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School Commute Time, Chronotype, and Altered HPA Axis Functioning during Adolescence

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Abstract

Hypothalamic pituitary adrenal gland (HPA) axis functioning has been linked with daily demands during adolescence. A ubiquitous, yet understudied daily demand in the lives of youth is the commute to school, which may be associated with the diurnal rhythm of cortisol as demonstrated in prior research among adults. The current study hypothesized that longer school commute times would be associated with altered HPA axis functioning as demonstrated by a heightened cortisol awakening response (CAR) and flatter diurnal slope. Additionally, given that the HPA axis follows a diurnal rhythm and adolescence is marked by changes in the circadian rhythm, adolescents with a more evening chronotype were hypothesized to evince even more altered HPA axis functioning in the face of long school commute times. A total of 269 adolescents ($M = 16.38$ years, $SD = 0.74$) provided saliva samples at wake, 15-min. post-wake, and 30-min. post-wake for the calculation of cortisol awakening response (CAR) and at dinnertime and bedtime for the calculation of diurnal slope, completed up to 8 nights of sleep actigraphy, and self-reported school commute time.

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Declarations of interest: none

Results suggest that more evening chronotype youth with longer school commute times evince a higher CAR, but not an altered diurnal slope. The present findings may have implications for adolescent mental health as higher CAR has been associated poor mental health and heightened stress.

Keywords

HPA axis functioning; commute; chronotype; adolescence; school

Altered hypothalamic pituitary adrenal gland (HPA) axis functioning has been linked with poor mental health and heightened stress among adolescents (Adam et al., 2017; Koss & Gunnar, 2018; Rickard et al., 2016). Therefore, it is important to uncover factors that contribute to the dysregulation of this biological system in youth, such as the demands that they face in their everyday lives (Bai et al., 2017; Chiang et al., 2016; Lee et al., 2020; Sladek et al., 2016). One consistent daily demand that has been understudied in adolescence is the commute to school, the duration of which can vary greatly among adolescents even within the same school (Voulgaris et al., 2019). Youth need to marshal their physical and mental resources early in the morning to prepare for the school commute and this process may be more demanding for those with longer travel times. In addition, the link between commute time and HPA axis functioning may be particularly strong among youth with evening chronotypes whose preferred later bed and wake times are misaligned with the typically early start of the school day (Tarokh et al., 2019). The current study examined whether adolescents with longer school commute times experience altered HPA axis functioning and if those with an evening chronotype are especially susceptible to these effects.

1.1   Commute Time & HPA Axis Functioning

Daily HPA axis functioning, as measured by the cortisol awakening response (CAR) and diurnal slope, may be influenced by commute times due to its diurnal rhythm and responsivity to daily experiences. Although the significance of CAR is not fully understood, it is presumed to play a role in preparing the body to cope with demands and stressors of the day (Fries et al., 2009). Altered HPA axis functioning may present in the form of heightened CAR in response to upcoming demands. For instance, adolescents show heightened CAR on days that they engage in family assistance behaviors and experience greater family demands (Armstrong-Carter et al., 2020; Chiang et al., 2016). Diurnal cortisol slope is another important indicator of HPA axis functioning that has been shown to be impacted by events occurring on the same day (Adam et al., 2006). For instance, on days when preadolescents report more peer problems, they demonstrate flatter diurnal cortisol slopes (Bai et al., 2017). As with a heightened CAR, a flatter diurnal cortisol slope is thought to be indicative of dysregulated HPA axis functioning that is linked with negative mental and physical health outcomes among adolescents (e.g. Adam et al., 2017; Doane et al., 2013; Rickard et al., 2016).

Commuting is a potential, although unstudied, daily demand that could influence CAR and diurnal cortisol slope among youth. Commuting to school, whether driving oneself or not,

can be an onerous task for those with longer commute times because it obligates these youth to prepare for the school day earlier, a challenge that those with shorter commute times may not face. Also, longer commutes have been strongly correlated with reduced subjective well-being among adults (Chatterjee et al., 2020). Furthermore, CAR is higher on workdays compared to weekend days among adults, demonstrating that workday demands have the potential to contribute to differential cortisol activity (e.g. Marchand et al., 2013; Schlotz et al., 2004). In a direct test of the impact of commuting among adults, an experimental study of commuters by rail demonstrated that longer work commute times gave rise to an elevated cortisol response post-commute compared to baseline and reported higher perceived stress (Evans & Wener, 2006). The current study extends this previous research from adulthood to adolescence by assessing whether school day commute time is associated HPA axis functioning.

In addition to the demands of commuting itself, longer commutes may impact HPA axis functioning because of earlier wake times and shorter sleep duration. Prior work shows that longer school commutes are associated with advanced wake times and reduced sleep duration (Adam et al., 2007; Pereira et al., 2014; Voulgaris et al., 2019). Wake time may play a role in daily activation of the HPA axis early in the morning to meet the school commute demand and may contribute to an elevated CAR and flattened diurnal slope for adolescents with longer commute times. Given prior work establishing a link between sleep and cortisol activity in adolescents, we tested whether school commute time was associated with cortisol activity over and above indices of sleep (e.g. Chiang et al., 2016; Kuhlman et al., 2019; Mrug et al., 2016; Sladek & Doane, 2015; Zeiders et al., 2011).

2.1 The Role of Chronotype

The links between commute time and daily HPA axis functioning may depend upon adolescents' own typical sleep-wake timings. Chronotype defines the spectrum of sleep-wake timing preferences with morning chronotypes following earlier and evening chronotypes following later sleep-wake timings (Roenneberg et al., 2003). Even though adolescents developmentally demonstrate a stronger evening chronotype such that they sleep and wake later as they age, some youth demonstrate even more eveningness than others (Bai et al., 2020; Fischer et al., 2017; Roenneberg et al., 2004). It is possible that, due to individual differences, morning chronotype adolescents may have less trouble waking-up early for long school commutes because they naturally rise earlier than their evening chronotype counterparts. However, those who are stronger evening chronotypes may be susceptible to the negative effects of long commute times because they naturally prefer to wake up later and may need more time preparing for the day which may be apparent in HPA axis functioning (i.e., CAR, diurnal cortisol slope).

