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Adolescent Sleep and School Start Times During Early COVID-19 School Closures

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By

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An abstract of a thesis submitted to the Faculty of the Rollins School of Public Health of Emory University in partial fulfillment of the requirements for the degree of Master of Public Health in Behavioral, Social, and Health Education Sciences
2021

Abstract

Background: Adolescent sleep health is a national priority, as less than 30% of teenagers report sufficient nightly sleep duration. Insufficient sleep is associated with poor physical health, mental health, and academic performance in this age group. Early school start times are a major environmental influence on adolescent sleep duration and timing. The arrival of COVID-19 in the United States caused a widespread transition to remote learning and afforded a unique opportunity to study adolescent sleep without the impact of external factors such as early school start times, bus pickups, and morning extracurricular activities.

Objective: This study investigates adolescent sleep and changes in sleep patterns during COVID-19-related school closures in the United States. This study also assesses the relationship between school start time during COVID-19 and adolescent sleep behaviors and examines other predictors of adolescent sleep behaviors during school closures.

Participants and Setting: An online cross-sectional survey instrument adapted from the School Sleep Habits Survey was distributed through local Start School Later chapters and administered to middle and high school students from May 7 to June 30, 2020. The final analytic sample was restricted to 590 participants in grades 6-12 who were attending remote classes in 35 U.S. states.

Methods: This study quantitatively examined descriptive statistics for seven sleep behaviors, including during school closures (weekday wake time, weeknight bedtime, weeknight sleep duration, weeknight time in bed, daytime sleepiness), and changes from pre- to post-school closures (in weekday wake time and sleep duration). Multivariate linear and logistic regression analyses assessed the relationship between selected predictors (gender, race/ethnicity, class start time, parent-set bedtime, trouble sleeping, and caffeine use) and sleep outcomes, stratified by grade category (6-8th, 9-10th, and 11-12th).

Results: Students reported waking up 2.1-2.9 hours later during school closures and averaged 7.9-8.7 hours of sleep and 8.6-9.5 hours in bed on school nights. Compared to middle schoolers, high school students had later bedtimes and wake times, accompanied by spending less time in bed and less time sleeping. High school students also reported a greater delay in wake time (2.9 hours) than did middle schoolers (2.1 hrs). High school students with later class start times went to bed later ($\beta_{11\text{-}12th}$=1.0 hrs), but also woke up later ($\beta_{9\text{-}10th}$=1.4 hrs, $\beta_{11\text{-}12th}$=1.9 hrs), slept longer ($\beta_{9\text{-}10th}$=1.0 hrs, $\beta_{11\text{-}12th}$=0.9 hrs), and spent more time in bed ($\beta_{9\text{-}10th}$=1.1 hrs, $\beta_{11\text{-}12th}$=0.9 hrs) compared to those starting class earlier. When comparing intra-individual sleep pre- and post-school closures, later class start times resulted in greater delays in wake time ($\beta_{9\text{-}10th}$=1.2 hrs, $\beta_{11\text{-}12th}$=1.5 hrs) and greater odds of increased sleep duration among high schoolers ($OR_{9\text{-}10th}$=5.6). Later class start times were also significantly associated with decreased odds of daytime sleepiness ($OR_{9\text{-}10th}$=0.3) and with a decreased proportion of participants reporting sleepiness during online class (p=0.0004). In addition, parent-set bedtimes were associated with earlier

bedtimes in all grade categories ($\beta_{6\text{-}8th}$=-1.5 hrs, $\beta_{9\text{-}10th}$=-1.2 hrs, $\beta_{11\text{-}12th}$=-1.2 hrs), as well as with other sleep outcomes among middle schoolers.

Conclusions: As a consequence of COVID-19-related school closures, more middle and high school students achieved recommended amounts of sleep, primarily by waking up later in the morning. Students with earlier synchronous class start times slept less and had smaller changes in their weekday wake times during COVID-19 school closures, confirming previous findings that school start time is a strong external influence on adolescent sleep behaviors. The implications of this study extend beyond COVID-19 school closures; adolescent sleep health improves with later school start times and fewer scheduled morning activities. Findings can inform policies on school start timing as well as sleep health education advocacy for parents and students, especially in those school districts that have not yet implemented later school start times.

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Abbreviations

AAP	American Academy of Pediatrics
AMA	American Medical Association
CDC	Centers for Disease Control and Prevention
CI	Confidence Interval
COVID-19	2019 Novel Coronavirus
IRB	Institutional Review Board
TIB	Time in Bed
SEM	Social-Ecological Model
NSF	National Sleep Foundation
OR	Odds Ratio
YRBS	Youth Risk Behavior Survey

Acknowledgments

I would like to extend this opportunity to express my deepest thanks to the people who helped and supported me throughout this process, including professors, advisors, colleagues, family, and friends.

I would like to express my sincere gratitude to Dr. Julie Gazmararian for serving as my thesis committee chair, for her mentorship, guidance, and patience, and for the opportunity to collaborate with and learn from her. Her devotion to the success and well-being of her students does not go unnoticed. I would also like to thank my committee member Dr. Lauren Hale for her willingness to serve on my committee, share expertise, and for inviting me to analyze these data. Thank you both for your constructive feedback and encouragement over the past year.

I would like to thank Dr. Max Van Gilder for developing survey instruments, collecting the data, and helping to develop a story around the findings. Additionally, I would like to thank Dr. Barbara Rosati, Devon Olson, and Cassandra Bryan for collaborating on the manuscript. I am especially grateful for the support I received from Cassandra and Devon, who spent countless hours working with me to refine the manuscript and analyses. I would also like to thank the middle and high school students who participated in this study despite all of the chaos and uncertainty going on in the world around them.

I am extremely appreciative of the other students who have supported me and held me accountable during this process, including Bridget Whaley, without whom I could not have completed this project. Finally, I would like to thank my friends and family who have supported me throughout all of my academic and professional pursuits.

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INTRODUCTION

Adequate sleep is essential to good health. Along with nutrition and physical activity, sleep is considered the "third pillar of health," and is just as important to health and well-being. However, approximately one in three adults get less than the recommended seven hours of sleep per night.[1] Insufficient sleep is associated with a range of health problems, including heart disease, stroke, obesity, type 2 diabetes, and poor mental health and cognitive functioning.[2] Additionally, poor sleep is associated with risk behaviors including tobacco, drug, and alcohol misuse.[2]

Adolescent sleep is a major public health concern and a national priority.[3] Adolescents have a physiological need for more sleep than adults.[4] However, 73% of high school students and 58% of middle school students do not get enough sleep,[5] as defined by the National Sleep Foundation (NSF)'s consensus panel recommendations for adolescent sleep duration (8-10 hours for those aged 14-17 years, and 9-11 hours for those aged 6-13 years).[4] A recent meta-analysis estimated an average school night sleep duration of seven hours among adolescents aged 12 to 18,[6] while studies have found that teenagers require 9-9.35 hours of sleep for cognitive function and attention.[7] Daytime sleepiness, fatigue, and napping are common indicators of chronic sleep deficiency among adolescents.[8] Insufficient sleep during the school week causes teenagers to sleep later and longer on weekends, which is also harmful to health.[8] Not getting enough sleep can have serious implications for teenagers' physical and mental health, safety, and learning, including cognition and academic performance.[8]

A number of biological and external factors impact teenagers' sleep, though perhaps the strongest external influence on adolescent sleep is school start times. In

contrast with teenagers' physiology that causes them to stay up later and wake later,[9] early school start times require students to wake early, cutting their sleep short. Studies of school start times have found that starting school earlier is associated with less sleep, more daytime sleepiness, and poorer academic and cognitive outcomes.[10] A host of professional and advocacy organizations have called for policy changes delaying school start times until after 8:30 a.m. to reduce barriers to adolescents obtaining sufficient sleep.[11-13] However, during the 2017-18 school year, only 17% of public high schools nationwide started after 8:30 a.m.[14] Early school start times are out-of-sync with teens' sleep needs and schedules, and delaying school start times may be a feasible and efficient way to improve adolescent sleep health.

The COVID-19 pandemic and subsequent school closures caused major disruptions to adolescent routine, including sleep habits.[15] One longitudinal study found that teenagers went to bed and woke up later, slept longer, and were less sleepy during the pandemic compared to prior.[16] These findings were confirmed by a qualitative study that found a two-hour shift towards eveningness, longer sleep duration, improved sleep quality, and reduced daytime sleepiness compared to pre-pandemic sleep.[17] However, neither study examined participants' school start times during the pandemic, which varied across school districts as schools quickly adjusted to deliver remote learning.[18]

Problem Statement

The impact of COVID-19-related school closures on adolescent sleep is not yet well understood. The impact of school start times on adolescent sleep, performance, and health has been well documented prior to the pandemic with in-person schooling, but there have been no studies examining the impact of remote learning start time on teen

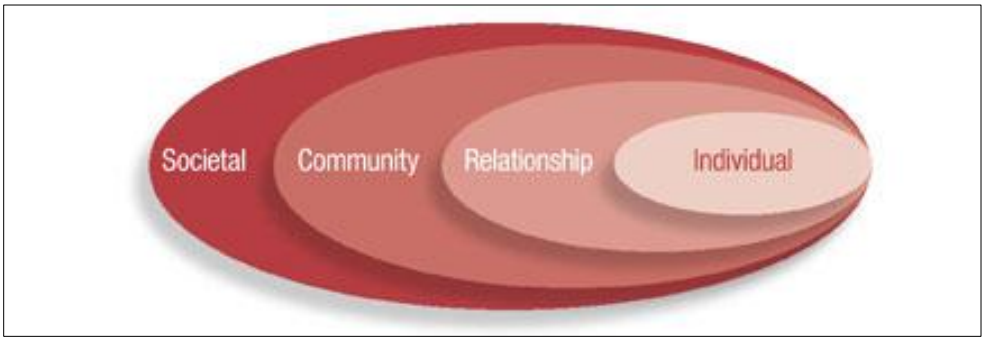
sleep during the COVID-19 pandemic. As the pandemic persists and many schools continue to rely on virtual instruction, there is a crucial need to understand what factors impact adolescent sleep duration and timing.

Theoretical Framework

The Social-Ecological Model (SEM) is a theoretical framework originally developed by Bronfenbrenner that is used to explain how a variety of factors interact to affect health and behavior.[19] The model centers the individual within their environment; each individual exists within a unique nested system of levels. The Centers for Disease Control and Prevention (CDC) uses a four-level version of the SEM highlighting factors at the individual, relationship, community, and societal levels that affect health and have implications for prevention (Figure 1).[20]

This framework is useful for identifying factors that contribute to sleep health in teenagers. The factors that cause poor sleep health in teenagers do not exist in isolation, so the SEM can help researchers understand the complex interplay between factors at various levels that can either improve or harm sleep duration, timing, and quality.[2] This model may also help practitioners develop approaches to sleep health promotion that operate both within and across levels.[2]

Figure 1. The Social-Ecological Model: A Framework for Prevention[20]



Purpose Statement

The purpose of this study is to examine the association between school start time and sleep behaviors in adolescents to assess whether later school start times are predictive of longer sleep, later bedtimes and wake times, and reduced daytime sleepiness during COVID-19-related school closures. This study will also provide descriptive data on adolescent sleep during the pandemic and will examine other predictors of adolescent sleep behaviors during COVID-19 school closures (e.g., parent-set bedtime).

