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5   **Title:** Associations between brain structure and sleep patterns across adolescent development

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KEY POINTS

Question: Does age modulate associations between gray matter structure and actigraphic sleep patterns across adolescent development?

Findings: This cross-sectional study reports stable associations between regional gray matter structure and shorter duration, later timing, and poorer continuity of sleep from ages 9 to 25 years-old, as well as developmentally-specific associations that are present only from late childhood to early-to-mid adolescence.

Meaning: Stronger coupling of gray matter and sleep patterns from late childhood to early-to-mid adolescence potentially implicates this discrete developmental window as a period of vulnerability to adverse sleep-brain interactions. Sleep intervention during this developmental stage may support healthier neurodevelopmental trajectories.

ABSTRACT

Importance: Structural brain maturation and sleep are complex processes that exhibit significant changes over adolescence and are linked to healthy physical and mental development. The precise timing and magnitude of these changes influence function throughout the lifespan. However, the relationships between gray matter structure and sleep patterns during adolescence are not fully understood. A detailed characterization of brain-sleep associations during this sensitive period is crucial for understanding factors contributing to optimal neurodevelopmental trajectories in adolescence.

Objective: To investigate whether sleep-gray matter relationships are developmentally-invariant (i.e., stable across age) or developmentally-specific (i.e., only present during discrete time windows) from late childhood through young adulthood.

Setting: The Neuroimaging and Pediatric Sleep Databank was constructed from 8 research studies conducted at the University of Pittsburgh between 2009 and 2020.

Participants: The final sample consisted of 240 participants without current psychiatric diagnoses (9-25 years), and with good quality sleep tracking and structural MRI (sMRI) data.

Design: Participants completed a sMRI scan and 5-7 days of wrist actigraphy to assess naturalistic sleep. We examined cross-sectional associations between sMRI measures and sleep patterns, as well as the effects of age, sex, and their interaction with sMRI measures on sleep.

Main Outcome(s) and Measure(s): Using Freesurfer software, we extracted cortical thickness and subcortical volumes from T1-weighted MRI. Sleep patterns (duration, timing, continuity, regularity) were estimated from wrist actigraphy.

97   **Results.** Shorter sleep duration, later sleep timing, and poorer sleep continuity were associated

98   with a stable pattern of thinner cortex and altered subcortical volumes in diverse brain regions

99   across adolescence. In a discrete subset of regions (e.g., posterior cingulate), thinner cortex

100 was associated with these sleep patterns from late childhood through early-to-mid adolescence,

101 but not in late adolescence and young adulthood.

102 **Conclusions and Relevance:** In childhood and adolescence, developmentally-invariant and

103 developmentally-specific associations exist between sleep patterns and gray matter structure, in

104 a wide array of brain regions linked to many sensory, cognitive, and emotional processes. Sleep

105 intervention during specific developmental periods could potentially promote healthier

106 neurodevelopmental outcomes.

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INTRODUCTION

Structural brain maturation and sleep are complex processes that exhibit significant changes during adolescent development. The precise timing and amount of these changes in youths likely influences multiple adult outcomes. Optimal sleep and brain maturation are each known to influence adolescent health and functioning, including academic/vocational achievement, mental health, and/or risk behaviors[1–10]. However, relationships between gray matter structure and sleep patterns over adolescence are not fully understood; furthermore, it is unknown whether these relationships vary as a function of age. A detailed characterization of brain-sleep relationships in adolescence is important for understanding factors contributing to optimal neurodevelopmental trajectories during this sensitive period.

Many brain regions implicated in cognitive and emotional outcomes show a protracted developmental course through adolescence[11–15], indicating that periods of heightened plasticity also come with greater vulnerability[15,16]. Cortical thickness usually peaks by age 9-10 and then decreases until early adulthood, particularly in frontal, parietal, and temporal regions[4,12,17–23]. Most subcortical regions increase in volume until ~14-15 years, with growth plateauing afterwards[13,24,25]. Deviations from these normative trajectories may increase vulnerability to diverse negative outcomes, including poorer academic performance, mental health difficulties, and/or risky behaviors.