The goal of the current study was twofold: 1) to examine if there is an association of school commute times with HPA axis functioning among adolescents on school days, and 2) to test if chronotype moderates the association between commute times and HPA axis functioning. It was hypothesized that longer commute times may require youth to be more alert in the morning and consequently lead to an elevated CAR and flatter diurnal slope on school days. Furthermore, longer commute times were hypothesized to be associated with altered

HPA axis functioning among more evening chronotype youth possibly because they need to prepare for a new day earlier than naturally preferred. The extent to which shorter sleep duration and earlier wake times accounted for any observed associations between commute time and HPA was examined.

Method

Participants.

A total of 316 adolescents (M = 16.38 years, SD = 0.74) were recruited through flyers and in-class presentations to tenth and eleventh graders from four high schools in the greater Los Angeles area. Participants were excluded from the present analyses if they did not complete actigraphy (n = 34), never provided saliva samples (n = 3), did not report age (n = 6), or commute time (n = 4), leaving 269 participants in the analytic sample. Participants identified as being from Latinx (42.38%), Asian American (23.05%), European American (28.62%), and other ethnic backgrounds (5.65%), and there was a slight majority of females (58.33%).

A sample of over 300 participants were recruited for the larger study because this sample size provided enough statistical power to detect the small-medium sized effects between aspects of psychosocial factors (e.g., stress, interpersonal conflict, etc.) and biomarkers of health such as cortisol. With this number of participants and three days of assessment of salivary cortisol, we had a total number of observations of salivary cortisol that was comparable to or greater than those observed in prior studies of associations between psychosocial factors and salivary cortisol (e.g., Doane & Adam, 2010; Heissel et al., 2018; Sladek et al., 2016; Stroud et al., 2019).

To test how participants who provided data (i.e., provided at least two samples of salivary cortisol on one day and were not missing data on sex, age, or parents' education) differed from those who did not with respect to demographic characteristics, we conducted chi-squared tests for gender and ethnicity, and t-tests for age and parents' education. Results indicated that participants in the current study did not differ from other participants in the cohort with respect to gender and ethnicity, χ^2 <1, p's >.3, or age and ethnicity, t's <1.5, p's >.1.

Procedure.

From 2011–2012, research staff completed home visits during which youth completed surveys independently on electronic devices. One caregiver per youth also participated and completed their surveys at the same time as their child. Adolescents wore actigraph watches (Micro Motionlogger Sleep Watch, Ambulatory Monitoring, Inc.; Ardsley, NY) on their non-dominant wrist for eight consecutive nights and provided five cortisol samples per day for three consecutive days. Adolescents and parents received $50 and $80 for participating in the study, respectively, and youth additionally received two movie tickets for completing the daily protocol.

Sleep duration and adolescent wake time were measured using actigraph watches. Adolescents were instructed to press the "event marker" button when they turned off the lights to sleep, at any point they left their bed at night, and when they got out of bed in

the morning. For days when the "event marker" button was not pressed, the adolescents' self-reported wake time or bedtime on a daily sleep log was used. Although we did not track the number of times the event marker information was missing, sleep information from the actigraph was always compared with self-reported sleep. Data were coded using Action4 software (Ambulatory Monitoring Inc.; Ardsley, NY). The Sadeh actigraph scoring algorithm was used to identify the probability that participants were awake or asleep across one-minute epochs (Sadeh et al., 1994). This method has been used and validated in numerous child and adolescent samples, (e.g., Acebo et al., 1998; Park et al., 2016).

During the first three days of the daily protocol, adolescents provided five cortisol samples per day: immediately after waking, 15 min. after waking, 30 min. after waking, before dinner, and at bed time. Cortisol samples were stored in the fridge until study staff collected the checklists and saliva samples from participants' homes two weeks later. Samples were then stored at −80°C and assayed at the Laboratory of Biological Psychology at the Technical University of Dresden, Germany, using high-sensitivity chemiluminescence-immunoassays (IBL International, Hamburg, Germany). The intra- and inter-assay coefficients for cortisol were below 8%.

Measures.

CAR.—Participants were instructed to provide three morning samples: wake, 15-min. post-wake, and 30-min. post-wake. The cortisol awakening response was calculated as the difference in cortisol concentration between the first and third sample (i.e., cortisol concentration at 30 min. post-waking – cortisol concentration at waking), with more positive values indicating a greater increase. Most participants provided saliva samples 30 min. after waking, as instructed (77.99% provided samples 25–35 min. post-wake, 96.27% provided samples 15–45 min. post-wake). Because adolescents provided samples both 15 min. and 30 min. after they reported waking, we used whichever sample was closer in time to 30 min. post-wakening based on actigraphy (i.e., collected fewer minutes earlier or later than exactly 30 min. following wake according to actigraphy; $N = 349$, 41.9% for 15 min. sample; $N = 484$, 58.1% for 30 min. sample). Negative CAR values may be due to error in timing of sample collection because cortisol samples must be collected within a narrow window following wake. Therefore, in line with previous work, negative values were recoded to zero to correct for the influence of samples that were collected too long after actual waking to correctly assess the CAR (e.g., Kuhlman et al., 2016, 2017; Okun et al., 2010). In total, 269 adolescents provided 802 observations for CAR, or 2.98 observations of CAR out of a maximum of three per person over three days. Adolescents generally had high levels of salivary cortisol at wake, which increased at 15 min. and 30 min. post-wake, $F = 1675.76$, $p < .001$. They also tended to show much lower levels of salivary cortisol at dinner and had lowest values at bedtime, $F = 1163.30$, $p < .001$ Descriptive statistics are provided in Table 1. Participant demographics, commute time, school start time, wake time, and sleep duration did not relate to the number of days that adolescents provided cortisol samples to calculate CAR (all p's > .1).

Diurnal slope.—Participants also were instructed to provide cortisol samples before dinner and at bedtime. The rate of cortisol decline throughout the day was calculated by

dividing the difference in cortisol concentration between the bedtime and waking sample by the number of hours that had elapsed, with more negative values indicating a steeper decline (Adam et al., 2017). For the 20 instances (2.68%) when participants were missing bedtime samples, the sample from before dinner was used to calculate diurnal slope. In total, 259 adolescents provided 745 observations for diurnal slope, or 2.91 observations of diurnal slope per person over three days. Youth with lower parents' education provided fewer bedtime and afternoon samples, resulting in fewer observations of diurnal slope, $B = -0.02$, $SE = 0.01$, $p = .051$. No other differences emerged.

Commute and school start time.—As part of a survey at the start of the study, adolescents reported how many minutes it typically takes them to get from home to school in the morning and what time their school starts each day. If participants reported a range of times, the value was replaced with the average. Adolescents needed 12 min on average to get to school, although commute times ranged from 2–60 min. Adolescents reported starting school on average at 7:35am ($SD = 0:30$) with an average commute time of slightly over 12 minutes ($M = 12.22$; $SD = 8.01$).

