD], .62 years). Thirty-six percent of the sample came from families with a household income of $\geq$\$80,000, 45% of \$40,000–\$79,999, and 19% of $<$\$40,000. Signed informed consent was obtained from a parent, and signed informed assent from adolescents. The protocol was approved by the university's institutional review board.

Study protocol

Participants visited the laboratory three times, each about 1 week apart (mean days apart, 8.12; SD, 2.02). The first visit served as a baseline. During this visit, parents and adolescents completed several questionnaires (details below), and adolescents received an actigraph (Respironics, Amsterdam, Netherlands) and sleep diaries to track sleep for the remainder of the study (about 2 weeks; details below). During the baseline visit, participants also were assigned randomly to an experimental order for the next two scheduled visits. Half (n = 27) were scheduled to return for a morning appointment in about a week after obtaining a full (8.5-hour) night's sleep the evening before. That visit would be followed by a morning appointment about 2 weeks after the initial visit following a restricted (4 hour) night's sleep the evening before. The other half of the sample (n = 28) had the order reversed, with sleep restriction scheduled first and a full night's sleep second. All participants were scheduled for standardized morning appointments. Average time between wake time and appointment time was 75.38 minutes (SD, 31.40 minutes) for the sleep restricted condition and 70.81 minutes (SD, 34.92 minutes) for the adequate sleep condition, and the variation between conditions was not statistically significant ($t[44] = .92$; $p = .36$). Caffeine consumption was prohibited in the mornings before visits. To ensure safety of adolescents after participation in the study, we strongly recommended that they take a nap on the day of the sleep restriction before engaging in any activities for which sleepiness might place them at risk of injury; all were non-drivers and left the laboratory with a parent whose sleep was not restricted for research purposes.

During the two morning visits, actigraphy data were reviewed to confirm that the adolescent had slept the required amount of time (details below). Participants then engaged in 25 street-crossing trials within the virtual pedestrian environment (details below). At the end of each appointment, participants received a modest incentive (\$20 cash for parents; \$10 gift card for adolescents).

Equipment and measures

Virtual reality environment. The virtual reality pedestrian environment replicates a two-lane, bidirectional, mid-block street crossing near a local elementary school. It was validated as an accurate measure of actual pedestrian behavior in a real-world environment [27].

To use the virtual environment, participants first walked along a 25-foot distance in a hallway five times. This provided average walking speed that was used for the virtual avatar. Participants then watched the experimenter complete two crossing trials, one successful and one in which the experimenter was purposely struck by a vehicle, to reduce curiosity. Next, participants performed eight practice trials in the virtual reality environment. These trials reduced learning effects. For each trial, participants stood on a wooden "curb", immersed inside three screens simulating the street environment, and watched vehicles pass from both directions. After deciding it was safe to cross, participants stepped down off the curb. The step triggered an avatar to cross the street at the predetermined walking speed. If the crossing was safe, a character provided positive feedback and the next trial was initiated. If the crossing was a close call (defined as being within 1 second of a collision), cautionary feedback was provided before initiation of the next trial. If the virtual avatar was struck by a vehicle, the screen froze, cautionary feedback was provided, and then the next trial was initiated.

Participants completed 25 experimental crossing trials during each visit (that is, 25 trials while sleep restricted and 25 trials while adequately rested). Vehicle traffic moved at 30 miles per hour and appeared at randomized intervals with an average density of 12 vehicles per minute.

Four indicators of safe pedestrian street crossing, adapted from previous research [28], assessed safety of pedestrian crossings in the virtual environment: (1) average start delay (time in seconds after a car passed and before participants initiated crossing); (2) average time to contact (the smallest temporal gap, in seconds, between the avatar and any oncoming vehicle during the crossing); (3) hits or close calls (when participants would have been struck by a vehicle in the real environment, or when the gap between the participants and the oncoming vehicle was <1 second); and (4) attention to traffic (times participants looked left and looked right before crossing, divided by wait time).

For analytic purposes, the start delay, time to contact, and attention to traffic measures were averaged across the 25 street crossings for each condition (sleep restricted and adequate sleep). The hits/close calls pedestrian behavior was summed over the 25 trials. Thus, each participant yielded four pedestrian behavior scores (start delay, time to contact, hits or close calls, and attention to traffic) in each of two conditions (sleep restricted or adequate sleep).