Research Questions

1. How did adolescents' sleep patterns change during COVID-19-related school closures?
2. What is the relationship between school start time during COVID-19 and adolescent sleep behaviors?
3. What other factors predict adolescent sleep during COVID-19-related school closures?

Significance Statement

There is a large body of research indicating that delaying school start times can have a profound impact on adolescents' sleep.[10] However, this topic can be difficult to study in an experimental setting; only two randomized controlled trials have been conducted to date.[21] The current study adds to this literature by exploring these issues within the context of the unprecedented COVID-19 pandemic. The range of virtual learning policies and start times across school districts in the United States allows us to examine the impact of school start times on adolescent sleep through a "natural experiment." Findings can inform policies on school start timing as well as sleep health education advocacy

campaigns for parents and students, particularly as the pandemic persists and many students continue to attend virtual classes.

LITERATURE REVIEW

Adolescent Sleep Health

Adolescent sleep health is a national priority. The federal *Healthy People 2030* initiative included an objective to increase the proportion of high school students who get sufficient sleep.[3] Teenagers are the least likely of any age group to get adequate sleep, and adolescent sleep duration has decreased over the past 20 years.[22] In 2017, 74.6% of high school students completing the national Youth Risk Behavior Survey (YRBS) did not get sufficient sleep on an average school night, defined as less than nine hours for children aged 6-12 years and less than eight hours for adolescents aged 13-18 years.[23] This represents an increase of nearly two percentage points from two years prior, when 72.7% of high school students in the YRBS had short sleep duration on school nights.[5] A recent meta-analysis estimated an average school night sleep duration of seven hours among adolescents aged 12 to 18,[6] while research has found that teenagers require 9-9.35 hours of sleep for cognitive function and attention.[7] Estimates of chronic sleep deprivation among U.S. high school students range from 50-90%, depending on the definition of sleep deprivation.[22,24] As adolescents get older, sleep durations decline, and sleep timing shifts later.[25] A smaller but still troubling proportion of middle schoolers suffered from short sleep; 57.8% of middle school students in the nine states that conducted the YRBS with this age group had short school night sleep duration (as defined above) in 2015.[5]

Adolescents with short school night sleep duration accumulate sleep debt during the week and often attempt to "catch up" on sleep during the weekend, resulting in oversleep (large differences between weekday and weekend sleep durations), social jetlag

(large differences in the midpoint of weekday and weekend sleep timing), and disrupted sleep-wake cycles.[8] Daytime sleepiness, napping, and fatigue are common among adolescents, again indicating chronic sleep deficiency in this population.[8] Many studies of teen sleep have relied on self- or parent-reported measures, which typically overestimated actual sleep duration when objectively measured with actigraphy.[26,27] Thus, sleep deprivation may be an even larger problem among adolescents than is currently known. Sleep is essential to adolescent health, and not getting enough sleep can have serious repercussions for teenagers' physical and mental health, safety, and learning.

Consequences of Poor Sleep in Adolescents

This section will highlight several key health behaviors, physical, and mental health consequences of poor sleep health in adolescence.

Health Behaviors. Insufficient sleep and poor sleep patterns have been associated with a range of harmful health behaviors, including risky sexual behavior, physical fighting and weapon carrying, poor diet, and substance abuse of tobacco, alcohol, marijuana, medication, stimulants, and caffeine.[8,28-37] The relationship between sleep and health behaviors is complex and often bidirectional, with linkages between the causes and consequences of sleep deprivation. For example, alcohol use has been associated with shorter and lower quality sleep and daytime sleepiness,[38,39] and sleep deprivation has been associated with increased alcohol and drug use.[8,29,36,40] Short sleep and daytime sleepiness have been associated with decreased physical activity, increased sedentary behavior, and increased unhealthy snacking.[28,41] Moreover, short sleep has been associated with increased risk of injury, including automobile accidents, sports injuries,

and occupational injuries,[42-44] as well as with injury-related risk behaviors, including drowsy driving, drunk driving, texting while driving, and not wearing a seatbelt.[32,45]

Physical Health. Adolescent sleep deprivation, poor sleep quality, and mistiming or timing variability have been associated with adverse health outcomes, including obesity, cardiovascular disease, type 2 diabetes, metabolic and endocrine dysfunction, and poor immune function.[35,46-55] Research has identified a dose-response relationship between sleep and weight, with increased likelihood of obesity as sleep duration decreases below the recommended amount of eight hours per night.[56] Additionally, obesity may cause obstructive sleep apnea, which has been associated with reduced sleep quality and further metabolic dysregulation.[57]

Mental Health. Mental health consequences of insufficient sleep and mistiming among adolescents include poor emotional wellbeing, irritability, depression, anxiety, inattention, and diminished quality of life and social relationships.[8,28,29,35,58-60] The relationship between sleep and mental health is also bidirectional, with disturbed sleep both causing and resulting from depression.[33,61,62] Additionally, both too short and too long sleep duration have been identified as risk factors for suicidal ideation and behavior in adolescents.[63,64]

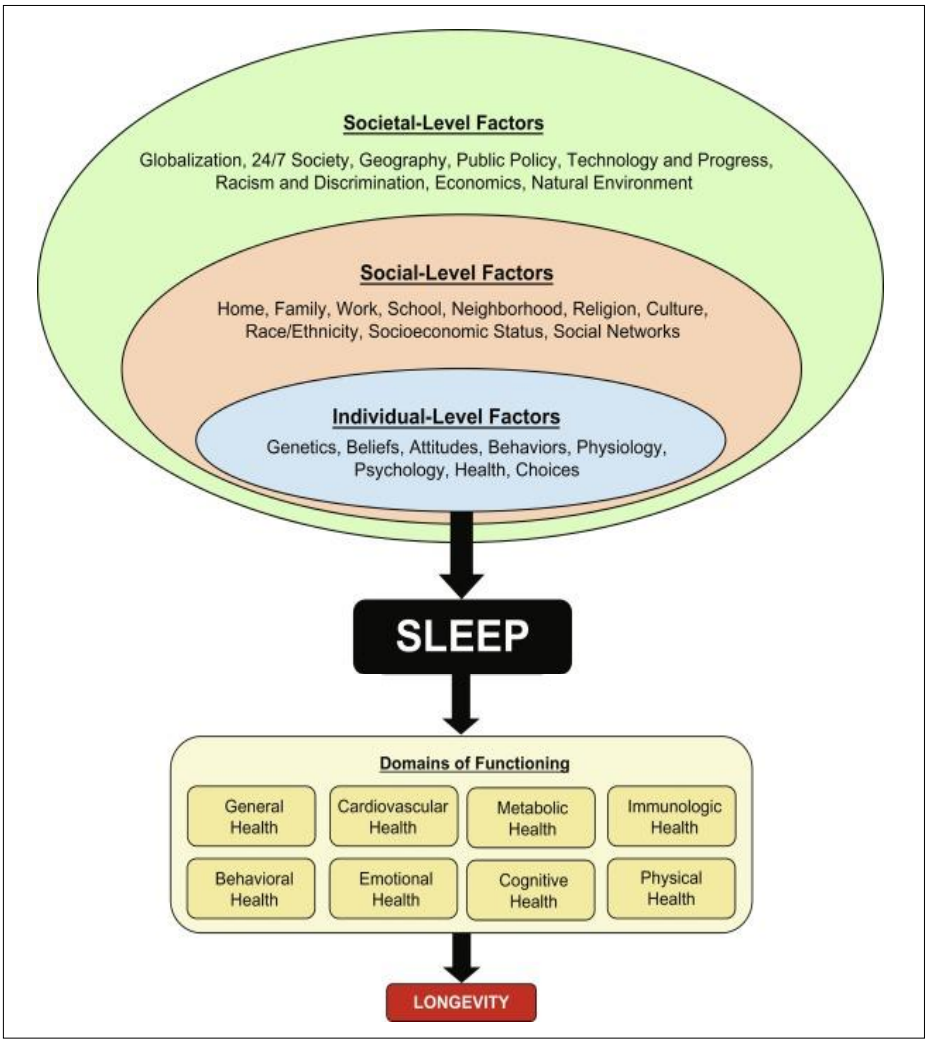
Cognitive Function and Academic Performance. Sleep deprivation in adolescents has been associated with impaired cognitive function, including decreased alertness, attention span, creativity, and working memory.[46,58,65-67] Cognitive functioning has been closely linked with academic achievement, and research has found that teenagers with insufficient, poor quality, or mistimed sleep performed worse in school.[60,66,68,69] The relationship between sleep and academic performance will be explored further in a later

section (*School Start Times and Adolescent Sleep Health*) within the context of school start time.

The Social-Ecological Model for Understanding Causes of Poor Sleep in Adolescents

The Social-Ecological Model (SEM) provides a framework for understanding the range of societal, social, and individual-level factors that impact adolescent sleep duration, timing, and quality.[2,70,71] By better understanding the risk and protective factors associated with poor sleep health in teenagers, we can more effectively design interventions to work both within and across levels of the model that target adolescents during this key stage of development. Figure 2 presents Grandner's model of how factors across levels of the SEM impact sleep and health.[2] This section will examine key factors at each level of the SEM that specifically impact teenagers' sleep and can result in poor sleep health.

Figure 2. Social-Ecological Model of Sleep Health[2]



Individual. The SEM centers around the individual, which includes biological and personal characteristics that impact sleep health. Adolescence (i.e., puberty) marks a drastic developmental shift in two biological processes regulating sleep duration and timing: the sleep-wake homeostatic system, and the 24-hour circadian timing system.[72] During the years following puberty, the homeostatic system changes so that teenagers experience less "sleep pressure" – or sleepiness – as they stay awake longer, causing delayed bedtimes, with older post-pubertal teenagers accumulating less sleep pressure

and delaying bedtimes later than younger teens. However, the rate at which sleep pressure dissipates does not change during adolescence, suggesting that teenagers' sleep needs do not change during this period.[8,72]

Adolescents going through puberty experience a shift in their central circadian clock known as phase delay. There are two primary hypotheses that explain this phenomenon. One suggests that puberty is associated with a lengthening of the circadian period to slightly over 24 hours, which can cause progressively later bedtimes and wake times. A second hypothesis suggests that increased evening light exposure or an altered circadian response to light in adolescents may cause phase delay.[8,72] Light exposure is a main driver of the circadian system; it suppresses melatonin, which causes sleepiness. Phase delay is associated with the delayed release of nocturnal melatonin, which makes it difficult for adolescents to fall asleep before 11:00 p.m. or to wake up before 8:00 a.m.[73] Delayed adolescent bedtimes and wake times are particularly clear when there are no societal constraints (see *Societal* below) such as on weekends. Delayed sleep timing and catch-up sleep on weekends – social jetlag – impacts the circadian system and may further delay the body's sleep signaling, causing poor or insufficient sleep when wake times are externally imposed.[8]

An individual's race, ethnicity, and socioeconomic status may also be associated with their sleep health. Research has identified racial/ethnic disparities in adolescent sleep duration that mirror many other health disparities, as white teenagers generally reported more sufficient sleep and earlier bedtimes than did Black and Hispanic teenagers.[74] While causal mechanisms require further investigation, discrimination has been associated with worse sleep.[75] Additionally, adolescents from families with low

income had increased risk for insufficient sleep and poor sleep quality and timing.[76] Additional research is needed to examine racial and socioeconomic disparities in adolescent sleep, including their impact on further disparities in health and academic outcomes.