Sleep duration.—Total sleep duration in the previous night was calculated as the amount of time in hours between the first 3 min. of uninterrupted sleep (sleep onset) and the last 5 or more min. of uninterrupted sleep (sleep offset), based on actigraph measurement, as has been done in previous studies of sleep in adolescence (e.g., Acebo et al., 1998; Park et al., 2016). Most students reported 7 hours and 33 minutes ($SD = 1:22$) of sleep duration.

Wake time.—Wake time was recorded via actigraphy as well as self-reports using daily checklists. Given that actigraphy is a more objective measure of wake time, we used actigraphy-based wake time in analyses. On average, students reported a wake time of 7:26am ($SD = 1:16$). Adolescents' wake time, as indicated by the time they reported providing their first saliva sample, was strongly related to wake time measured by actigraphy ($B = 0.85$, $SE = 0.03$, $p < .001$ according to multilevel models across all observations; $r(268) = .78$ across participants). The correspondence between these measures was assessed using multilevel models, with days nested within participants, which examined both the between-person and within-person associations by predicting wake time based on daily checklists from both the individual's mean actigraphy-based wake time and values of actigraphy-based wake times centered at the individual's mean. These two measures were highly related at the level of between-individuals ($B = 0.95$, $SE = 0.02$, $p < .001$, $t^2 = 1.32$) and within individuals ($B = 0.87$, $SE = 0.03$, $p < .001$, $t^2 = 3.07$), with actigraphy-based wake time explaining approximately 87.48% of the variance in checklist-based wake-times. More specifically, adolescents with later wake times based on actigraphy also had later wake times based on daily checklists, and adolescents had later wake times on checklists on days when they had later wake times based on actigraphy.

Chronotype.—Chronotype was calculated as a participant's average midsleep point (MSF), or the time between sleep onset and offset, on non-school days (i.e., summer, school holidays, weekends). Non-school days provide an assessment of an individual's chronotype

that is not influenced by the school schedule. Chronotype was adjusted for sleep debt from non-free (i.e., school) days using the following formula (Roenneberg et al., 2004):

$$MSF_C = MSF - 0.5\left(\text{Sleep Duration}_{NS} - \text{Sleep Duration}_{avg}\right)$$

SD_{NS} represents sleep duration on non-school days and SD_{avg} is indicative of sleep duration across all days. On average, adolescents wore actigraphs on 3.49 non-school nights ($SD = 1.94$). On average, youth had a MSF_C at 3:39AM ($SD = 1:15$).

Parent Education.—Participants' primary caregivers reported education levels for themselves and for their spouse (1 = some elementary school; 2 = completed elementary school; 3 = some junior high school; 4 = completed junior high school; 5 = some high school; 6 = graduated from high school; 7 = trade or vocational school; 8 = some college; 9 = graduated from college; 10 = some medical, law, or graduate school; 11 = graduated from medical, law, or graduate school). The majority of caregivers earned the equivalent of a trade or college degree after averaging self-reported education level between both caregivers ($M = 7.16$, $SD = 1.84$).

Ranges for all study variables are provided in Table 1. To ensure that extreme values of cortisol could not have undue influence on the observed associations in three-level multilevel models, we winsorized these observations to 60 nmol/L in line with prior studies (Barker et al., 2012; Wong et al., 2014). This resulted in winsorizing 14 observations (two waking sample, three 15-min. post-waking, six 30-min. post-waking, three dinnertime samples). Extreme values were not observed for other study variables, and no other variables were winsorized.

Analytic Plan.

Diurnal slope and CAR were examined in two ways. First, the rate of change in cortisol from wake to bedtime was calculated as an index of diurnal slope. This was calculated as the difference in salivary cortisol concentration between wake and bedtime, divided by the elapsed time. The change in cortisol from wake to 30-min post-wake was calculated as an index of CAR. This resulted in one value of diurnal slope and CAR for each day, with up to three days per adolescent. These indices were predicted from two-level multilevel models with days at Level 1 nested within adolescents at Level 2. Two-level multilevel models with days nested within adolescents were used to predict cortisol indicates from the cross-level Commute Time (Level 2) × School Day (Level 1) interaction, with separate models for CAR and diurnal slope. Next, two-level multilevel models were used to examine the Commute Time (Level 2) × Chronotype (Level 2) interaction.

$$L1: \widehat{CAR}_{tij} \text{ or } \widehat{Slope}_{tij} = \beta_{0j} + \beta_{1j}(School\ Day) + \beta_{2j}(Wake\ Time) + \beta_{3j}(Sleep\ Duration)$$

$$L2: \beta_{0j} = \gamma_{00} + \gamma_{01}(Commute\ Time) + \gamma_{02}(Wake\ Time) + \gamma_{03}(Sleep\ Duration) + \gamma_{04}(Gender)$$
$$+ \gamma_{05}(Age) + \gamma_{06}(Parents'\ Education) + \gamma_{07}(Ethnicity\ Dummy\ Codes)$$
$$+ \gamma_{08}(Gender) + u_{0j}$$

$$\beta_{1j} = \beta_{10} + \gamma_{11}(Commute\ Time) + u_{1j}$$

$$\beta_{2j} = \gamma_{20} + u_{2j}$$

$$\beta_{3j} = \gamma_{30} + u_{3j}$$

$$L1: \widehat{CAR}_{tij}\ or\ \widehat{Slope}_{tij} = \beta_{0j} + \beta_{1j}(School\ Day) + \beta_{2j}(Wake\ Time) + \beta_{3j}(Sleep\ Duration)$$

$$L2: \beta_{0j} = \gamma_{00} + \gamma_{01}(Commute\ Time) + \gamma_{02}(Chronotype) + \gamma_{03}(Chronotype * Commute\ Time)$$
$$+ \gamma_{04}(Wake\ Time) + \gamma_{05}(Sleep\ Duration) + \gamma_{06}(Gender) + \gamma_{07}(Age)$$
$$+ \gamma_{08}(Parents'\ Education) + \gamma_{09}(Ethnicity\ Dummy\ Codes) + \gamma_{10}(Gender) + u_{0j}$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11}(Commute\ Time) + u_{1j}$$

$$\beta_{2j} = \gamma_{20} + u_{2j}$$

$$\beta_{3j} = \gamma_{30} + u_{3j}$$

Second, in order to leverage all of our data and check the robustness of the results from the two-level models, we used three-level multilevel models to examine the samples of cortisol, with samples nested within days nested within adolescents as a function of time. Specifically, models examining diurnal slope included the waking, dinnertime, and bedtime samples. Time was coded in hours, representing the time that each sample was taken. Models examining CAR included the waking, 15-min post-waking, and 30-min post-waking samples. Time was coded in minutes for ease of interpretation. To examine the effect of Commute Time, we tested the Commute Time × Sample Time interaction, and then tested whether this model varied by school days by testing the School Day × Commute Time × Sample Time interaction. Finally, models examined whether the effects of commute time were driven by differences in sleep patterns. Therefore, the Commute Time × School Day and the Commute Time × Chronotype interactions all models were repeated covarying for sleep duration and for wake time.