During adolescence, brain structural maturation is accompanied by multiple cognitive, behavioral, and emotional changes, including changes in sleep. Adolescence is characterized by a circadian phase delay and reduced homeostatic sleep drive, contributing to later sleep timing[26,27]. These biological shifts converge with psychosocial and behavioral factors (e.g., school start times, peer socializing) to result in insufficient sleep and, at times, poorer sleep regularity or continuity[26,27]. Disruptions to the timing, duration, continuity, and regularity of sleep predict and track with the severity of adverse cognitive and emotional outcomes (e.g., poor school performance, depression, substance use)[28–32].

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135   Developmental shifts in sleep characteristics may possess reciprocal relationships with

136   brain structural maturation[33–36], ultimately influencing diverse outcomes. While sleep serves

137   multiple purposes, one such function is to support synaptic plasticity and reorganization of brain

138   circuitry[24]. Sleep disruption was originally considered a *consequence* of brain structural

139   abnormalities; however, recent animal data indicate that sleep disruption during periods of

140   heightened developmental plasticity also *cause* deviations in brain maturation[37–39]. These

141   translational studies imply stronger brain-sleep relationships in certain developmental

142   windows[37,40]. Yet, in humans it is unknown whether brain-sleep relationships are stable across

143   adolescent development (i.e., developmentally-invariant relationships) or only occur during a

144   discrete window of development (i.e., developmentally-specific relationships). Developmentally-

145   specific brain-sleep relationships could inform the optimal timing of brain and/or sleep-based

146   interventions that promote healthier neurodevelopmental outcomes. Several initial reports have

147   identified ties between diverse gray matter structures and sleep in pediatric populations[41–48].

148   However, developmentally-specific relationships have not been examined and these studies

149   have been restricted to retrospective self-report or lab-based sleep measures that do not reflect

150   usual sleep. An important next step is to evaluate how brain structure relates to objective,

151   ecologically-valid sleep patterns (as captured by wrist actigraphy) through a developmental lens.

152   To address these open questions, we created the Neuroimaging and Pediatric Sleep

153   (NAPS) Databank, a large, harmonized cross-sectional databank comprised of healthy children,

154   adolescents, and young adults (ages 9-25yr). We estimated sleep from wrist actigraphy and

155   sMRI measures from T1-weighted MRI. Given that a wide array of sMRI measures have been

156   associated with sleep, we conducted data-driven regularized regression analyses, to test many

157   potential predictors while minimizing the issues of predictor inter-correlation and multiple

158   comparisons. We explored developmentally-invariant and developmentally-specific associations

159   between sMRI measures (subcortical volume, cortical thickness) and core sleep dimensions

160   (sleep duration, timing, continuity, regularity). Because there are important sex differences in

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161 sleep and brain development[17,49–54], we also explored the interaction between self-reported sex

162 and neuroimaging measures on sleep outcomes.

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164 **METHODS**

165 **Participants**

166 The initial NAPS databank includes a total of 307 participants drawn from eight

167 University of Pittsburgh studies conducted between the years of 2009 to 2020. Studies were

168 considered for inclusion in NAPS if they included: a) actigraphic sleep monitoring; b) a sMRI

169 scan; c) a baseline assessment reflecting naturalistic sleep; and d) participants aged 8-30

170 years-old (inclusive). Participant-level inclusion criteria were: a) 8-25 years-old; b) absence of

171 current psychiatric diagnosis based on clinical interview (i.e., KSADS, SCID); c) no current

172 psychotropic or hypnotic medication use; d) ≥5 days of good quality actigraphic sleep monitoring

173 composed of both weekday and weekend days; e) good quality MRI scan. Demographics of the

174 final analytic sample of N=240 are described in **Table 1.** Demographics by protocol are reported

175 in **eTable 1** and reasons for participant exclusion are documented in the **eMethods**.

176 **Neuroimaging Methods and Outcomes**

177 Please see **eTable 2** for sMRI protocol parameters. We used the FreeSurfer analysis

178 software[55–58] (v6.0) to extract measures of cortical thickness (Desikan-Killiany atlas[59], n=34

179 measures) and subcortical volume (aseg.mgz atlas, n=8 measures) averaged across two

180 hemispheres. We implemented a quality assessment pipeline developed by and used for the

181 Enhancing Neuroimaging Genetics through Meta-Analysis consortium[60–70]. An automated

182 MRIQC T1w-classifier determined individual scan quality based on a reference template[71]. We

183 adjusted neuroimaging data for scanner protocol effects with ComBat[72,73].