A number of individual behaviors and practices related to cognition, emotional regulation, sleep environment, substance use, napping, and bedtime routine may cause poor sleep among adolescents.[77] One key behavior impacting adolescents' sleep is screen time, including use of smartphones, televisions, computers, tablets, and video games. Device use has increased dramatically in the past decade; only 41% of adolescents had their own smartphone in 2012, compared to 89% of adolescents in 2018.[78] On average, U.S. adolescents spent around 7.5 hours per day consuming electronic media, including one hour on social media.[78] However, this estimate does not include time spent learning or completing homework, which is often done using computers and other screens. Screen-based media consumption, particularly before or during bedtime hours, has been associated with delayed bedtimes and decreased sleep duration.[79,80] Screen use in bed or in the bedroom, including storing smartphones in bed or next to the bed overnight, may be particularly harmful to sleep health.[8,80] Studies have shown that teens who spend more time using their electronic devices had less time for sleep, and media keeps teenagers engaged and psychologically active later into the night, reducing their desire to fall asleep.[81,82] Additionally, light emitted from screens impacts circadian rhythms and suppressed melatonin release, causing increased alertness and delayed feelings of sleepiness and bedtimes.[83]

Caffeine consumption is another key factor that impacts adolescent sleep. Increased caffeine use – including coffee, soda, and energy drinks – has been associated with shorter sleep duration, difficulty falling and staying asleep, poorer quality sleep, earlier wake times, and increased daytime sleepiness, the last of which may cause teens to further increase their caffeine consumption.[8,84,85] Though discussed earlier as potential outcomes of insufficient sleep, tobacco and alcohol use have also been identified as risk factors for short and poor sleep, in addition to poor mental health and stress, limited physical activity, and obesity.[8,79]

Interpersonal. The second level of the SEM includes the individual's close relationships and social circle, such as friends and parents. Parent involvement can be a strong positive influence on adolescent sleep health. Parent-set bedtimes have been associated with earlier bedtimes, longer sleep duration, reduced daytime sleepiness, and reduced depressive symptoms in adolescents.[86-88] Parents also play a key role in limiting or enabling adolescents' technology use; parental rules on screen time were associated with reduced screen use and improved sleep duration.[89,90] Additionally, parental enforcement of rules on caffeine consumption were associated with longer sleep duration.[90] However, parents of older adolescents were less likely to enforce sleep-related rules than were parents of younger adolescents and children.[90]

Family stress and home environment may also negatively impact adolescent sleep.[91] Among adolescents with high family stress, greater parental support was associated with improved sleep duration and quality.[92] Peer friendships also influenced adolescent sleep, including by prompting teens to stay up late texting or hanging out with

friends.[93] Considered separately from total screen time, social media use was also an independent risk factor for short sleep duration, late bedtimes, and poor sleep quality.[94,95]

Community. The third level of the SEM, community, includes the settings and context in which teenagers live, work, socialize, and learn. As teenagers age, they are subjected to more social expectations and academic pressures. More time spent on extracurricular activities, such as sports, homework, school clubs, and part-time employment, was associated with shorter sleep duration.[88,96,97] Increased school-related pressures and academic stress were also associated with insufficient and poor quality sleep among adolescents, as they may increase bedtime rumination and cause difficulty falling and staying asleep.[98-100]

The home and neighborhood environment can cause increased exposure to disruptive sleep conditions, such as indoor and outdoor noise, light, hot or cold temperature, and electronics (e.g., television in the bedroom or devices left on during the night), that cause poor sleep health.[101] Neighborhood safety concerns were also associated with increased prevalence of sleep problems.[102] These conditions were more common in families with lower socioeconomic status and, in addition to pre-sleep worries, may have contributed to socioeconomic disparities in sleep.[101]

Societal. The fourth level of the SEM includes broader societal factors that facilitate or prevent healthy sleep. Perhaps the single largest exogenous influence on adolescent sleep is early school start times, which require teenagers to wake early in the morning – far earlier than their biological systems prompt them to – in order to attend school.[8,11] The following section will examine school start times' impact on adolescent sleep health and other key outcomes.

School Start Times and Adolescent Sleep Health

Early school start times have been associated with earlier wake times, shorter weekday sleep duration, and increased daytime sleepiness among middle and high school students.[10] Even a small delay in school start times (30 minutes) significantly increased sleep duration.[10,103] While school start time is challenging to study in an experimental setting, a systematic review of experimental studies found that that delays in school start time of 25 to 60 minutes corresponded to increased total sleep time of 25 to 77 minutes per weeknight, in addition to reduced daytime sleepiness, depressive symptoms, caffeine consumption, and tardiness.[21] A recent quasi-experimental study of changes to adolescent sleep following a 50-minute delay in high school start times in Fairfax County, Virginia found a 30.1-minute increase in sleep duration and reduced daytime sleepiness, whereas middle school students experiencing a 30-minute advance in start times experienced a 14.8-minute decrease in sleep duration and increased daytime sleepiness.[104]

Another recent observational study objectively measured sleep over two years among a cohort of high school students in Minneapolis and St. Paul, Minnesota experiencing district-initiated delays to start time. Students attending delayed-start schools (delayed by 50 and 65 minutes) slept an additional 41 minutes one year later and an additional 43 minutes two years later, when compared to students without delayed start times.[105] Notably, delayed school start times did not cause teenagers in this study to stay up later,[105] though there is no general consensus on the effect of delayed school start times on bedtimes.[106] Students with delayed start times also experienced reduced weekend sleep duration (24 minutes less at one year and 34 minutes less at two years)

relative to comparison school students, suggesting less need for catch-up weekend sleep as a result of increased weekday sleep duration.[105]

Delayed school start times have also been associated with academic and cognitive outcomes, including better attendance, reduced tardiness, decreased sleepiness during class, better grades and standardized test scores, improved motivation and attention, decreased depressive symptoms, and improved psychological health.[10,103,107-109] Moreover, research has found that disadvantaged students benefitted most from later school start times.[110] Delaying school start times has the potential to increase student achievement such that their lifetime earnings increase by an estimated $17,500 per student.[110] While there are costs associated with delaying school start times (e.g., due to changes in bussing strategies), researchers have estimated that the ratio of benefits to costs is nine to one.[110] Economists have projected that delaying middle and high school start times to 8:30 a.m. or later would improve academic performance and reduce car crash rates such that an $8.6 billion would be added to the national economy within two years, $83 billion after ten years, and $140 billion after 15 years, far outweighing costs.[111]

Delaying school start times is a cost-effective, population-level strategy to improve adolescent health and performance. However, many school districts have yet to adopt later school start times. During the 2017-18 school year, approximately 10% of U.S. public high schools started before 7:30 a.m., 32% started between 7:30-7:59 a.m., 40% started between 8:00 a.m. and 8:29 a.m., and only 17% started after 8:30 a.m.[14] In 2014, a similar proportion – 83% – of middle schools in the United States started before 8:30 a.m.; more recent data are not available.[112] Government and professional organizations including the American Academy of Pediatrics (AAP), American Medical

Association (AMA), and CDC have advocated for delaying middle and high school start times until 8:30 a.m. or later as a key policy change to improve adolescent sleep and subsequent health outcomes, including academic performance.[11-13] In 2019, California became the first state to require later middle and high school start times (no earlier than 8:00 a.m. and 8:30 a.m., respectively) by 2022.[113] Legislators in many states have tried to follow suit, including by commissioning advisory committee reports investigating the issues, benefits, and options related to instituting later start times in their states.[114,115] Many states and school districts have been resistant to implement this policy change due to concerns about transportation and bus schedules, parental supervision, sports and extracurricular activities, and after-school jobs.[116] However, adolescent sleep health is a national public health concern, and early school start times have far-reaching implications for teens, their families, and society.

Adolescent Sleep During COVID-19

The first case of the 2019 novel coronavirus (COVID-19) was detected in the United States in January 2020. COVID-19 quickly spread across the United States, and the pandemic was declared a national emergency on March 13, 2020.[117] Shortly afterwards, many states enacted mandatory stay-at-home orders and other social distancing measures such as school and business closures to reduce the spread of COVID-19.[118]

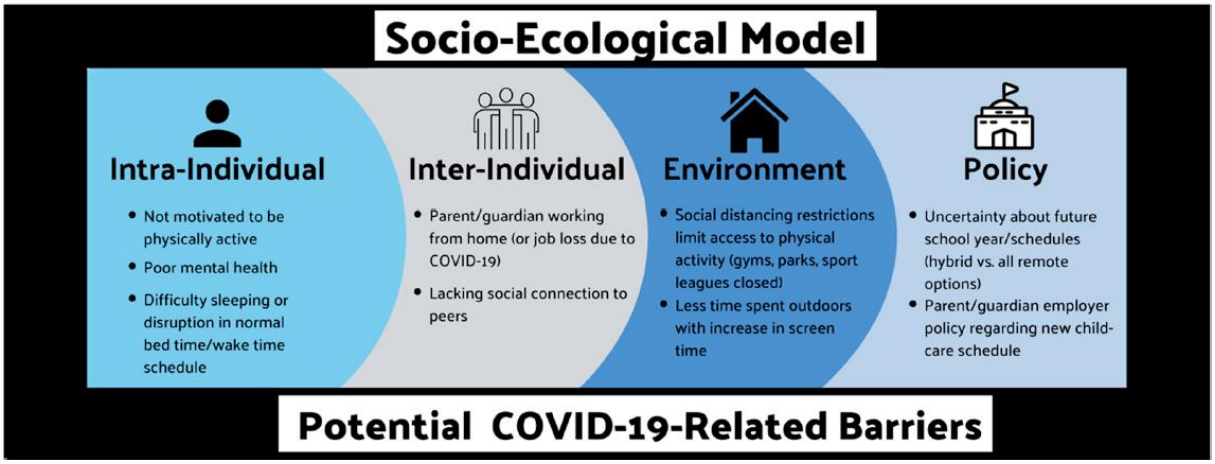
During the first few months of COVID-19 stay-at-home orders, adolescent schedules were dramatically altered. Many school districts closed beginning in early March 2020, with over half of all students in the United States impacted by school closures by March 16, 2020. By the end of March, all U.S. public school buildings were

closed. By early May 2020, nearly all states ordered schools to close for the remainder of the academic year, impacting at least 55.1 million students attending 124,000 public and private schools.[18,119]

Following school closures, most students began to receive remote instruction synchronously and/or asynchronously, with the majority of high school students spending far fewer hours on online learning than they did during a pre-pandemic regular school day.[120] Without early morning school start times, commutes, and extracurricular activities, students followed a less structured daily schedule no longer impacted by externally imposed early wake times, potentially allowing them to sleep later and longer on school days. With increased opportunity for getting sufficient sleep during the week and for sleep habits to more closely align with adolescents' circadian rhythms, students may have experienced less daytime sleepiness and less social jetlag as the need for weekend catch-up sleep was reduced.[15,70]

School closures, virtual learning, and general pandemic conditions also affected many adolescent behaviors known to impact sleep duration, timing, and quality. Bates et al. explored potential COVID-19-related barriers to healthy behaviors, including sleep, across levels of the SEM in Figure 3.[15] Some of these COVID-19-related factors are examined in more depth below.