Multilevel models are generally robust to distributional properties of variables (Schielzeth et al., 2020). These models generally assume normality of residuals at each level of analysis and normality of residuals of random effects, although these models are generally robust to slight deviations from these assumptions. For all models, we examined the distribution of residuals at each level and for all random effects, which were generally normal (range of skewness −0.88 – 1.09) and appeared normal when visually inspected using histograms. Multilevel models used unstructured variance-covariance matrices, which allows for all covariance parameters to be freely estimated, because this structure showed better fit relative to the auto-regressive structure as indicated by lower Akaike information criterion Bayesian information criterion (Liu et al., 2012)

School day varied at the daily level (Level 1) and was dummy coded (0 = non-school day, 1 = school day). Gender was effect coded (male = −1, female = 1), and ethnicity was dummy coded with European American as the referent group. Continuous variables at the person level (Level 2; i.e., parents' education, chronotype, commute time, school start time) were grand mean-centered. Continuous variables at the daily level (Level 1; i.e., sleep duration, wake time) were centered at each adolescent's mean. School day, sleep duration, and wake time were treated as random effects.

Results

Two-level multilevel models examined whether commute time corresponded to CAR and diurnal slope, over and above gender, ethnicity, parents' education, and school start time. First, the Commute Time × School Day interaction was tested to examine whether commute time related to HPA-axis activity on school days. Models indicated that there was a significant effect of commute time, and that the association of commute time with CAR did not vary by school day (Table 2, Cortisol Awakening Response, Column 1). Prior research has also recoded negative CAR values as zeroes in order to reduce the influence of these values, in case they are a result of methodological error, and to reduce confounding between the diurnal slope and the CAR (Kuhlman et al., 2015, 2016, 2017, 2020). Therefore, we also analyzed data for CAR after recoding the negative values (30.85% of observations) to 0. Using these values, we found that CAR varied by school day, such that adolescents with a longer commute time had a larger CAR on school days but not on non-school days (Table 2, Recoded Cortisol Awakening Response, Column 1; Fig. 1). As a result, adolescents with a school commute of 9 minutes or longer had significant higher CAR on school days than non-school days. There was no school-day difference for those with commutes shorter than 9 minutes. On average, participants reported a commute of approximately 12 min., which corresponded to adolescents showing a 2.02 nmol/L larger CAR on schooldays than on free days (i.e., 37.2% higher on school days than free days). Findings demonstrated that adolescents with a 20 min. commute, or one standard deviation above the mean, showed a 3.82 nmol/L larger CAR on schooldays than on free days (i.e., 70.3% higher), whereas adolescents with a 4 min. commute, or one standard deviation below the mean, showed only a 0.23 nmol/L larger CAR on schooldays than on free days (i.e., 4.2% higher). Although differences emerged for CAR, adolescents with longer commute times had flatter diurnal slopes, although this association did not vary with school day (Table 3, Column 1).

The Commute Time × Chronotype interaction was included as a predictor in models in order to test whether the association between commute time and HPA axis function was stronger in adolescents with an evening chronotype. Results indicated that the association of commute time with CAR varied by chronotype (Table 2, CAR, Column 2). Simple slope analyses indicated that commute time was not associated with CAR among earlier chronotypes. In contrast, commute time was linked with a larger CAR in adolescents with average and more evening chronotypes (Fig. 2). This interaction remained significant after limiting the sample to school days (Table S1), and an identical pattern of results also emerged when recoding negative values of CAR to 0 (Table 2, Recoded CAR, Column 2). The Commute Time X Chronotype interaction was not significantly related to diurnal slope (Table 3, Column 2), and this interaction remained non-significant after limiting the sample to school days.

When examining diurnal slope using three-level multilevel models (i.e., samples nested within days within adolescents), we found that whereas the main findings from the two-level models were maintained for CAR, the findings for the diurnal slope differed somewhat. As before, there was a significant interaction between chronotype, commute time, and sample time ($B = 0.002$, $SE = 0.001$, $p = .018$) by which the association between a longer commute time and a greater CAR was significant only among adolescents with a later chronotype, even after controlling for sleep and wake time ($B = 0.002$, $SE = 0.001$, $p = .039$). When covarying for average and daily differences in sleep duration and wake time, we found that adolescents had lower morning cortisol values on days when they woke later than they did on average, $B = −0.97$, $SE = 0.23$, $p < .001$. For the diurnal slope, we found that the previously reported association between commute time and diurnal slope was only marginally significant ($B = 0.006$, $SE = 0.003$, $p = .052$) and was no longer significant after controlling for sleep and wake time ($B = 0.005$, $SE = 0.004$, $p = .149$. Longer average sleep duration across the three days was associated with lower cortisol levels across the day, $B = −0.46$, $SE = 0.20$, $p = .024$. In turn, later average wake times were associated with higher cortisol levels across the day, $B = 0.78$, $SE = 0.21$, $p < .001$.

In order to test the role played by sleep, models were repeated in order to examine whether the previously-significant associations were maintained after controlling for sleep duration and wake time. When covarying for wake time and sleep duration, adolescents who woke up later on average across the three days tended to have higher CAR. In analyses modeling CAR, the Commute Time × Chronotype interaction remained significant for the unadjusted CAR values and both the Commute Time × School Day interaction and the Commute Time × Chronotype interaction remained significant for the recoded CAR values after controlling for sleep duration and wake time (Table 2, CAR, Column 3; Recoded CAR, Column 3). These associations remained non-significant for diurnal slope after controlling for sleep duration and wake time (Table 2, Column 3). .