184 **Wrist Actigraphy**

185 Actigraphy is a well-validated and widely-used tool for objectively assessing naturalistic

186 sleep in children, adolescents, and adults[74–76]. Participants continuously wore wrist actigraphs

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187 on their non-dominant wrist during a monitoring period of 5 or more consecutive days[77]. **eTable**

188 **1** describes the number of participants who wore watches from Philips Respironics (PR;

189 Actiwach-64, Actiwatch2, Spectrum series) or Ambulatory Monitoring, Inc. (AMI; Basic

190 Octagonal Motionlogger). Wrist activity was sampled in 1-minute intervals (epochs). Participants

191 were asked to indicate via button press the start and end of each sleep interval.

192 We estimated sleep from wrist actigraphy using a combination of validated brand-

193 specific sleep algorithms (PR Medium Threshold; AMI Sadeh) and standardized visual editing

194 procedures[78–80]. Trained scorers blinded to neuroimaging data manually identified rest intervals

195 based on a combination of event markers indicated by participants and clear changes in activity

196 and (if available) environmental light level recorded by the device. Brand-specific sleep scoring

197 algorithms estimated sleep within each rest interval[74,75,79,81–83]. We implemented additional semi-

198 automated quality assurance procedures using in-house R scripts, including identification of the

199 main rest interval (defined as the longest rest interval each day), removal of invalid sleep

200 intervals containing ≥1 hour of off-wrist time or recording errors[79,84], time adjustment for daylight

201 savings time, and final visual inspection of sleep intervals on raster plots.

202 **Sleep Outcomes**

203 Primary actigraphy sleep outcomes were based on the main rest interval. We selected

204 four sleep outcomes corresponding to key dimensions of sleep health[85]: sleep duration (total

205 sleep time in minutes), timing (midpoint between sleep onset and offset in minutes from

206 midnight), continuity (minutes awake after sleep onset; WASO), and regularity (intra-individual

207 standard deviation of midpoint in minutes). The first three outcomes were averaged over the 5-7

208 tracking days most proximal to their MRI scan; regularity was calculated from the available days

209 of recording. Sleep variables were natural log transformed to normalize distributions.

210 **Statistical Analyses**

211 We first conducted general additive models to confirm that the four sleep outcomes

212 showed age-associated patterns consistent with prior research (**eFigure 1**). We observed the

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213   characteristic decline in sleep duration, delay in sleep timing, and increased sleep variability

214   over adolescent development. Sleep continuity did not vary with age.

215   We were interested in developmentally-invariant effects (i.e., main effects) of

216   neuroimaging measures on the four sleep outcomes, as well as developmentally-specific effects

217   (i.e., interactions between age and neuroimaging measures). Due to the large number of and

218   multicollinearity amongst neuroimaging measures, we used regularized regression[86] to identify

219   non-zero predictors associated with sleep outcomes. We used the R package, Group-Lasso-

220   INTERaction-NET (glinternet[87,88]) to examine main effects of structural neuroimaging measures,

221   as well as their interaction with age and sex, for each sleep variable. Only potential interactions

222   between non-zero main effects are considered. We included multiple actigraphy covariates (i.e.,

223   tracking days, season, ratio of weekday to weekend days, actigraph model) as potential

224   predictors in the models. **eTable 3** contains the full list of 48 predictors. We repeated 10-fold

225   cross validation 100 times, using the penalty parameter (λ) one standard deviation away from

226   the minimal cross-validation error. The final model was the model was selected most often

227   during this procedure. Regularized regression selects variables based on minimizing error in the

228   model as opposed to statistical significance as in standard regression. Thus, p-values are not

229   reported for non-zero coefficients.