Figure 3. Examples of Potential Barriers to Healthy Behaviors during COVID-19[15]



As teenagers remained indoors during lockdown, they may have been exposed to less natural sunlight, which is a crucial driver of circadian rhythm and sleep timing regulation.[15,121] One study of adolescent sleep during COVID-19 found that spending less time outside was associated with greater delays in bedtime and wake time during the pandemic, when compared to pre-pandemic sleep.[16] School closures also reduced opportunities for adolescents to engage in sufficient physical activity; without gym classes, sports, and pedestrian commutes, early evidence indicated that teenagers were less active during the pandemic and increased their screen time.[15,122,123] Classes that were formerly held in person shifted to remote delivery via screen, and adolescents seeking social connection turned to texting, social media, and video calls with friends. Teenagers were likely to engage in technology-related behaviors that contributed to poor sleep hygiene, such as attending remote classes in bed, spending too much non-sleep time in their bedroom, and increased device use and blue light exposure in the hour before bedtime.[15,70,124,125]

Additionally, general pandemic conditions may have caused poor mental health among adolescents. While Twenge et al. found that adolescents' mental health did not collectively suffer during the pandemic,[126] several other studies reported increased symptoms of depression, anxiety, stress, and loneliness related to the pandemic among teenagers and young adults.[120,127-131] A survey of adolescents with pre-existing mental health conditions in the United Kingdom found that 83% experienced worsened symptoms during the pandemic, and 26% were unable to access mental health support and treatment.[130] Social distancing and lockdown measures created numerous mental health risks for adolescents. Closing schools, cancelling extracurricular activities, restricting in-person gatherings with friends, and quarantine may have caused social isolation and negatively impacted mental health.[132-135] As teenagers spent more time at home with their families under stay-at-home orders, adolescent mental health may have also been impacted by home stressors such as financial difficulties, parental substance use, or domestic violence and child maltreatment.[136] As previously discussed, the relationship between mental health and sleep is complex, but consistent with evidence prior to the pandemic, teenagers who experienced depression during the pandemic were more likely to report short sleep duration.[126] Additionally, over 25% of adolescents in a nationally representative sample reported losing sleep because of pandemic-related worries.[120]

Most studies focusing on sleep during the COVID-19 pandemic have assessed sleep behaviors in adult populations. Research has documented increased sleep duration, delayed bedtimes and wake times, and poor sleep quality among adults during the pandemic, both in the United States and internationally.[137-140] One large study of individuals aged 13-74 years found that younger participants slept longer on weekdays,

had later weekday bedtimes and waketimes, and had more social jetlag during the pandemic than did older participants.[141] There has been limited published research examining changes to adolescent sleep during school closures. One study found that 84% of adolescents in a sample of 1,523 U.S. teens in May-July 2020 reported sleeping seven or more hours per night while attending school online during the pandemic, compared to only 55% of a comparable sample in 2018.[126] A qualitative study of 45 adolescents in Canada found a two-hour shift towards eveningness in pandemic sleep schedules, longer sleep duration, improved sleep quality, and reduced daytime sleepiness compared to pre-pandemic sleep.[17] A longitudinal study comparing sleep before and during the early stages of the COVID-19 pandemic among 122 10th grade students in Ohio, Kentucky, and Virginia presented the strongest evidence to date of delayed bedtimes and wake times, increased weekday sleep duration, and decreased daytime sleepiness during the pandemic. Participants reported average weekday bedtime and wake time delays of one hour and one and a half hours, respectively.[16] However, this study did not examine whether school start times changed or remained the same for students in the sample during the pandemic. As discussed previously, school start time is a major external influence on adolescent sleep behaviors, and students' varying school start times should be considered when examining changes to adolescents' sleep during school closures.

Summary of Current Problem and Study Relevance

Poor sleep health affects the health and well-being of the majority of adolescents in the United States. A substantial body of research has found that insufficient sleep is associated with a range of poor physical and mental health and academic outcomes, and has identified school start time as a major exogenous influence on adolescent sleep.

However, the impact of the COVID-19 pandemic on adolescent sleep is not yet well understood. This study leveraged the range of class start times implemented during COVID-19-related virtual learning to explore the impact of school start times on adolescent sleep health during the pandemic. While we may not experience another global pandemic anytime soon, studying adolescent sleep during COVID-19 contributes to the body of research on adolescent sleep health and school start times and allows parents, school administrators, and public health professionals to better understand and intervene upon sleep behaviors.

STUDENT CONTRIBUTION

This secondary data analysis was initially conceptualized through discussion with thesis committee member Dr. Lauren Hale, Professor of Family, Population, and Preventive Medicine at Stony Brook University. Dr. Max Van Gilder of Start School Later, New York developed the survey instrument, which was based on the validated School Sleep Habits Survey (SSHS).[142] Dr. Van Gilder collected data from 718 teenagers reached through chapters and contacts of Start School Later. Dr. Van Gilder initially examined descriptive statistics using SurveyGizmo, the online survey platform used to conduct the survey. Dr. Van Gilder oriented the student to the survey instrument, which contained survey logic so that students with different types of instruction (i.e., virtual synchronous, virtual asynchronous, or in person) would be presented with only relevant survey items.

The MPH student submitted the research proposal for approval from Emory University's Institutional Review Board (IRB), which determined that the project was exempt from review given that identifying data (IP addresses) were removed from the dataset prior to sharing. Dr. Van Gilder directly uploaded the dataset (a Microsoft Excel file) into Emory OneDrive for Business, a HIPAA-approved cloud storage provider only accessible to those explicitly granted permission by the owner of the folder (the student). The student created unique, descriptive variable names for all items in the dataset and created a dataset codebook before importing the data into SAS 9.4. The student deleted all partial survey completes from the dataset and performed data cleaning including converting text variables to numeric variables, storing bedtimes and wake times in SAS

datetime format, and combining variables across survey skip patterns. A detailed description of variable recoding performed by the student is included below.

Recoding

The MPH student recoded select response options for sleep duration, timing, and sleepiness variables where necessary. “More than 11 hours” of reported sleep duration (total sleep time [TST]) was recoded to 11.5 hours, as other response options ranged from four to 11 in 30-minute increments. A wake time of “5:00 a.m. or before” was recoded to 5:00 a.m., and “1:00 p.m. or later” was recoded to 1:00 p.m. Similarly, a bedtime of “9:00 p.m. or before” was recoded to 9:00 p.m., and “3:00 a.m. or later” was recoded to 3:00 a.m. The item on changes to sleep duration during school closures was recoded into two categories: increased sleep duration during school closures, and no increase in sleep duration during school closures. The five-level item on daytime sleepiness was recoded into three categories: no problem at all, a little problem, and more than a little problem (including those who reported sleepiness as a big problem or a very big problem). Items on sleepiness during school-related activities (e.g., online class) were recoded into dichotomous variables (yes/no). Additionally, reported bedtimes and wake times were used to calculate a second measure of sleep duration (time in bed [TIB]), and reported wake times pre- and post-school closures were used to calculate intra-individual change in wake time.

The MPH student also recoded other predictor variables included in regression models. The “select all that apply” race/ethnicity survey item was recoded into a variable with the categories Hispanic, non-Hispanic Black/African American, non-Hispanic white, non-Hispanic Asian, and non-Hispanic multiracial/other. Hispanic participants could be

of any race. The other/multiracial group included those who responded that they were Native American/Pacific Islander, selected more than one race, or selected "Other" and supplied an open-ended response. These categories were combined due to small sample sizes. Open-ended responses to this item were reviewed and recoded into other racial categories as the student deemed appropriate.

The grade variable was recoded into three categories: middle school (6-8th grade), early high school (9-10th grade), and late high school (11-12th grade). Participants outside of grades 6-12 were removed from the dataset (n=4). Individuals reporting a gender identity other than male or female (non-binary, prefer not to state, or other) were removed from the dataset due to small sample sizes (n=30 across the three response options). SurveyGizmo also identified a small number of individuals as taking the survey from outside the United States (n=9); these individuals were excluded as well. Finally, those students attending schools that were open (n=40) or were closed and not providing instruction (n=20) during the pandemic were excluded from analysis to allow for meaningful comparison of class start times across participants.

Additionally, the item on changes in caffeine consumption during school closures was recoded into four levels: less caffeine intake during school closures; about the same caffeine intake during school closures; more caffeine intake during school closures; and no use of caffeine now and have not used in the past. A survey item asking participants to specify the main reason they go to bed at a particular time on weekends was coded into a variable on parent-set bedtime, with those who selected "my parents have set my bedtime" recoded as "yes" and those who selected any other response option recoded as

"no." Finally, earliest live class start time was recoded into the following categories: 7:30-8:15 a.m., 8:30-9:00 a.m., 9:15 a.m. or later, and no designated start time.

Analysis

As the first step of this study, the MPH student conducted descriptive analyses to examine trends in sleep behavior during the pandemic across grade categories. The MPH student calculated frequencies and proportions for categorical variables (e.g., daytime sleepiness) and calculated means, standard deviations, and medians for continuous variables (e.g., sleep duration), both for the total sample and stratified by grade category. ANOVA and chi-square tests were used to assess significant differences in sleep variables between the three grade categories, and the student designed and completed the data output table for these data.

The manuscript was initially conceptualized as a Brief Report for the journal *Sleep Health*. Additional students involved in the manuscript – Cassandra Bryan and Devon Olson – initially estimated seven multivariate models, including six linear regression models and two logistic regression models, and designed and completed the data output table for these models. The MPH student led the development of all aspects of the Brief Report manuscript, including conducting a literature review, writing all sections, managing revisions, and submitting to the journal.

Due to space constraints imposed by the journal, additional analyses were not able to be included for publication. However, for the thesis project, the MPH student built on the models initially estimated by Devon and Cassandra by developing an eighth model (daytime sleepiness), testing for statistical interaction in each model, and subsequently stratifying and re-estimating each model by grade category. The MPH student then

revised the Brief Report manuscript to reflect the updated results of the stratified models, as well as additional literature review, methods, and discussion. Therefore, the manuscript that appears in this report does not reflect the version submitted for publication.

Thesis committee chair Dr. Julie Gazmararian and committee member Dr. Lauren Hale provided insight and mentorship throughout the process, including regular check-in meetings, guidance on appropriate variables to include in the model, input on table shells and data presentation, and revisions to manuscript and chapter drafts. Dr. Barbara Rosati, Dr. Max Van Gilder, Cassandra Bryan, and Devon Olson also contributed insight and feedback on manuscript drafts throughout the process. Dr. Hale also provided suggested journals for manuscript submission. As previously stated, the journal for first manuscript submission is *Sleep Health: Journal of the National Sleep Foundation*. While the manuscript already submitted to *Sleep Health* follows their Brief Report format, the following manuscript is presented as an Original Research Article.

JOURNAL ARTICLE

Adolescent Sleep Duration and Timing During Early COVID-19 School Closures

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Word Count: 4,369

Abstract

Objectives: The purpose of this study is to investigate adolescent sleep and changes in sleep patterns during COVID-19-related school closures in the United States. This study also examines the association between class start time and adolescent sleep behaviors during school closures.

Design: Cross-sectional.

Setting: Online survey administered in May/June 2020.

Participants: Analytic sample included 590 adolescents (grades 6-12) attending remote classes in 35 U.S. states.