Finally, in order to assess the robustness of the associations of commute time with CAR, models tested whether the Commute Time × Chronotype interaction remained significant after limiting the data to samples collected on school days and only on-time samples. The results presented were consistent with follow-up analyses limited to observations from schooldays (Table S1; main effect of commute time: $B = 0.17$, $SE = 0.08$, $p = .001$;

Commute Time × Chronotype interaction: $B = 0.22$, $SE = 0.08$, $p = .041$) and limited to timely observations from schooldays that were collected between 25–35 min. after wake (Tables S2; main effect of commute time: $B = 0.18$, $SE = 0.08$, $p = .032$; Commute Time × Chronotype interaction: $B = 0.13$, $SE = 0.06$, $p = .042$). The main effect of commute time was significant and the Commute Time × Chronotype interaction was marginally significant in subsequent analyses limited to observations from schooldays and covarying the number of minutes between samples (Table S3; main effect of Commute Time: $B = 0.18$, $SE = 0.09$, $p = .036$; Commute Time × Chronotype interaction $B = 0.11$, $SE = 0.06$, $p = .091$).

Discussion

Building on previous research that has demonstrated an association between daily demands and HPA axis functioning during adolescence (e.g. Bai et al., 2017; Sladek et al., 2016), the present study examined whether longer commutes to school, a common and understudied daily demand for school-age youth, was associated with altered HPA axis functioning. These findings demonstrate that longer commutes to school are associated with greater CAR on school days and for youth with more evening chronotypes. These results suggest that longer commutes to school may negatively impact adolescents' physiological functioning, particularly for adolescents whose sleep and wake timings are naturally delayed. Importantly, results are generally maintained over and above sleep duration and wake time.

Prior research has established that the HPA axis is sensitive to daily demands, and the current study extends this work by finding that school commute time is another daily demand that relates to HPA axis functioning in adolescence (Armstrong-Carter et al., 2020; Bai et al., 2017; Chiang et al., 2016). The average commute time in this sample of 10th and 11th graders was about 12 minutes, which is comparable with school commute times of 10–15 minutes among 9th graders across 5 large U.S. cities: Denver, Detroit, New Orleans, New York City, and Washington D.C. (Urban Institute Student Transportation Working Group, 2018). Our results provide some support that adolescents with longer school commutes evinced a greater CAR on school days. This research contributes to a growing body of work regarding adolescent CAR, and it remains unclear what values constitute a "normal" CAR. However, research on CAR has also established links between higher CAR and depressions, demonstrating that individuals with depression show 2–10% higher CAR values than healthy control subjects, both among adults and youth (Ulrike et al., 2013; Vreeburg et al., 2009). Whereas shorter commutes were associated with a relatively small differences between CAR on free days and school days (4.2% larger), larger commutes were associated with a much larger difference between CAR on free days and school days (70.3% larger), indicating that commute times may have a large impact on daily differences in adolescents' CAR.

Results for diurnal slope were somewhat less consistent, varying slightly with analytic strategy. Specifically, the models analyzing the computed index of diurnal slope suggested that longer commute times were consistently related to shallower diurnal slope. The effect of commute time on diurnal slope did not vary by school day, possibly because there is less day-to-day fluctuation in this indicator of HPA activity (Kuhlman et al., 2019). Additionally, this finding may indicate that the school commute has a lingering effect

on the HPA axis via diurnal slope on non-school days. Findings were not moderated by chronotype. Additionally, the association became only marginally significant in the three-level models, suggesting that this association may be less robust. Additional studies will need to determine whether school commuting has consistent associations with the diurnal slope. Importantly, both a heightened CAR and flatter diurnal slope have been linked with increased psychopathology in adolescence (e.g. Adam et al., 2017; Kuhlman et al., 2020), which is especially concerning given that the onset of many psychiatric disorders occurs during this period of development (Paus et al., 2008).

Additionally, results pointed to heightened CAR, but not flatter diurnal slope, among evening chronotype youth with longer school commute times. This suggests that adolescents with delayed circadian rhythms may be particularly sensitive to long commutes. Since more evening chronotypes engage in later bed and wake times, they may mount a higher CAR in preparation for the early school day schedule as it is misaligned with their internal circadian rhythm. Furthermore, sleep duration and wake-time did not account for the association between longer commutes and heightened CAR among more evening chronotype youth, suggesting that chronotype is uniquely playing a role. Prior research shows that a heightened CAR is linked with psychopathology in adolescence (e.g. Adam et al., 2017; Koss & Gunnar, 2018; Rickard et al., 2016), and similarly adolescents with more evening chronotype generally have poorer outcomes with respect to mental health, physical health, and academic performance (Bai et al., 2020; Cohen-Zion & Shiloh, 2018; Owens et al., 2016). Longer commutes relate to physiological function with respect to CAR for more evening chronotypes and may also contribute to how these youth experience poorer outcomes in other domains of health and well-being.

Interestingly, our findings are at odds with prior work suggesting that more morning chronotypes generally tend to have a larger CAR in general. However, these studies examined small samples (N = 45; Randler & Schaal, 2010), older adults (Kudielka et al., 2006), and utilized self-report questionnaires to assess chronotype, as opposed to computing midsleep point with actigraph sleep data as done in the current study (e.g. Petrowski et al., 2020). Our results may differ from prior studies because self-report questionnaires of chronotype emphasize subjective circadian preference, whereas actigraphy examines individuals' objective sleep patterns. For instance, whereas previous work has suggested that individuals who prefer to sleep and wake-up earlier tend to have a larger CAR, findings from this study suggest that adolescents who generally sleep and wake up earlier—potentially due to biological preference and behavioral tendencies—are less influenced by the impact of commute time with respect to CAR (Kudielka et al., 2006; Randler & Schaal, 2010). The association between CAR and chronotype may be further complicated during adolescence because of the developmental shift toward later bed and wake times during adolescence and the transition back toward early bed and wake times during adulthood (Bai et al., 2020; Roenneberg et al., 2004). More research is needed examining chronotype and HPA axis activity during this developmental period.

Importantly, the effects of commute time were not driven by differences in sleep duration. Adolescence is characterized by poor sleep across various domains, and sleep has been associated with HPA axis functioning during this period of the human lifespan (e.g. Crowley

et al., 2018). Shorter sleep duration has been linked with a flatter diurnal slope (Zeiders et al., 2011), lower waking levels of cortisol (Vargas & Lopez-Duran, 2014), and a heightened CAR (Lemola et al., 2015; Vargas & Lopez-Duran, 2014). Furthermore, research on school commute times and sleep among a sample of Brazilian adolescents revealed that longer school commute times were associated with an earlier wake-up time and shorter sleep duration (Pereira et al., 2014). However, our findings suggest that longer school commute times were associated with HPA axis alterations on school days and for more evening chronotypes over and above sleep duration and wake time. These results indicate that the commute to school may influence HPA axis functioning independently of changes in sleep, and future research can examine the psychological and behavioral means by which commute times can influence physiological function.