Actigraphy and sleep diaries. Participants wore an Actiwatch 2 actigraph (Respironics, Amsterdam, Netherlands) on the nondominant wrist for the full 2-week experiment. Actigraphs are small, wristwatch-size devices containing a piezoelectric accelerometer that yields estimates of sleep and wake patterns over time. Previous work demonstrates validity of actigraphy data. For example, correlations of sleep duration data measurements using actigraphy and sleep duration data using traditional polysomnography are $>.80$ [29,30].

In this study, data downloaded from the actigraph were analyzed to assess total sleep duration for each night. This was calculated by the actual minutes of scored sleep, excluding any awakenings after sleep onset. Most relevant, of course, was sleep duration the night before the laboratory visits. A range of 1 hour more or less than the desired sleep durations of 4 and 8.5 hours for the sleep restricted and adequate sleep conditions, respectively, were accepted as valid. Across the full sample, participants slept a mean of 4.13 hours (SD, .67 hours; range, 3.16–4.97 hours) in the 4-hour condition and a mean of 8.28 hours (SD, .52 hours; range, 7.51–9.43 hours) in the 8.5-hour condition. In instances when participants arrived for a session having slept over 1 hour more or less than the required sleep amount, the appointment was rescheduled. About 17% of the sample was rescheduled one time owing to inadequate sleep, and it was not necessary to reschedule participants more than once.

Actigraphy data also assessed nightly total sleep duration for the 3 nights before the target night for each condition. Because chronic sleep deprivation is known to influence cognition, average total sleep duration served as a covariate of the primary analyses. This was measured by averaging the total sleep duration over the 3 nights before the target night for each condition. The 3-night window was chosen to permit full recovery from the sleep restriction/adequate sleep night that had occurred about 7 nights prior. Across the full sample, sleep duration before the sleep restricted condition averaged 7.61 hours (SD, 1.25 hours) and 7.25 hours (SD, 1.09 hours) before the adequate rest condition. The two rates were not statistically different.

As a backup in case the actigraphy equipment failed, adolescents completed sleep diaries every morning throughout the study. The sleep diary was brief, simply asking adolescents to record when they fell asleep and woke up daily. Research suggests that 28% of actigraph data are lost on average, primarily for technical problems [31]; in this study, 18.9% of data were lost owing to battery failure. In those cases, total sleep duration recorded on the sleep diary was used instead. In instances when actigraph data were valid, actigraph data correlated well with diary reports ($r[88] = .96$, $p < .001$), providing evidence of diary data validity.

Questionnaires. Parents completed a demographics questionnaire and the Pediatric Sleep Questionnaire (PSQ) during the baseline visit. Adolescents completed the Pediatric Daytime Sleepiness Scale (PDSS). The demographics questionnaire assessed adolescents' age, gender, race/ethnicity, and household income. The PSQ is a 22-item instrument that assesses sleep-related breathing disorders ranging from a score of 0 to 22 (higher scores indicate greater disorder). All items are dichotomous (yes/no) and internal reliability data are adequate (Cronbach $\alpha = .89$) [32]. Adolescents completed the PDSS to obtain a level of daytime sleepiness [33]. The PDSS is an eight-item instrument. Items are answered on a 5-point scale ranging from Always (4) to Never (0), yielding scores ranging from 0 to 32; higher scores indicate greater daytime sleepiness. Internal reliability is adequate (Cronbach $\alpha = .80$) [33].

Results

Descriptive statistics were examined first. The Shapiro-Wilk test suggested that the start delay, hits or close calls, and attention to traffic variables were non-normal in both conditions, so they were transformed using square root transformations. Outliers were removed ±2 SD from the mean for all variables. Table 1 lists descriptive statistics.

To test our primary hypothesis that adolescents would engage in riskier pedestrian behaviors when sleep-restricted, repeated measures t tests were computed for each of the four pedestrian variables. No covariates were included. As hypothesized, adolescents took more time to initiate crossings when sleep restricted (mean 1.22, SD 2.15) than when adequately rested (mean 1.42, SD 1.47); $t(47) = 2.68$, $p < .05$; crossed with less time to contact between vehicles when sleep restricted (mean 4.58, SD .92) than when adequately rested (mean 4.91, SD .96); $t(49) = -2.38$, $p < .05$; experienced more hits or close calls when sleep restricted (mean 2.22, SD .36) than when adequately rested (mean 1.42, SD .38); $t(51) = 2.17$, $p < .05$; and looked left and right more often before crossing when sleep restricted (mean .51, SD .15) than when adequately rested (mean .46, SD .15); $t(50) = 2.08$, $p < .05$ in the sleep restricted condition versus the adequate sleep condition (Table 1).