Measurements: Bedtimes, wake times, sleep duration, sleep quality and problems, sleepiness, and other sleep behaviors; class start times; caffeine use; and demographics.

Results: Students woke up later during school closures and averaged 7.9-8.7 hours of sleep and 8.6-9.5 hours in bed on school nights. Compared to middle schoolers, high school students had later bedtimes and wake times, accompanied by spending less time in bed and less time sleeping. High school students also reported a greater delay in wake time (2.9 hours) than did middle schoolers (2.1 hrs). High school students with later class start times went to bed later, but also woke up later, slept longer, and spent more time in bed than those with earlier start times. When comparing intra-individual sleep pre- and post-school closures, later class start times resulted in greater delays in wake time and greater odds of increased sleep duration among high schoolers. Later class start times were also significantly associated with decreased odds of daytime sleepiness in high schoolers and with less sleepiness during online class.

Conclusions: COVID-19-related school closures and remote instruction allowed students to sleep later and longer. As a consequence, more middle and high school students achieved recommended amounts of sleep, primarily by waking up later in the morning. Students with earlier synchronous class start times slept less and had smaller changes in their weekday wake times during COVID-19 school closures, confirming other researchers' findings that school start time is a strong external influence on adolescent sleep behaviors. The implications of this study extend beyond COVID-19 school closures; adolescent sleep health improves with later school start times and fewer scheduled morning activities.

Keywords: adolescents, COVID-19, school start time, sleep health, school closures

Introduction

Sleep health for adolescents is a national priority.[3] Short sleep duration in this age group is associated with poor physical health, mental health, and academic performance.[8] The National Sleep Foundation (NSF) has recommended that children aged 6-13 years get nine to 11 hours of sleep per night, teenagers aged 14-17 years get eight to ten hours of sleep per night, and adults aged 18 and older get seven to nine hours of sleep per night.[4] However, less than 30% of teens reported sufficient nightly sleep before the COVID-19 pandemic due to physiological factors (e.g., pubertal phase delay), behavioral factors (e.g., screen time, caffeine use), and environmental constraints (e.g., early high school start times).[5,23] In 2017, 74.6% of high school students completing the national Youth Risk Behavior Survey (YRBS) did not get sufficient sleep on an average school night,[23] representing a nearly 2% increase from only two years prior, when 72.7% of high school students in the YRBS had short sleep duration on school nights.[5] A recent meta-analysis estimated an average school night sleep duration of seven hours among adolescents aged 12 to 18,[6] while research has found that teenagers require 9-9.35 hours of sleep for cognitive function and attention.[7] Estimates of chronic sleep deprivation among U.S. high school students range from 50-90%, depending on the definition of sleep deprivation.[22,24] As adolescents get older, sleep durations decline, and sleep timing shifts later.[25] A smaller but still troubling proportion of middle schoolers suffer from short sleep; 57.8% of middle school students in the nine states that conducted the YRBS with this age group had short school night sleep duration in 2015.[5]

Perhaps the largest exogenous influence on adolescent sleep is early school start times, which require teenagers to wake early in the morning – far earlier than their

biological systems prompt them to – in order to attend school.[8,11] Early school start times are associated with earlier wake times, shorter weekday sleep duration, and increased daytime sleepiness among middle and high school students.[10,143] A recent quasi-experimental longitudinal study found that students attending delayed-start schools (delayed by 50 and 65 minutes) slept an additional 41 minutes one year later and an additional 43 minutes two years later, when compared to students without delayed start times.[105] Notably, delayed school start times were not associated with delayed weeknight bedtimes,[105] though there is no general consensus on the effect of school start time on bedtimes.[106] Delayed school start times are also associated with academic and cognitive outcomes, including better attendance, reduced tardiness, decreased sleepiness during class, better grades and standardized test scores, improved motivation and attention, decreased depressive symptoms, and improved psychological health.[10,103,107-109]

Many professional organizations, including the American Academy of Pediatrics (AAP), have advocated for delaying middle and high school start times until 8:30 a.m. or later as a key policy change to improve adolescent sleep and health and education outcomes.[11] However, many school districts have not adopted later start times; in 2017-18, only 17% of high schools started after 8:30 a.m.[14]

During the first few months of the COVID-19 pandemic, nearly all school districts across the United States closed, dramatically altering the schedules of at least 55.1 million teens.[119] Schools' transition to virtual learning removed a major constraint on teens' wake times and affected adolescents' behaviors associated with sleep duration, timing, and quality, such as increased screen time and reduced daily structure, physical activity, exposure to natural light, and mental health.[15,70,124,126,127,130] Early evidence

demonstrated that teens were getting more sleep during the pandemic. One study found that 84% of adolescents reported sleeping seven or more hours per night while attending school online during the pandemic, compared to only 55% of a comparable sample in 2018.[126] A longitudinal study comparing sleep before and during the COVID-19 pandemic among 122 adolescents found delayed weekday bedtimes (1 hour) and wake times (1.5 hours), increased weekday sleep duration, and decreased daytime sleepiness during the pandemic;[16] a cross-sectional study conducted in Italy reported significant delays in bedtimes and wake times as well.[144] Additionally, a qualitative study of adolescents found a two-hour shift towards eveningness in pandemic sleep schedules, longer sleep duration, improved sleep quality, and reduced daytime sleepiness compared to pre-pandemic sleep.[17] However, these studies did not examine whether school start times changed or remained the same for students in the sample during the pandemic, despite prior evidence on school start times' influence on adolescent sleep.[10]

Healthy sleep is particularly important during the COVID-19 pandemic to help adolescents cope with stress, maintain focus, and engage in online classes. In this manuscript, we provide descriptive data on adolescent sleep during COVID-19-related school closures, as well as self-reported changes in sleep patterns. We hypothesized that with the disruption of established morning schedules, students' wake times would be later during school closures and sleep duration would be longer compared to pre-pandemic sleep patterns. This study also reports on other predictors of adolescent sleep behaviors during COVID-19 school closures, including class start time. We hypothesized that students with later class start times would report longer sleep duration and time in bed and later wake times compared to students with earlier class start times.

Methods

Study Design and Participants

A cross-sectional, anonymous online survey was distributed via email and social media to a convenience sample of middle and high school students (grades 6-12) through a network of local Start School Later chapters across the United States.[145] Chapter leaders were given a one-page explanatory flyer with a survey link to distribute widely to local parents, and recipients were encouraged to share the survey with other interested students. The survey was open from May 7 to June 30, 2020. The instrument was adapted from the School Sleep Habits Survey, a validated instrument used to assess sleep/wake habits and daytime functioning of school aged-children and adolescents.[142] The survey was administered electronically in approximately 15-20 minutes using SurveyGizmo (now Alchemer).[146]

Because this study only uses retrospective, de-identified data, it was determined as 'exempt' from review by the Emory University and Stony Brook University Institutional Review Boards.

Measures

Outcome Measures: Sleep

This study examined seven outcomes: weeknight sleep duration, weeknight time in bed (TIB), bedtime, wake time, and daytime sleepiness during school closures, and changes in wake time and sleep duration from pre- to post-school closures. Participants reported bedtimes and wake times in response to three questions: (1) “What time do you usually go to bed on days you have instruction?” (2) “What time do you usually wake up on days you have instruction?” and (3) “Before school was closed down, what time did

you wake up to go to school most school days?" Response options for bedtimes ranged from ≤9:00 p.m. to ≥3:00 a.m., and wake times ranged from ≤5:00 a.m. to ≥1:00 p.m., in 15-minute increments. Change in wake time was calculated as the difference between self-reported weekday wake time pre-school closure and post-school closure.

TIB was calculated as the difference between self-reported weekday bedtimes and wake times. Sleep duration was measured by the question: "How many hours of sleep do you usually get on a typical night when you have had instruction during the day?" Response options ranged from four hours to 11 hours in 30-minute increments. Change in sleep duration was determined by the following question: "Since school has been closed, how is your sleep?" In response, students reported whether their sleep duration was less than, the same as, or more than pre-school closures.

Daytime sleepiness was measured by the question: "During your daytime activities, how much of a problem do you have with sleepiness (feeling sleepy, struggling to stay awake)?" Response options ranged from no problem at all to a very big problem, and the variable was recoded from five levels into three (no problem; a little problem; more than a little problem). Four items on recent sleepiness during school activities (e.g., during online class) and three items on the impact of sleepiness on school activities (e.g., falling asleep in morning class) were recoded as yes/no for analysis.

Covariates

Participants reported their gender identity, race/ethnicity, grade, difficulty falling or staying asleep, change in caffeine use, existence of a parent-imposed bedtime, and the time of their earliest synchronous (live) class. Individuals reporting a gender identity other than male or female were excluded from analysis due to small sample sizes.

Race/ethnicity was coded as non-Hispanic white, non-Hispanic Black, Hispanic, non-Hispanic Asian, and non-Hispanic other, which included multiracial students and those who did not provide their race/ethnicity. Grade was categorized into middle school (grades 6-8), early high school (grades 9-10), and late high school (grades 11-12). Options for school closure status included open (with regular or limited class schedule), closed with instruction (synchronous, asynchronous, or a combination of the two), and closed with no instruction. This manuscript includes only those students who attended schools that were closed and providing instruction at the time of the survey.

Participants reported how often they experienced trouble going to sleep or staying asleep in the past two weeks (never, once, twice, several times, or every day/night). Change in caffeinated beverage consumption was categorized as no caffeine use, using more caffeine during school closures, and using less caffeine during school closures. Participants noted the existence of a parent-set bedtime in response to a question on their reason for going to bed (response option: “My parents have set my bedtime”). Earliest live class time was categorized as before 8:30 a.m., 8:30-9:00 a.m., 9:15 a.m. or later, and no designated start time.

Country of residence was obtained from Alchemer’s location data, and individuals taking the survey from outside the United States were excluded from analysis.

Statistical Analyses

Descriptive statistics (means, standard deviations, frequencies, and proportions) were examined for the full sample as well as by grade category (middle school, early high school, or late high school). One-way ANOVA and chi-square tests were performed to assess statistically significant differences in sleep outcomes by grade category.

Additionally, chi-square tests were conducted to determine whether sleepiness during school activities differed by school start time.

Analyses included seven multivariate regression models (M) estimating the relationship between school start time and sleep outcomes. Five continuous outcome variables (bedtime [M1], wake time [M2], sleep duration [M3], TIB [M4], and change in wake time [M6]) were assessed using ordinary least squares regression. Binary logistic regression was used to examine one dichotomous variable, increase in sleep duration vs. no increase (M7), and ordinal logistic regression was used to examine one three-level categorical outcome: daytime sleepiness during school closures (no problem; a little problem; more than a little problem) (M5), with results reported as odds ratios (ORs). First, the models tested whether the relationship between school start time and sleep outcomes varied by grade category by including a school start time by grade category interaction in the model. The interaction was significant in five of the seven models (significant interaction was present for all sleep outcomes except weeknight bedtime and daytime sleepiness). All models were stratified by grade category (middle school, early high school, and late high school) for consistency and to allow examination of the relationships between school start time and sleep within each group.

For all analyses, models adjusted for participants' gender, race/ethnicity, difficulty falling or staying asleep, change in caffeine use, reporting a parent-imposed bedtime, and earliest start time for a live class. All regression models assessed statistical significance for each predictor at the alpha 0.05 level. The linear regression models met assumptions of normality and displayed no heteroscedasticity. None of the predictors met conditions for collinearity, which was assessed using variance inflation factors (VIF values greater

than five indicated possible collinearity). All data were analyzed in SAS 9.4 (SAS Institute, Cary NC).