Across the models, we observed that adolescents with longer sleep duration had lower cortisol levels across the day. These findings align with existing work suggesting that sleep duration and wake time are related to the diurnal rhythm of salivary cortisol (Zeiders et al., 2011). Specifically, prior work has indicated that longer sleep duration is related to lower overall cortisol output. In turn, we found that adolescents who woke up later on average had higher cortisol levels across the day, and adolescents showed a larger CAR on days when they woke up later than their average waketime. Research among adults has also demonstrated a link between later wake-times and higher waking cortisol levels, possibly indicating the ability to mount a greater rise in cortisol upon waking due to increased REM sleep (Buckley & Schatzberg, 2005; Van Lenten & Doane, 2016). Such pathways would need to be tested in future research, especially among adolescent samples.

The morning commute to school may require physiological mobilization for evening chronotype youth due to early school start times in the United States. In 2014, the American Academy of Pediatrics released a policy statement underscoring the importance of not starting high schools before 8:30 am in order to allow adolescents sufficient time to sleep and prepare for school and to reduce the amount of disturbance caused to the circadian rhythm (Adolescent Sleep Working Group, 2014). However, data from the National Center for Education Statistics (2020) shows that the average public high school start time in the United States was 8:00 AM during the 2017–2018 school year, with only 17% of schools enacting a start time at 8:30 AM or later. Most students in the current study started at 7:35 AM on average, thus we lacked sufficient variability in school start times to examine its role. However, longer commutes can further limit adolescents' time to prepare in the morning for an early school start time. Delaying school start times may reduce the impact of commute time on CAR among evening chronotype youth by affording them more time in the morning to prepare for school. Future investigations should examine the moderating role of school start time on school commute time and adolescent HPA axis functioning.

Findings should be interpreted in the context of study limitations. Data were collected prior to release of consensus guidelines regarding measurement of CAR (Stalder et al., 2016). Samples were collected at wake, 15 min. after wake, and 30 min. after wake. We did not have the 45 min. post-wake sample as recommended by the consensus guidelines. Exclusion of this assessment could have resulted in and attenuated measure of CAR, given that salivary cortisol levels remain elevated 30–45 min. following wake (Smyth et

al., 2015; Stalder et al., 2016). Although the current investigation measured chronotype using actigraphy data, a self-report chronotype questionnaire was not administered. Future assessments should include both an objective and subjective measure of chronotype to better clarify the relationship between CAR and chronotype and contextualize previous findings. Although work in children and adults suggest that there is a strong association between actigraphy computations of chronotype and self-report measures of chronotype, this has not been examined among adolescents, a population experiencing changes in sleep-wake timings (Santisteban et al., 2018). Another limitation is that midsleep point was computed based on free days and youth provided data for three nights of non-school day sleep on average. Assessing adolescents over a greater number of free days may increase the stability of the midsleep point computation. We unfortunately did not record the number of instances when the event marker button was not pressed. Future assessments could determine whether such instances were more likely for certain groups of adolescents (i.e., chronotype) or for certain days (e.g., free days versus school days).

The morning commute to school seems to be a daily demand that is linked diurnal slope and CAR in adolescents. Given that heightened CAR has been linked with poor psychopathology, evening chronotype adolescents with long school commute times may be at a greater risk of worsening psychopathology via HPA axis dysfunction. Conversely, perhaps allotting more time for adolescents to prepare for the school day may be sufficient to buffer against higher CAR amongst evening chronotype adolescents with long school commutes.

Conclusion

The present study found that longer school commute times were associated with heightened CAR on school days. Furthermore, adolescents with a more evening chronotype demonstrated altered HPA axis functioning with respect to CAR compared to more morning chronotype adolescents who did not exhibit this pattern. Taken together, these results highlight the school commute as a daily demand that affects HPA axis functioning, particularly adolescents with a biological preference for later bed and wake times.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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$B = 0.24, SE = 0.06, p < .001$

$B = 0.03, SE = 0.07, p = .69$
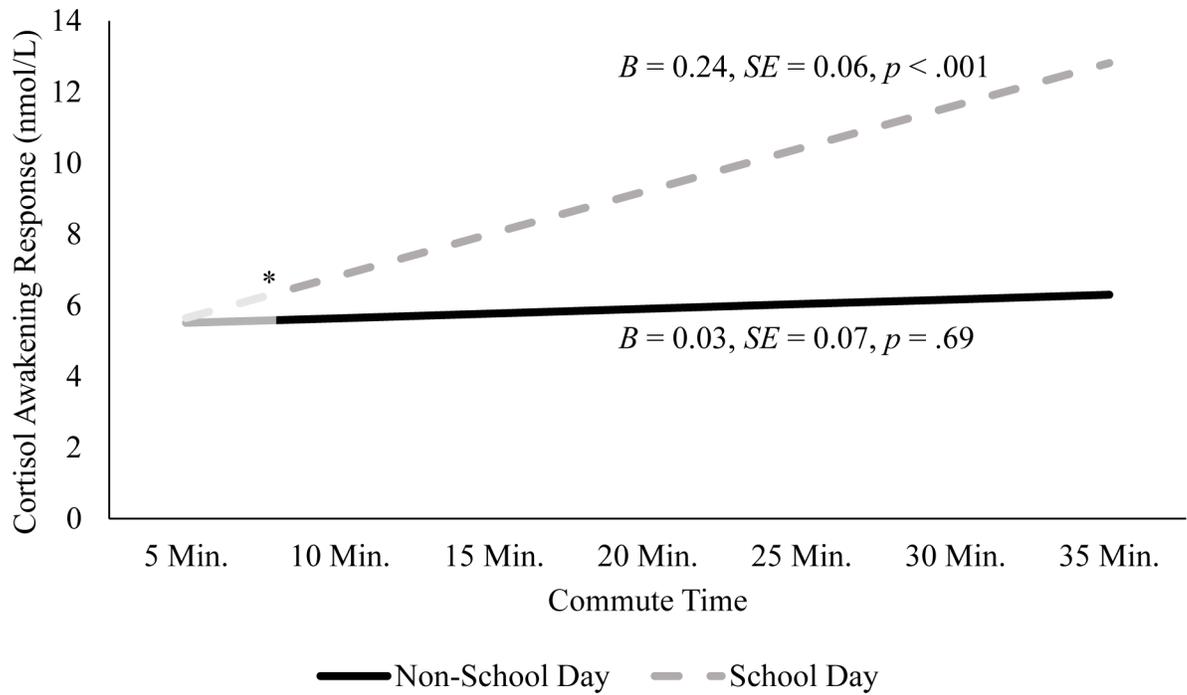
Figure 1.
Cortisol Awakening Response as a Function of School Day and Commute Time.
Note: There was a significant effect of school day on cortisol awakening response for commute times longer than 9 min., as indicated by the *.