Given results suggesting that sleep restriction affected pedestrian behavior, the authors conducted further analyses to test whether various factors may influence the effect of sleep restriction on pedestrian behavior. The outcome measures for these analyses were difference scores, computed by subtracting pedestrian behavior after adequate sleep from pedestrian behavior after restricted sleep. Thus, significant findings would indicate differential effects of acute sleep restriction on subsamples of interest.

First, randomized experimental order was considered (sleep restriction first vs. second). Randomized order served as an independent variable in a series of independent-sample t tests,

Table 1
Descriptive statistics

Variable	Sleep-Restricted condition, mean (standard deviation)	Adequate rest condition, mean (standard deviation)	Degrees of freedom	t	Cohen's d
Start delay (mean), seconds	1.22 (± .36)	1.07 (± .38)	47	2.68*	.36
Time to contact (mean), seconds	4.58 (± .92)	4.91 (± .96)	49	−2.38*	.35
Hits/close calls out of 25 crossings, n	2.22 (± 2.15)	1.42 (± 1.47)	51	2.17*	.32
Attention to traffic (n looks/wait time in seconds)	.51 (± .15)	.46 (± .15)	50	2.08*	.31

* $p < .05$.

with the four difference scores (start delay, time to contact, hits/close calls, and attention to traffic) as dependent variables. No statistically significant effects emerged.

Second, the researchers considered whether age (mean 14.89 years, SD .62 years), the average of the two sleep durations over the 3 nights before each condition (mean 7.43 hours, SD 1.17 hours), PSQ scores (mean 2.87, SD 2.77), or PDSS scores (mean 15.07, SD 4.57) influenced the effect of sleep restriction on pedestrian behavior. Bivariate Pearson correlations were performed between these variables and pedestrian behavior difference scores, and no statistically significant correlations emerged. Similarly, to examine race/ethnicity and gender, two sets of independent-sample *t* tests were performed with race (Caucasian [n = 26] vs. African-American [n = 29]) and with gender (boys [n = 23] vs. girls [n = 32]) as the independent variables and pedestrian behavior difference scores as the dependent variable. No statistically significant effects emerged. This set of bivariate analyses was then extended using multivariate linear regression. Each of the four pedestrian behavior difference scores was used as a dependent variable in a model with gender, race, average sleep duration over the 3 nights before each condition, PDSS score, and PSQ score as independent variables. No models were significant (Table 2).

Discussion

Sleep restriction influenced adolescents' pedestrian behavior. When fatigued, adolescents had greater temporal delays before entering a crossing gap to initiate street crossing, left less time between themselves and oncoming vehicles, experienced more hits or close calls with virtual vehicles, and attended less carefully to traffic before crossing. Stated numerically, adolescents who were sleep restricted—who had slept <5 hours the night before—had over a 50% increase in hits or close calls with virtual vehicles while sleep restricted compared with when they were adequately rested. While sleep restricted, adolescents experienced a hit or close call on 2.22 of the 25 simulated crossings, or 8.9% of the time, whereas they experienced a hit or close call on 1.42 of the 25 crossings (5.6%) after an adequate night of sleep. Results did not vary across any of the covariates tested, including randomized experimental condition order, average sleep duration before each condition, baseline measures of self-reported sleep quality, age, gender, or race/ethnicity.

The generally riskier pedestrian behaviors among sleep-restricted adolescents were likely caused by the cognitive effects of sleep restriction [15–18]. Safe pedestrian behavior requires multiple aspects of cognitive function. First, safe pedestrian behavior requires impulse control; sleep-restricted adolescents made risky decisions by crossing in potentially dangerous traffic gaps. Second, safe pedestrian behavior requires efficient, rapid, and precise decision making; a pedestrian must perceive and judge the safety of a traffic gap quickly and then initiate movement into it. As measured by the start delay variable, adolescents who were tired also performed poorly at quickly initiating the crossing when a safe opportunity was present.

Finally, safe pedestrian behavior requires attention to oncoming traffic [34]. It appears that the tired adolescents looked more frequently at traffic but made risky and poor decisions, yielding more risky behavior overall when acutely sleep restricted. Adolescents may have increased their looking at traffic while acutely sleep restricted as a means of compensation. They may have recognized their deficient processing and tried to compensate by looking more frequently at the pedestrian environment. Simply looking at the environment does not translate into safer pedestrian behavior, however, because a safe pedestrian must not only perceive the environment, but also process the perceived information and decide how to act. Given these findings on the cognitive and decision-making aspects of pedestrian behavior that were measured, it appears the acutely sleep-restricted adolescents demonstrated poor cognitive processing and decision making about the pedestrian environment even though they looked back and forth more frequently.