Results

Demographics

Analyses include data from 590 middle and high school students (grades 6-12) in 35 U.S. states who were attending remote schooling (Table 1). The average age of the sample was 15.0 years (SD 1.9 years). Participants were fairly evenly divided between grade categories, with 201 (34.1%) in 6-8th grade, 201 (34.1%) in 9-10th grade, and 188 (31.8%) in 11-12th grade. The majority of participants were female (58.8%). Most participants were non-Hispanic white (71.5%); 10.3% were non-Hispanic Asian, 9.5% were Hispanic, 5.3% were multiple or other race, and 3.6% were non-Hispanic Black.

Approximately 9.0% of the sample had synchronous classes, 18.8% percent had asynchronous classes, and 73.2% percent had a combination of the two. During school closures, participants' synchronous class start times varied, with 17.1% starting before 8:30 a.m., 20.2% starting between 8:30-9:00 a.m., 35.6% starting at 9:15 a.m. or later, and 27.1% with no designated start time (including those without synchronous classes). While 19.5% of the total sample had a parent-set bedtime, this varied across grade levels; 37.8% of middle school students, 14.9% of early high school students, and 4.8% of late high school students had parent-set bedtimes. The proportion of caffeine users varied by grade level as well (47.8% of middle schoolers, 54.2% of early high schoolers, and 61.7% of late high schoolers). Additionally, 65.1% of participants reported trouble going to sleep or staying asleep in the past two weeks, with 38.0% reporting this experience several times or every night.

Sleep During COVID-19-Related School Closures

Across the entire sample, average weekday sleep duration during school closures was 8.2h±1.5h, and average TIB was 9.0h±1.5h (Table 2). Middle school students reported longer mean sleep duration (8.7h) and TIB (9.5h) than did high school students (8.0h sleep duration and 8.9h TIB among 9-10th graders; 7.9h sleep duration and 8.6h TIB among 11-12th graders) ($p<0.0001$). Approximately 60.7% of 6-8th graders, 60.2% of 9-10th graders, and 67.0% of 11-12th graders reported sufficient weeknight sleep duration based on age-specific recommendations (9+ hours per night for those aged 6-13 years; 8+ hours for 14-17 years; 7+ hours for 18+ years),[4] while 76.1%, 75.6%, and 79.8% of each group respectively reported sufficient weeknight TIB. The proportion of students reporting sufficient sleep duration and TIB did not significantly differ across grade categories ($p=0.3052$ and $p=0.5690$ respectively). Nearly four out of five participants (79.0%) reported an increase in sleep duration during school closures, with significantly more high schoolers reporting increased sleep duration than middle schoolers; 66.7% of 9-10th graders, 85.1% of 9-10th graders, and 85.6% of 11-12th graders reported increased sleep duration ($p<0.0001$).

On weekdays during school closures, the average participant went to bed at 11:58 p.m. Students reported rising early prior to the pandemic (mean of 6:20 a.m.) and reported later wake times during school closures (mean of 8:58 a.m.). On average, middle school students went to bed earlier (11:03 p.m.) and woke up earlier (8:32 a.m.) during school closures than did high school students (12:16 a.m. and 9:09 a.m. for 9-10th graders; 12:38 a.m. and 9:13 a.m. for 11-12th graders) ($p<0.0001$).

On average, students reported waking 2.6h (±1.6h) later during school closures compared to their pre-pandemic wake times, with high schoolers reporting a greater delay in wake time (2.9h) than middle schoolers (2.1h) ($p<.0001$). The vast majority of participants (93.5%) reported a delay in wake times during school closures, and nearly three quarters (74.2%) reported a delay in bedtimes during school closures.

Two-thirds of participants (66.1%) reported feeling sleepy or struggling to stay awake during the daytime. Nearly half (49.3%) reported a little problem with daytime sleepiness, and 16.8% of participants reported more than a little problem with daytime sleepiness. Though a smaller proportion of middle schoolers reported any daytime sleepiness (60.2% of middle schoolers, compared to 69.1% of high schoolers), daytime sleepiness did not significantly vary across grade categories ($p=0.2532$). Additional details on sleep behaviors during COVID-19-related school closures can be found in Table 2.

Multivariate Models

To examine predictors of adolescent sleep during school closures, four linear regressions were run with the following outcomes: (M1) weekday bedtime during school closures, (M2) weeknight wake time during school closures, (M3) weeknight sleep duration during school closures, and (M4) weeknight TIB during school closures. Additionally, one ordinal logistic regression modeled three levels of daytime sleepiness during school closures (M5) (Table 3). To examine changes in adolescent sleep from pre- to post-school closures, two models were performed, including one linear regression examining change in weekday wake time (M6) and one logistic regression modeling increased sleep duration vs. no increase (M7) (Table 4). All models were stratified by

grade category (middle school, early high school, and late high school). All associations described below are significant at the $p<0.05$ level; additional information on p-values can be found in Table 3 and Table 4 and confidence intervals are available upon request.

Class Start Times. Later class start times were not significantly associated with sleep outcomes among middle school students, but were significantly associated with many sleep outcomes among high schoolers. Among those in grades 9-10, participants with synchronous class start times between 8:30-9:00 a.m. reported an additional 58 mins of sleep duration and 46 mins of TIB on average during school closures, and had 5.6 (95% CI: 1.4-22.5) times the odds of reporting an increase in sleep during school closures, compared to those starting class before 8:30 a.m. Starting class between 8:30-9:00 a.m. was not significantly associated with sleep outcomes in other models.

Starting synchronous class after 9:00 a.m. was significantly associated with all sleep outcomes in high schoolers. On average, those in 9-10th grade with start times after 9:00 a.m. woke 82 mins later, slept 82 mins longer, and reported 64 mins of additional TIB on weekdays/nights during school closures compared to those starting before 8:30 a.m. Those in 11-12th grade with start times after 9:00 a.m. woke 114 min later, slept 51 mins longer, and reported 56 mins of additional TIB compared to those starting before 8:30 a.m. When comparing intra-individual wake times pre- to post-school closures, 9-10th graders starting after 9:00 a.m. delayed their wake time by an additional 72 mins and 11-12th graders starting after 9:00 a.m. delayed their wake time by an additional 91 mins, compared to their counterparts starting before 8:30 a.m. Additionally, 9-10th grade students starting after 9:00 a.m. had reduced odds of daytime sleepiness (OR: 0.30; 95% CI: 0.13-0.69) and higher odds of reporting increased sleep duration pre- to post-school

closures (OR: 7.2; 95% CI: 2.0-26.9) compared to those starting before 8:30 a.m. In the majority of models reported above, effect sizes and odds ratios were similar or even larger when comparing those without a designated class start time to those starting before 8:30 a.m. (see Table 3 and Table 4 for details).

Compared to those starting class earlier in the morning, 11-12th graders with later class start times had delayed weeknight bedtimes. Those starting class after 9:00 a.m. reported going to bed 58 mins later and those without a designated class start time reported going to bed 63 mins later, on average, than those starting class before 8:30 a.m. There were no other significant associations between bedtime and school start time.

Parent-Set Bedtimes. Having a parent-set bedtime was significantly associated with most sleep outcomes among middle school students. On average, middle schoolers with parent-set bedtimes went to bed 89 mins earlier, woke up 35 mins earlier, slept 51 mins longer, and reported 55 mins additional TIB during school closures compared to those without parent-set bedtimes. Middle school students with parent-set bedtimes also reported a smaller change in pre- to post-school closure wake time (28 mins less) compared to those without parent-set bedtimes. Parent-set bedtimes were also significantly associated with earlier bedtimes in high schoolers (73 mins earlier among 9-10th graders, 74 mins earlier among 11-12th graders) and with longer TIB (43 additional mins) in 9-10th graders. There were no other significant associations between parent-set bedtimes and sleep outcomes.

Other Predictors. In one model (M3), Hispanic and non-Hispanic Black 9-10th grade students reported shorter sleep duration (51 mins and 74 mins less, respectively) than white students. Gender was not significantly associated with sleep outcomes.

Caffeine use was associated with sleep outcomes among middle schoolers, including later bedtimes and wake times, shorter sleep duration and TIB, increased odds of daytime sleepiness, and a larger delay in weekday wake time from pre- to post-school closures. In 6-8th and 11-12th graders, frequent trouble falling or staying asleep in the past two weeks was significantly associated with later bedtimes and shorter sleep duration, and in 9-10th graders, was significantly associated with later wake times and a greater pre- to post-school closure change in wake times. Additionally, trouble sleeping was associated with increased odds of daytime sleepiness in all grade categories (see Table 3 and Table 4 for additional details).

Sleepiness During School-Related Activities. Chi-square tests identified significant differences in the proportion of students who reported difficulty staying awake or falling asleep during online class by class start time (p=0.0004) (Table 5). One-third (33.7%) of students starting before 8:30 a.m. experienced sleepiness during online class, compared to 21.9% of those starting between 8:30-9:00 a.m., 15.2% of those starting after 9:00 a.m., and 14.4% of those with no designated class start time. Additionally, a larger proportion of students with earlier class times arrived late to class due to oversleeping (p=0.0043), and a larger proportion fell asleep in online morning class (p=0.0194) compared to those with later class start times (Table 6). There were no significant differences in sleepiness while doing homework or taking a test online, or in falling asleep during afternoon online class, by students' earliest class start time.

Discussion

With the closing of in-person schooling, students woke up later and slept longer. Bedtimes and wake times were progressively later with higher grades, consistent with

circadian rhythm changes with age.[9] School closures had a larger effect on high schoolers than middle schoolers, with over 85% of high school students reporting increased sleep duration since COVID-19 and a mean delay in weekday wake time of 2.9 hours.

The delay in wake time reported by study participants (2.1-2.9 hours) exceeds that found by Becker et al. (1.5 hours), perhaps because students enrolled in the latter study did not experience delays in school start time.[16] Sleep duration ranged from a mean of 8.7 hours for middle schoolers, 8.0 hours for 9th and 10th graders, and 7.9 hours for 11th and 12th graders, while mean TIB was 9.5 hours, 8.9 hours, and 8.6 hours respectively. Only 39.3% of middle schoolers and 36.5% of high schoolers reported insufficient sleep during school closures, compared to 57.8% and 72.7% respectively among students taking the YRBS prior to the pandemic.[5] These findings are consistent with those of Becker et al., as only 36% of their sample of 10th graders reported insufficient sleep during COVID-19.[16] A large proportion of participants reported difficulty falling and staying asleep, consistent with other research on adult and adolescent sleep during COVID-19[16,139] and potentially reflecting increased stress and worries during the pandemic.