a)

$B = 0.30, SE = 0.09, p = .001$

$B = 0.17, SE = 0.06, p = .007$

$B = 0.04, SE = 0.08, p = .585$

b)

$B = 0.27, SE = 0.07, p < .001$

$B = 0.16, SE = 0.05, p = .001$

$B = 0.05, SE = 0.06, p = .38$
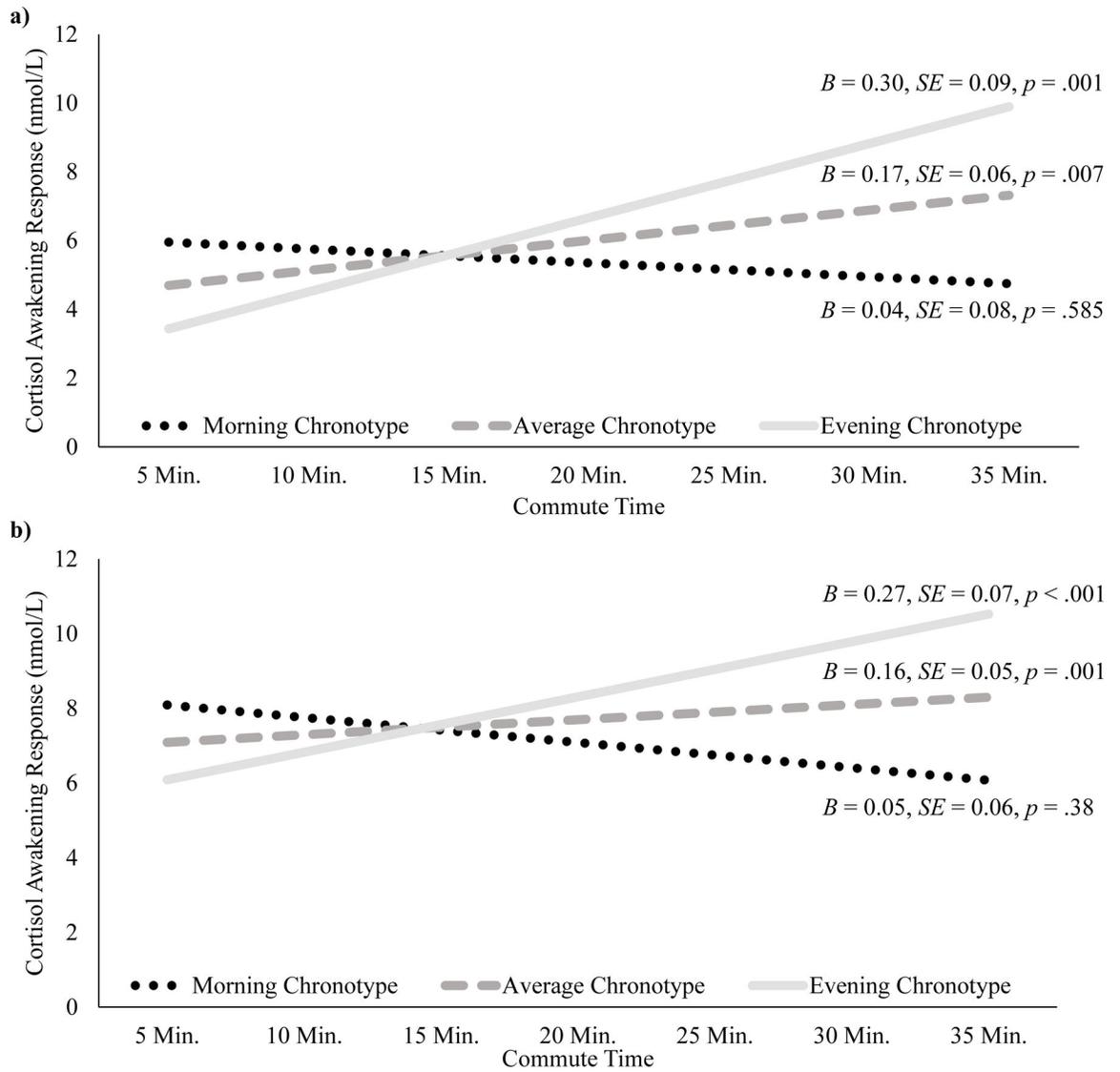
Figure 2.
Cortisol Awakening Response as a Function of Chronotype and Commute Time. Results for unadjusted Cortisol Awakening Response are presented in (a) and results after recoding negative values of Cortisol Awakening Response to 0 are presented in (b).

Table 1.

Descriptive Statistics for Study Variables.

	M	*SD*	Range	Level[a]
Age (years)	16.38	0.74	14.5–22.17	Adolescent
Parental Education	7.16	1.84	1.5–11	Adolescent
School Start Time (time am/pm)	7:35	0:30	6:30–12:45	Adolescent
Commute Time (hours)	12.37	7.89	2–60	Adolescent
Chronotype (time am/pm)	3:39	1:15	0:31–8:06	Adolescent
Waking Cortisol (nmol/L)	17.85	9.67	0.71–121.45	Day
15 Min Post-Wake Cortisol (nmol/L)[b]	21.94	10.73	0.10–97.06	Day
30 Min Post-Wake Cortisol (nmol/L)[b]	22.74	12.46	0.29–114.51	Day
Dinner Time Cortisol (nmol/L)	7.12	66.95	0.09–62.73	Day
Bedtime Cortisol (nmol/L)	2.86	4.51	0.05–47.67	Day
Cortisol Awakening Response (nmol/L)	4.94	11.23	−47.43–51.89	Day
Recoded Cortisol Awakening Response (nmol/L)	6.93	8.52	0–51.89	Day
Diurnal Slope (nmol/L)	−1.01	0.65	−4.03–1.42	Day
Sleep Duration (hours)	7.55	1.20	2.51–10.12	Day
Wake Time (time am/pm)	7:26	1:16	4:40–10:58	Day

Note.