230   Non-zero predictors selected by group-lasso models were entered into linear regression

231   models, as in prior reports[89,90]. R-squared was computed to estimate variance explained by the

232   full model as well as groups of predictors (i.e., demographics, neuroimaging measures,

233   actigraphy covariates). We assessed non-zero interactions between age and neuroimaging

234   predictors with the Johnson-Neyman technique, which obtains parameter estimates and points

235   of significance from the interaction between two continuous variables[91–93]. Non-zero interactions

236   between sex and neuroimaging predictors were probed by comparing estimated marginal

237   means[94].

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239   **RESULTS**

240   All neuroimaging measures, and their interactions with age and sex, selected as non-

241   zero predictors of sleep outcomes are reported in **Table 2**. Non-zero actigraphy covariates (e.g.,

242   season, actigraph type) are reported in **eTable 4**.

243

244   **Sleep Duration (Total Sleep Time)**

245   The main effects of neuroimaging measures, age, sex, and their respective interactions

246   accounted for 25% of the total variance in sleep duration (**Table 2A**). Shorter sleep duration was

247   associated with older age and males had shorter sleep duration in comparison to females.

248   We observed several developmentally-invariant relationships between brain structure

249   and sleep duration. From 9-25 years old, greater volume in the pallidum, hippocampus, and

250   amygdala was associated with shorter sleep duration. Additionally, thinner medial orbitofrontal

251   and isthmus (posterior) cingulate cortices were associated shorter sleep duration. Thinner

252   cortex in the posterior cingulate was associated with shorter sleep duration in both sexes, but

253   there was a stronger relationship in males. Conversely, thinner parahippocampal cortex and

254   shorter sleep duration were associated in females, but not males.

255   We also found developmentally-specific relationships between gray matter structure and

256   sleep duration (**Figure 2A**). In late childhood through middle adolescence, thinner cortex in the

257   cuneus (9-17.3 years) and superior parietal regions (9-16.0 years) was associated with shorter

258   sleep duration; however, this relationship was not observed at older ages. From 21.9-25.9 years

259   old, greater lateral ventricle volume was associated with longer sleep duration.

260   **Sleep Timing (Midsleep)**

261   The main effects of neuroimaging measures, age, and their interactions accounted for

262   20% of the variance in midsleep (**Table 2B**). Midsleep was later in males and among older

263   participants.

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264   Developmentally-invariant relationships were identified for several brain regions.

265   Specifically, lower thalamus volume was associated with later midsleep; this was relationship

266   driven by males. In females only, greater lateral ventricle volume was associated with later

267   midsleep. Thinner superior parietal and lateral occipital cortices were associated with later sleep

268   timing.

269   Developmentally-specific relationships were also observed between neuroimaging

270   measures and sleep timing (**Figure 2B**). From late childhood through middle adolescence,

271   thinner cortex in the pars orbitalis (9-15.2 years), rostral middle frontal (9-14.1 years), and

272   posterior cingulate regions (9-14.5 years) was associated with later midsleep. Thinner medial

273   orbitofrontal cortex in late childhood (9-10 years) was also associated with later midsleep.

274   Greater pallidum volume was associated with later midsleep only from ages 9 to 16.8 years.

275   **Sleep Continuity (WASO)**

276   The combined effects of neuroimaging measures, age, sex, and their interactions

277   accounted for 16% of the variance in sleep continuity (**Table 2C**). WASO was longer among

278   older participants and in females.

279   With regard to developmentally-invariant relationships, greater palladium and thalamus

280   volume was associated with greater WASO. Thinner cortex in middle temporal, precentral, and

281   lateral occipital regions was associated with greater WASO. Greater precentral and entorhinal

282   cortical thickness was associated with greater WASO in females.

283   Thinner parahippocampal (9-14.6 years) and superior parietal cortices (9-16.0 years)

284   were associated with greater WASO from late childhood to mid-adolescence, but not in older

285   adolescents and young adults (**Figure 2C**).