High school students with earlier synchronous class start times woke earlier, slept less, reported less TIB, and had increased odds of daytime sleepiness during COVID-19-related school closures. High schoolers with earlier start times were less likely to report an increase in sleep duration during school closures and reported smaller changes in their weekday wake times than those starting class later, confirming other researchers' findings that school start time is a strong external influence on adolescent sleep behaviors.[105,147,148]

Consistent with the AAP's recommendation that middle and high schools start classes at 8:30 a.m. or later to improve adolescent sleep,[11] this study found significantly

longer sleep durations among high school students starting at 8:30 a.m. or later compared to those starting prior to 8:30 a.m. Findings also suggest that starting high school after 9:00 a.m. is associated with additional sleep benefits, including later wake times, longer sleep duration, more time in bed, and reduced daytime sleepiness. Although the AAP also recommends that middle schools start at 8:30 a.m. or later, this study did not identify differences in sleep behaviors among middle schoolers starting class later, suggesting that high schools should be prioritized for delayed start times. This study also corroborates other mixed findings on the impact of school start times on bedtimes,[10] as older high schoolers starting class after 9:00 a.m. reported later bedtimes, but other students did not. Findings on the association between delayed school start times and decreased daytime sleepiness warrant further investigation into whether improved sleep may lead to improved academic performance during the pandemic, as has been found in other studies of school start time.[10]

The data are also consistent with previous literature on the impact of parent involvement in regulating adolescent sleep habits, particularly among younger adolescents.[87] Middle school students with parent-set bedtimes went to bed and woke up earlier and reported longer sleep duration and TIB during school closures, and high school students with parent-set bedtimes also reported significantly earlier bedtimes. The effect of parental involvement in bedtime and sleep duration is particularly notable given teens' reduced daily structure during COVID-19-related closures.

COVID-19 school closures afforded a unique opportunity to study adolescent sleep, as the pandemic disrupted long-established patterns and practices such as early school start times, bus pickups, commutes, and morning extracurricular activities. During

the pandemic, adolescents – particularly high schoolers with later school start times – were able to delay their sleep timing to more closely align with their circadian rhythm and increase their sleep duration to get recommended amounts of sleep, primarily by delaying wake times. Studies have also identified delayed sleep timing in adults during this time period,[137,149] which may have contributed to delayed adolescent sleep timing as well. Results provide further evidence that adolescents should begin morning activities substantially later than is the case in most school districts. Findings can inform policies on school start timing as well as sleep health education advocacy for parents and students, especially in those school districts that have not adopted later school start times. As many students continue to learn remotely during the pandemic and schools consider new options for instruction following the pandemic, future research should investigate the impact of remote learning on adolescent sleep and subsequent health and educational outcomes.

This study's strengths include its geographic diversity and its use of a validated instrument slightly modified to fit these unusual circumstances. Limitations include its cross-sectional design, which did not allow for collection of data on bedtimes, sleep duration, and TIB prior to school closures, and its reliance on self-reported sleep measures, which may be subject to recall bias. The majority of students were non-Hispanic white and female, which may hinder generalizability.

Acknowledgments

The authors would like to thank Start School Later Local Chapter Leaders for their help with disseminating the survey.

Tables

Table 1. Sample Demographics, by Grade Category

Variables	Full Sample n=590	Middle School (6-8th grade) n=201	Early High School (9-10th grade) n=201	Late High School (11-12th grade) n=188
	N (%)	N (%)	N (%)	N (%)
Age, Mean (SD)	15.0 (1.9)	12.9 (0.9)	15.2 (0.8)	17.1 (0.7)
Gender				
Male	243 (41.2%)	96 (47.8%)	70 (34.8%)	77 (41.0%)
Female	347 (58.8%)	105 (52.2%)	131 (65.2%)	111 (59.0%)
Race				
Asian, NH^	61 (10.3%)	9 (4.5%)	37 (18.4%)	15 (8.0%)
Black, NH	21 (3.6%)	7 (3.5%)	7 (3.5%)	7 (3.7%)
Hispanic	56 (9.5%)	14 (7.0%)	15 (7.5%)	27 (14.4%)
White, NH	421 (71.4%)	156 (77.6%)	136 (67.7%)	129 (68.6%)
Multiple/other, NH	31 (5.3%)	15 (7.4%)	6 (3.0%)	10 (5.3%)
Earliest synchronous class time				
Before 8:30 a.m.	101 (17.1%)	28 (13.9%)	39 (19.4%)	34 (18.1%)
8:30-9:00 a.m.	119 (20.2%)	51 (25.4%)	38 (18.9%)	30 (16.0%)
After 9:00 a.m.	210 (35.6%)	63 (31.3%)	62 (30.9%)	85 (45.2%)
No set start time	160 (27.1%)	59 (29.4%)	62 (30.9%)	39 (20.7%)
Parent-set bedtime				
Yes	115 (19.5%)	76 (37.8%)	30 (14.9%)	9 (4.8%)
No	475 (80.5%)	125 (62.2%)	171 (85.1%)	179 (95.2%)
Trouble going or staying asleep (past 2 weeks)				
Never	206 (34.9%)	77 (38.3%)	76 (37.8%)	53 (28.2%)
Once	74 (12.5%)	33 (16.4%)	17 (8.5%)	24 (12.8%)
Twice	86 (14.6%)	23 (11.4%)	37 (18.4%)	26 (13.8%)
Several times	164 (27.8%)	52 (25.9%)	52 (25.9%)	60 (31.9%)
Every day/night	60 (10.2%)	16 (8.0%)	19 (9.5%)	25 (13.3%)
Change in caffeine consumption during school closures				
No caffeine use	269 (45.6%)	105 (52.2%)	92 (45.8%)	72 (38.3%)
More caffeine use	278 (13.2%)	25 (12.4%)	27 (13.4%)	26 (13.8%)
Same caffeine use	127 (21.5%)	50 (24.9%)	32 (15.9%)	45 (23.9%)
Less caffeine use	116 (19.7%)	21 (10.5%)	50 (24.9%)	45 (23.9%)

Table 2. Adolescent Sleep Behaviors Prior to and During COVID-19 School Closures, by Grade Category

Variables	Full Sample n=590	Middle School (6-8th grade) n=201	Early High School (9-10th grade) n=201	Late High School (11-12th grade) n=188
	N (%) or Mean (SD)	N (%) or Mean (SD)	N (%) or Mean (SD)	N (%) or Mean (SD)
Weekday wake time, pre-closures [a]	6:20 a.m. (0.6 h)	6:28 a.m. (0.6 h)	6:12 a.m. (0.6 h)	6:20 a.m. (0.7 h)
Weekday wake time, post-closures [ab]	8:58 a.m. (1.6 h)	8:32 a.m. (1.5 h)	9:09 a.m. (1.6 h)	9:13 a.m. (1.6 h)
Weeknight bedtime, post-closures [abc]	11:58 p.m. (1.7 h)	11:03 p.m. (1.6 h)	12:16 a.m. (1.4 h)	12:38 a.m. (1.5 h)
Weeknight sleep duration, post-closures [ab]	8.2 h (1.5 h)	8.7 h (1.5 h)	8.0 h (1.6 h)	7.9 h (1.4 h)
Weeknight time in bed, post-closures [ab]	9.0 h (1.5 h)	9.5 h (1.3 h)	8.9 h (1.6 h)	8.6 h (1.3 h)
Change in weekday wake time, pre- to post-closures [ab]	2.6 h (1.6 h)	2.1 h (1.5 h)	2.9 h (1.6 h)	2.9 h (1.5 h)
Increase in sleep duration, pre- to post-closures, N (%)*	466 (79.0%)	134 (66.7%)	171 (85.1%)	161 (85.6%)
Delayed bedtime, pre- to post-closures, N (%)	437 (74.2%)	142 (71.0%)	156 (77.6%)	139 (73.9%)
Delayed wake time, pre- to post-closures, N (%)*	550 (93.5%)	181 (90.1%)	190 (95.0%)	179 (95.7%)
Sufficient sleep duration, post-closures, N (%)	369 (62.5%)	122 (60.7%)	121 (60.2%)	126 (67.0%)
Sufficient time in bed, post-closures, N (%)	455 (77.1%)	153 (76.1%)	152 (75.6%)	150 (79.8%)
Daytime sleepiness, post-closures, N (%)				
Not a problem	200 (33.9%)	80 (39.8%)	62 (30.9%)	58 (30.9%)
A little problem	291 (49.3%)	91 (45.3%)	106 (52.7%)	94 (50.0%)
More than a little problem	99 (16.8%)	30 (14.9%)	33 (16.4%)	36 (19.2%)

^ NH = non-Hispanic

*Chi-square tests indicated significance across the three grade groups for categorical sleep variable (p-value < .05)

ANOVA tests indicated significance across the three grade categories for all continuous sleep variables (all p-values <.0001).

[a] Post-hoc tests indicated significant difference between middle school and early high school groups (p-value <0.05)

[b] Post-hoc tests indicated significant difference between middle school and late high school groups (p-value <0.05)

[c] Post-hoc tests indicated significant difference between early high school and late high school groups (p-value <0.05)

Table 3. Adolescent Sleep During COVID-19-Related School Closures, Stratified by Grade Category

Predictor Variables 6-8th grade: n=201 9-10th grade: n=201 11-12th grade: n=188	Model 1: Weeknight bedtime (hrs)			Model 2: Weekday wake time (hrs)			Model 3: Weeknight sleep duration (hrs)			Model 4: Weeknight time in bed (hrs)			Model 5: Daytime sleepiness		
	6-8th	9-10th	11-12th	6-8th	9-10th	11-12th	6-8th	9-10th	11-12th	6-8th	9-10th	11-12th	6-8th	9-10th	11-12th
	β	*β*	*β*	*β*	*β*	*β*	*β*	*β*	*β*	*β*	*β*	*β*	OR	OR	OR
Adjusted R^2	0.38***	0.12***	0.09**	0.07*	0.25***	0.19***	0.26***	0.16***	0.14***	0.18***	0.14***	0.10**	-	-	-
Intercept	10:26p	12:19a	11:48p	8:15a	7:47a	7:47a	9.3	7.3	7.9	9.8	7.5	8.0	-	-	-
Gender															
Female	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Male	0.3	0.0	0.1	0.2	0.2	0.0	0.1	0.2	-0.4	-0.1	0.2	-0.2	1.4	0.8	0.6
Race															
White, NH^	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Asian, NH	0.4	0.2	0.4	0.5	0.2	-0.1	0.1	0.0	-0.4	0.1	0.0	-0.5	0.8	0.7	0.8
Black, NH	0.8	-0.7	-0.1	0.1	-0.4	0.4	-0.9	-1.2*	-0.3	-0.7	0.3	0.5	2.4	0.7	1.0
Hispanic	0.6	0.4	0.2	-0.1	0.0	0.1	-0.3	-0.8*	-0.2	-0.6	-0.4	-0.2	0.7	0.7	0.5
Multiple/other, NH	0.3	-0.7	-0.3	-0.1	-0.4	-0.7	-0.1	0.0	-0.4	-0.4	0.2	-0.4	0.7	0.4	0.3
Earliest synchronous class time															
Before 8:30 a.m.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8:30-9:00 a.m.	-0.1	-0.3	0.0	-0.3	0.4	0.5	-0.5	1.0**	0.2	-0.2	0.8*	0.5	1.7	1.1	0.6
After 9:00 a.m.	0.4	0.3	1.0***	0.4	1.4***	1.9***	-0.1	1.0**	0.9**	0.0	1.1***	0.9***	0.6	0.3**	0.7
No set start time	0.3	0.1	1.0***	0.2	1.8***	2.1***	-0.1	1.5***	0.7*	-0.1	1.7***	1.0***	0.9	0.3**	0.6
Parent-set bedtime															
No	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Yes	-1.5***	-1.2***	-1.2*	-0.6*	-0.5	-0.5	0.9***	0.1	0.1	0.9***	0.7*	0.8	0.6	0.5	0.5
Trouble going or staying asleep (past 2 weeks)															
Never	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Once	0.1	-0.7	-0.2	0.0	-0.6	0.0	-0.2	-0.3	0.1	-0.1	0.1	0.2	1.7	1.3	0.5
Twice	0.5	-0.1	-0.2	0.2	0.4	0.2	-1.0**	0.1	0.1	-0.3	0.5	0.4	3.2*	3.0**	2.7*
Several times	0.5*	0.0	0.3	0.2	0.2	0.2	-0.9***	-0.7	-0.3	-0.4	0.2	-0.1	3.5***	4.6***	1.2
Every day/night	1.1**	0.7	0.8*	0.6	1.2**	0.2	-1.6***	-0.8	-1.4***	-0.5	0.5	-0.6	10.6***	13.7***	9.1***
Change in caffeine use during school closures															
Never used caffeine	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
More caffeine use	1.2***	0.1	-0.2	0.9*	0.2	0.0	-0.4	-0.2	0.0	-0.4	0.0	0.2	8.8***	0.7	1.7
Same caffeine use	0.9***	0.0	-0.1	0.2	0.4	-0.1	-0.7**	0.1	-0.3	-0.7**	0.4	0.0	3.0**	1.4	1.6
Less caffeine use	0.7*	0.1	0.1	0.3	0.2	0.1	-0.5	0.2	0.0	-0.5	0.1	-0.1	3.7**	1.6	2.0