[a] For variables collected at the level of the adolescent, there is one value per adolescent which does not vary across days. For variables collected at the level of the day, there is one value per day with up to three days per adolescents, such that these values can vary across days.

[b] Adolescents provided these cortisol samples 15 and 30 min. after they reported waking up. Descriptive statistics for variables collected at the day-level (i.e., waking cortisol, 30 min. post-wake cortisol, bedtime cortisol, Bedtime Cortisol, Cortisol Awakening Response, Diurnal Slope, Sleep Duration, Wake Time) average values across all days, with multiple days per participant.

Table 2.

Cortisol Awakening Response as a Function of Commute Time, School Day, and Chronotype.

| | Cortisol Awakening Response | | | | | | Recoded Cortisol Awakening Response | | | | | |
| | (1) School Day X Commute Time | | (2) Chronotype X Commute Time, Unadjusted | | (3) Chronotype X Commute Time, Adjusted | | (1) School Day X Commute Time | | (2) Chronotype X Commute Time, Unadjusted | | (3) Chronotype X Commute Time, Adjusted | |
Variable	B	SE	B	SE	B	SE	B	SE	B	SE	B	SE
Constant	4.33***	0.95	4.34***	0.94	−10.80	5.53	5.71***	0.76	5.71***	0.76	−4.97	4.37
School Day	1.11	0.85	1.04	0.84	−0.45	1.22	1.77**	0.65	1.72**	0.65	0.90	0.91
Commute Time	0.07	0.08	0.09	0.08	0.12	0.09	0.03	0.07	0.04	0.07	0.08	0.07
School Day X Commute Time	0.14	0.11	0.16	0.11	0.12	0.11	0.21*	0.08	0.23**	0.08	0.22**	0.08
Chronotype	−0.18	0.38	−0.22	0.38	−1.43*	0.60	−0.10	0.30	−0.14	0.30	−1.24*	0.48
Chronotype X Commute Time	—	—	0.10*	0.05	0.14**	0.05	—	—	0.09*	0.04	0.12**	0.04
Asian American	1.09	1.35	1.15	1.34	0.14	1.39	1.03	1.07	1.11	1.06	0.44	1.12
Latino	−1.03	1.22	−0.88	1.21	−1.18	1.25	−0.32	0.96	−0.18	0.95	−0.51	1.00
Other Ethnicities	−1.95	2.23	−2.00	2.21	−1.82	2.31	−2.22	1.74	−2.25	1.72	−2.42	1.83
Female	1.64***	0.48	1.67***	0.48	1.97***	0.50	1.39***	0.38	1.42***	0.38	1.75***	0.40
Parents' Education	0.29	0.28	0.29	0.27	0.21	0.29	0.22	0.22	0.23	0.22	0.13	0.23
Age	−0.58	0.65	−0.55	0.65	−1.01	0.71	−0.34	0.51	−0.32	0.51	−0.87	0.56
School Start Time	−0.91	1.30	−1.26	1.29	−1.83	1.34	−0.71	1.03	−1.01	1.02	−1.26	1.08
Mean Sleep Duration	—	—	—	—	−0.13	0.43	—	—	—	—	−0.25	0.35
Daily Sleep Duration	—	—	—	—	0.01	0.43	—	—	—	—	−0.20	0.31
Mean Wake Time	—	—	—	—	2.36***	0.70	—	—	—	—	1.80**	0.56
Daily Wake Time	—	—	—	—	−0.87	0.45	—	—	—	—	−0.43	0.33

Note.

*
$p < .05$

**
$p < .01$

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Cortisol Awakening Response refers to models predicting unadjusted values of cortisol awakening response including negative values, and Recoded Cortisol Awakening Response refers to models predicting values of cortisol awakening response in which negative values were recoded to be 0; Sex was effect-coded (−1=male, 1=female); Commute Time, Chronotype, Parents' Education, Age, School Start Time, Mean Sleep Duration, and Mean Wake Time were grand mean-centered; Ethnicity was dummy-coded with European American as the reference group; School day was dummy-coded (−1=weekend, 1=weekday); Sleep Duration and Wake Time were centered at the adolescent's mean across the three days.

***
$p < .001$

Table 3.

Diurnal Slope as a Function of Commute Time, School Day, and Chronotype.

	Diurnal Slope					
	(1) School Day X Commute Time		(2) Chronotype X Commute Time, Unadjusted		(3) Chronotype X Commute Time, Adjusted	
Variable	B	SE	B	SE	B	SE
Constant	-0.95***	0.06	-0.95***	0.06	-0.73*	0.35
School Day	-0.14**	0.05	-0.15**	0.05	-0.11	0.08
Commute Time	0.01*	0.01	0.01**	0.01	0.01*	0.01
School Day X Commute Time	-0.01	0.01	-0.01	0.01	-0.01	0.01
Chronotype	0.02	0.02	0.02	0.02	-0.01	0.04
Chronotype X Commute Time	—	—	0.00	0.00	0.00	0.00
Asian American	0.10	0.08	0.11	0.08	0.12	0.09
Latino	-0.01	0.07	0.00	0.07	0.03	0.08
Other Ethnicities	0.11	0.12	0.11	0.12	0.14	0.14
Female	-0.02	0.03	-0.02	0.03	-0.02	0.03
Parents' Education	0.03	0.02	0.03	0.02	0.04*	0.02
Age	0.04	0.04	0.04	0.04	0.04	0.04
School Start Time	-0.14	0.08	-0.15	0.08	-0.11	0.08
Mean Sleep Duration	—	—	—	—	-0.04	0.03
Daily Sleep Duration	—	—	—	—	0.00	0.03
Mean Wake Time	—	—	—	—	0.01	0.04
Daily Wake Time	—	—	—	—	0.03	0.03

Note.

*
$p < .05$

**
$p < .01$

***
$p < .001$

Sex was effect-coded (–1=male, 1=female); Commute Time, Chronotype, Parents' Education, Age, School Start Time, Mean Sleep Duration, and Mean Wake Time were grand mean-centered; Ethnicity was dummy-coded with European American as the reference group; School day was dummy-coded (–1=weekend, 1=weekday); Sleep Duration and Wake Time were centered at the adolescent's mean across the three days.