286   **Sleep Regularity (Midsleep Variability)**

287   Regularized regression did not identify any nonzero predictors of midsleep regularity.

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290 **DISCUSSION**

291   Using a large sample of typical adolescent development (9.0-25.9 years), we identified

292 developmentally-invariant and developmentally-specific relationships between gray matter

293 structure and naturalistic sleep patterns. Shorter sleep duration, later sleep timing, and poorer

294 sleep continuity — all of which are associated with adverse health outcomes — were associated

295 with a stable pattern of thinner cortex and altered subcortical volumes in diverse brain regions

296 over adolescent development. In discrete regions, developmentally-specific relationships were

297 also observed. In these regions, thinner cortex from late childhood through early-to-mid

298 adolescence — a pattern associated with accelerated maturation — was associated with less

299 optimal sleep, but these relationships were not detected in late adolescence and young

300 adulthood. Our results provide a novel view of brain-sleep structure relationships within brain

301 structures implicated in a wide array of cognitive, emotional, and psychological processes over

302 adolescent development[2,95–100].

303 ***Cortical thickness in a diverse set of brain regions show developmentally-invariant***

304 ***relationships with sleep***

305   Across adolescent development, thinner cortex in frontal, temporal, parietal, and visual

306 processing areas was associated with shorter sleep duration, later sleep timing, and longer time

307 awake after sleep onset. These brain regions are implicated in salience detection (pars

308 orbitalis), motor function (precentral), memory (entorhinal, middle temporal), and attention and

309 visuospatial perception (superior parietal cortex, lateral occipital)[101]. Given that sleep is

310 associated with diverse range of mental, cognitive and physical health outcomes in

311 adolescence[1–10], it is reasonable that naturalistic sleep is related to brain structure in regions

312 that support multiple functions. Some of these relationships were modulated by self-reported

313 sex, consistent with reported sex differences in sleep patterns and brain development[17,49–54].

314 Future studies should also examine the extent to sex effects may be better explained by

315 pubertal maturation.

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316   ***Increased cortical thickness was associated with healthier sleep patterns from late***

317   ***childhood to middle adolescence***

318   This is the first study, to our knowledge, to demonstrate that brain structure is related to

319   individual differences in naturalistic sleep patterns at different ages, from late childhood through

320   adulthood. Thicker cortex in multiple brain regions was associated with "healthier" sleep (as

321   indicated by longer, more continuous, and earlier sleep) during late childhood and early

322   adolescence. These findings, in conjunction with other work[102], present the possibility that

323   biological factors exert differential influences on behavior at distinct points in development.

324   Accelerated cortical thinning/growth patterns in discrete brain regions could contribute to

325   disruptions in sleep characteristics during late childhood and early adolescence, but not during

326   other periods. Alternatively, disruptions in the typical age-related changes in sleep could lead to

327   accelerating cortical thinning, particularly during this late childhood-early adolescence age

328   range, but not during others. Multiple neurobiological mechanisms likely underlie individual

329   differences in cortical thickness. Cortical thinning is traditionally believed to be caused by

330   synaptic pruning, a re-wiring of synapses[103,104]. Translational models find that, in mice, synaptic

331   pruning is *higher* during sleep than wakefulness in adolescents, but not adults[105]. More recent

332   data suggest that age-associated changes in cortical thickness may also be driven by white

333   matter maturational processes, i.e. myelination[106]. Sleep disruption is detrimental to the

334   formation and maintenance of myelin in murine models[107,108]. Future longitudinal within-person

335   investigations, particularly during late childhood and early adolescence, will be necessary to

336   disentangle the directionality and neurobiological mechanisms of relationships between sleep,

337   cortical thickness measures, and white matter integrity.

338   ***Unexpected relationships between poorer sleep and larger subcortical volumes***

339   Surprisingly, in many cases, we also discovered that *larger* subcortical (i.e.,

340   hippocampal, amygdala, thalamus, and caudate) volumes are associated with more disrupted

341   sleep patterns. One possibility is that exposure to sleep disruption at certain developmental

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342   stages may be correlated with or cause *accelerated* subcortical growth patterns, akin to the

343   acceleration-deceleration hypothesis of chronic stress and neurodevelopment[109–111].

344   Importantly, this result stands in contrast with prior research showing lower subcortical gray

345   matter volumes in relation to poor sleep[46] and mental health conditions[60,112,113]. Thus, replication

346   of these findings, as well as work examining the relationship between structural brain measures

347   and sleep, needs to be further explored in informative subgroups such as individuals with

348   mental disorders.