These results may have implications for adolescents engaging in everyday activities such as crossing streets, in at least three

Table 2
Linear regression analysis for pedestrian difference scores (N = 55)

	B	Standard error B	β	t	p
Start Delay					
Gender	−.09	.07	−.24	−1.37	.18
Race	−.05	.06	−.13	−.78	.44
Prior 3 nights' sleep	.00	.00	−.03	−.21	.84
PDSS	.00	.01	−.03	−.18	.86
PSQ	−.01	.01	−.03	−.21	.28
Time to contact					
Gender	.13	.31	.07	.43	.67
Race	−.24	.30	−.13	−.78	.44
Prior 3 nights' sleep	.00	.00	.14	.87	.39
PDSS	.02	.03	.12	.74	.46
PSQ	.03	.06	.08	.48	.63
Hits/close calls					
Gender	−.31	.28	−.18	−1.08	.29
Race	.36	.27	.22	1.32	.19
Prior 3 nights' sleep	.00	.00	−.08	−.49	.63
PDSS	.00	.03	−.01	−.07	.94
PSQ	−.03	.05	−.10	−.61	.54
Attention to traffic					
Gender	.19	.11	.32	1.82	.93
Race	.01	.10	.01	.06	.32
Prior 3 nights' sleep	.00	.00	.12	.71	.59
PDSS	−.02	.01	−.25	−1.50	.40
PSQ	.03	.02	.26	1.55	.26

PDSS = pediatric daytime sleepiness scale; PSQ = pediatric sleep questionnaire.

domains. First, the results confirm the benefit of pediatricians promoting sleep health among adolescent patients. Well-patient visits typically involve counseling on preventative health topics [35], and such counseling can instigate healthy behavior change [36,37]. Sleep health is often not included in such counseling, but given the present results, the scope of unintentional injury as the leading cause of adolescent death in the US, and the other consequences of inadequate sleep (e.g., on school performance) [38–40], it may be worthwhile for pediatricians to consider including sleep health among topics addressed during preventative counseling discussions with adolescent patients and their parents.

Second, this information could educate policy decisions about school start times [41]. Changes in the circadian rhythms of adolescents cause many teens to fall asleep later, and early school start times prevent them from achieving adequate amounts of sleep [12–14]. Previous work suggests that inadequate sleep leads to decreased academic performance [38–40], and later school start times are associated with longer sleep duration in adolescents [42]. Our findings offer initial data of another benefit that might arise from later school start times: reduced pedestrian injury risk among adolescents walking to and from school.

Finally, the results might have implications for parents concerning adolescent bedtime enforcement. Parent–adolescent conflict at bedtime is common. Adolescents are more likely to feel controlled by parents if the parents make decisions, such as bedtimes, for them [43]; and in a study of family conflict, parents and adolescents identified bedtimes as an issue causing conflict [44]. Research suggests that most parents do not understand developmental sleep patterns such as the shift in adolescents' circadian rhythms [45], and adolescents also have low knowledge of sleep and sleep hygiene themselves [46]. However, appropriate parental-set bedtimes are associated with longer sleep duration in adolescents [42], behavior that may help adolescents in multiple domains of functioning, including pedestrian safety.

This experiment had strengths and limitations. Methodological strengths include the use of actigraphy to measure sleep and a virtual reality environment to assess pedestrian behavior. Another strength is the repeated-measures research design, which minimized measurement error across samples. One limitation is that it studied only one developmental stage (14- to 15-year-olds), and the results may not generalize to other age cohorts. Another limitation was the omission of other sleep-restriction categories. The researchers studied only 4 versus 8.5 hours of sleep, and it is unknown how adolescents might function with 6, 7.5, or 2 hours of sleep, or with other sleep accumulations or debts. Finally, the study relied on an artificial laboratory design. Sleep was restricted for an experiment, not for natural reasons; similarly, pedestrian behavior was measured in the ethically sound but not perfectly realistic virtual environment. Future research might seek research designs with greater ecological validity.

Safe pedestrian behavior requires precise cognitive functioning, and human cognition is compromised by sleep restriction. This study demonstrated the risk of acute sleep restriction on multiple aspects of adolescents' pedestrian safety.

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