* p-value < .05, ** p-value < .01, *** p-value < .001

^ NH = non-Hispanic

Table 4. Changes in Adolescent Sleep, Pre- to Post-COVID-19-Related School Closures, Stratified by Grade Category

Predictor Variables 6-8th grade: n=202 9-10th grade: n=201 11-12th grade: n=189	**Model 6: Change in weekday wake time (hrs)**			**Model 7: Increase in sleep duration**		
	6-8th	9-10th	11-12th	6-8th	9-10th	11-12th
	β	*β*	*β*	OR	OR	OR
Adjusted R^2	0.06*	0.26***	0.20***	-	-	-
Intercept	1.9	1.6	1.5	-	-	-
Gender						
Female	-	-	-	-	-	-
Male	0.0	0.0	-0.1	1.6	2.2	0.7
Race						
White, NH^	-	-	-	-	-	-
Asian, NH	0.5	0.1	0.0	0.5	1.5	3.9
Black, NH	-0.1	-0.1	0.4	1.3	0.2	0.8
Hispanic	0.4	0.0	-0.1	2.4	0.7	1.5
Multiple/other, NH	-0.1	-0.2	-0.8	1.6	^^	0.2
Earliest synchronous class time						
Before 8:30 a.m.	-	-	-	-	-	-
8:30-9:00 a.m.	-0.3	0.4	0.3	0.4	5.6*	1.0
After 9:00 a.m.	0.2	1.2***	1.5***	0.8	7.2**	2.5
No set start time	0.1	1.9***	1.9***	0.7	2.1	4.1
Parent-set bedtime						
Yes	-0.5*	-0.4	-0.4	1.2	0.8	0.2
Trouble going or staying asleep (past 2 weeks)						
Never	-	-	-	-	-	-
Once	-0.1	-0.3	0.3	1.7	0.3	2.2
Twice	0.0	0.4	0.3	1.4	3.3	1.9
Several times	0.3	0.3	0.4	1.1	0.6	1.1
Every day/night	0.6	1.6***	0.4	0.7	0.9	0.3
Change in caffeine use during school closures						
Never used caffeine	-	-	-	-	-	-
More caffeine use	0.8*	0.1	0.0	0.5	1.2	0.2*
Same caffeine use	0.2	0.4	0.0	0.8	2.1	0.7
Less caffeine use	0.4	0.1	0.3	3.4	3.3	0.8

* p-value < .05, ** p-value < .01, *** p-value < .001

^ NH = non-Hispanic

^^ Due to complete quasi-complete separation of data points, an odds ratio was not calculated for this group and persons of multiple/other NH race were omitted from this model.

Table 5. Sleepiness During School Activities, by Class Start Time

Difficulty Staying Awake or Falling Asleep, Past Few Days	Full Sample n=590		Class Start Time Before 8:30 a.m. n=101		Class Start Time 8:30-9:00 a.m. n=119		Class Start Time After 9:00 a.m. n=210		No Set Class Start Time n=160		Chi Square p-value
	n	%	n	%	n	%	n	%	n	%	
Online class	115	19.4%	34	33.7%	26	21.9%	32	15.2%	23	14.4%	0.0004
Doing homework on the computer	156	26.4%	35	34.7%	30	25.2%	51	24.4%	40	25.2%	0.2442
Reading, studying, or doing homework	174	29.5%	40	39.6%	37	31.1%	52	24.8%	45	28.1%	0.0571
Taking a test online	44	7.5%	10	10.0%	9	7.6%	16	7.7%	9	5.6%	0.6318

Table 6. Impact of Sleepiness on School Activities, by Class Start Time

Sleepiness During Class, Past Two Weeks	Full Sample n=479*		Class Start Time Before 8:30 a.m. n=101		Start Time 8:30-9:00 a.m. n=119		Start Time After 9:00 a.m. n=210		No Set Start Time n=49		Chi Square p-value
	n	%	n	%	n	%	n	%	n	%	
Arrived late to class because overslept	183	38.3%	49	48.5%	51	42.9%	73	34.9%	10	21.4%	0.0043
Fallen asleep in online morning class	70	14.6%	24	23.8%	18	15.1%	22	10.5%	6	12.2%	0.0194
Fallen asleep in online afternoon class	33	6.9%	7	6.9%	7	5.9%	14	6.7%	5	10.2%	0.7922

*Sample was restricted to exclude students who did not attend synchronous classes

PUBLIC HEALTH IMPLICATIONS

This thesis aimed to investigate adolescent sleep and changes in sleep patterns during COVID-19-related school closures in the United States, as well as to investigate the relationship between class start times and sleep in middle and high school students. With the closing of in-person schooling, students woke up later and slept longer. Bedtimes and wake times were progressively later with higher grades, consistent with circadian rhythm changes with age.[9] School closures had a larger effect on high school students than middle school students, with over 85% of high school students reporting increased sleep duration since COVID-19 and a mean delay in weekday wake time of 2.9 hours. Additionally, high school students with later class start times woke up later, slept longer, spent more TIB, and reported less daytime sleepiness than those with earlier class start times. When comparing sleep pre- to post-school closures, high school students with later class start times also reported larger changes in wake time and increases in sleep duration compared to those starting class earlier.

Teenagers are the least likely of any age group to get adequate sleep,[22] and nearly three quarters of high school students get insufficient sleep on an average school night.[23] While sleep duration increased during the pandemic, a large proportion of students reported difficulty falling and staying asleep, consistent with other research on adult and adolescent sleep during COVID-19[16,139] and potentially reflecting increased stress and worries during the pandemic. Interventions seeking to improve teen sleep health can operate at different levels of the SEM by targeting adolescents, parents, communities, schools, and even state and national legislative bodies.

At the individual level, educational campaigns can teach teenagers the importance of sufficient sleep duration and timing and promote modifiable sleep hygiene behaviors impacted by school closures and lockdown, including finding at-home options for physical activity, spending time outdoors to increase natural light exposure, and limiting caffeine intake and screen time before bed. Individual-level interventions can also seek to improve teens' mental health during the pandemic by building resilience, leveraging digital technology for mental health support, and encouraging practices including meditation and yoga.

Results support previous literature on the impact of parent involvement in regulating adolescent sleep habits, particularly among middle schoolers.[87] The effect of parental involvement in bedtime and sleep duration is especially notable given teens' reduced daily structure during COVID-19-related closures. Interventions at the interpersonal level may involve education campaigns informing parents of their role in regulating their children's sleep habits and teach them strategies for promoting healthy sleep, including by establishing bedtimes, limiting screen time, and promoting physical activity and family time outdoors. Parents can also set up their children's bedrooms to promote healthy sleep, including by removing televisions, limiting noise, or adding room-darkening shades to limit light exposure during nighttime. Additionally, parents can play a key role in supporting their children's mental health by providing support, positive social interaction, and meaningful connection, particularly while teens are confined in their households. Interpersonal-level interventions can also target peer relationships, including by developing peer support networks, maintaining the structure, quality, and

quantity of social networks, and promoting activities to feel part of a group during pandemic-related isolation.[150]

At the community level, school systems can become involved in promoting adolescent sleep health. During remote instruction, schools can build break time specifically for physical activity or outdoor walks into students' daily remote course schedules and allow opportunities for socialization with other students during the school day. Communities can also encourage outdoor behaviors by closing streets and opening public parks to allow for safe, socially distanced physical activity. Moving forward beyond the pandemic, sleep health can be integrated into middle and high school health education curricula to teach teenagers the importance of healthy sleep timing and duration as well as how to practice good sleep hygiene. Sleep health education campaigns can also target influential school staff such as athletic coaches and guidance counselors to better reach and impact students.

Importantly, this study confirms other researchers' findings that school start time is a strong external influence on adolescent sleep behaviors.[105,147,148] Findings are consistent with the AAP's societal-level recommendation that high schools start classes at 8:30 a.m. or later to improve adolescent sleep,[11] and suggest that starting high school even later – after 9:00 a.m. – may be associated with additional sleep benefits. Although the AAP also recommends that middle schools start at 8:30 a.m. or later, this study did not identify differences in sleep behaviors among middle schoolers starting class later, suggesting that high schools should be prioritized for delayed start times if school districts have limited capacity to implement this change. This policy change can be costly, with implications for bus schedules, parent supervision and commutes, and teens'

after-school jobs and activities. However, even beyond the clear positive effects on teen sleep, delaying school start times has a high return on investment and is projected to add to the national economy by improving academic performance and reducing injury rates.[111] This policy change can occur through multiple avenues, including at the school district level or through state legislative action, as in California, which will require middle and high schools to start no later than 8:00 and 8:30 a.m. respectively starting in 2022. Delayed school start time advocacy can target teens, parents, school administrators, and state legislators to promote this policy change and improve teen sleep and health and education outcomes.

Additionally, these findings call for future research in several areas. As many students continue to learn remotely during the pandemic and schools consider new options for instruction following the pandemic, research should investigate the impact of remote learning on adolescent sleep and subsequent health and educational outcomes. Findings on the association between delayed school start times and decreased daytime sleepiness also call for future research on whether improved sleep during the pandemic may lead to improved academic performance, as has been found in other studies of school start time.[10] Research should also investigate the impact of the COVID-19 pandemic on existing sleep disparities among adolescents, particularly as the pandemic has disproportionately impacted racial and ethnic minority groups in the United States.[151]

COVID-19 school closures afforded a unique opportunity to study adolescent sleep, as the pandemic disrupted long-established patterns and practices of schools such as early school start times, bus pickups, commutes, and morning extracurricular activities. During the pandemic, adolescents – particularly high schoolers with later

school start times – were able to delay their sleep timing to more closely align with their circadian rhythm and increase their sleep duration in order to get recommended amounts of sleep, primarily by delaying wake times. Results provide further evidence that adolescents should begin morning activities substantially later than is the case in most school districts.

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