349   We also observed subcortical volume-sleep relationships in the expected direction. In

350   females, larger lateral ventricle volume was associated with shorter sleep duration and later

351   midsleep. Greater ventricle size has been linked to serious mental health conditions, including

352   schizophrenia[114]. Furthermore, study of older adults also found longitudinal reduction in sleep

353   duration corresponded to ventricular expansion over the follow-up period[115].

354   ***Implications for optimal timing and targets for sleep intervention***

355   If sleep patterns prove to be a causal contributor to individual differences in sMRI

356   measures, our findings have the potential to inform developmentally-sensitive optimization of

357   evidence-based behavioral sleep interventions[116]. As an example, both shorter sleep duration

358   and later sleep timing were associated with thinner cortex in default mode network (DMN)

359   regions (medial orbitofrontal and posterior cingulate cortices), a neural signature tied to

360   outcomes such as depression, insomnia, and poor cognitive function[98,117]. DMN cortical

361   thickness and sleep duration relationships were developmentally-invariant. However, DMN

362   cortical thickness-sleep timing association were only present in late childhood/mid-adolescence.

363   Thus, a sleep treatment geared toward promoting healthy DMN-relevant outcomes should

364   include sleep extension regardless of age but also advance sleep timing in late childhood and

365   early/mid adolescence. Taken as a whole, our findings suggest that sleep interventions,

366   particularly in late childhood through mid-adolescence, may be advantageous for

367   neurodevelopment and thus downstream effects on psychological well-being.

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368   *Limitations*

369   Our sample, while representative of the Pittsburgh Metropolitan area, was limited in its

370   racial and ethnic diversity, factors which contribute to individual differences in brain structure

371   and sleep[28,118]. Although we adjusted for salient actigraphy covariates, actigraphy brand

372   differences may have contributed noise in our data that was not captured by covarying for watch

373   type in our models. Because our analyses were cross-sectional across a range of ages, rather

374   than longitudinal within participants, it is unclear whether sleep patterns are a cause, correlate,

375   or consequence of gray matter structure. Future, prospective longitudinal studies are necessary

376   to disambiguate causal relationships between sleep and sMRI measures, and assess

377   relationships between within-subject trajectories of sleep and brain development.

378   *Conclusions & Future Directions*

379   We found compelling and novel evidence for developmentally-invariant and

380   developmentally-specific associations between sMRI measures and sleep across adolescent

381   development. We plan to build on these findings and examine how individual differences in

382   neuroimaging and sleep measures may identify youth at high-risk for developing adverse

383   cognitive, mental, and physical outcomes.

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782   **FIGURE CAPTIONS**

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784   **Figure 1.** Relationships between sleep and gray matter (cortical thickness, subcortical volume)

785   that are developmentally-invariant (i.e., stable across age) or developmentally-specific (i.e., only

786   present during discrete time windows) from late childhood through young adulthood.

787   **Figure 2**. Johnsyon-Neyman plots of age by neuroimaging measure interactions on sleep

788   dimensions (A. duration, B. timing, and C. continuity). A statistically significant relationship

789   between age and the neuroimaging measures (p<.05) is represented by the red color. Non-

790   significant relationships are represented by the gray color. To aid in the interpretation of the

791   plots, we provide one example of the age by cuneus cortical thickness interaction on sleep

792   duration. a. From 9-17.3 years old, thicker cuneus cortex is associated with longer sleep

793   duration (r=0.33, p=1.0×10^{-4}). b. From 17.4-25.9 years old, this relationship is not present (r=-

794   0.003, p=0.97).

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811 **Table 1:** NAPS sample characteristics

| Variable	Mean or n (sd or %)
Sample N	240
Age (Years)	18.13 (5.26)
Self-reported Sex	
Female	133 (55%)
Male	107 (45%)
Ethnicity	
Non-Hispanic	223 (93%)
Hispanic	15 (6%)
Missing	2 (1%)
Race	
White	170 (71%)
Black	40 (17%)
Asian	11 (5%)
Multiple	16 (7%)
Unknown/Missing	3 (1%)
Wrist Actigraph Type	
AMI Octagonal MotionLogger	36 (15%)
PR/MiniMitter Actiwatch64	25 (10%)
PR Actiwatch2	113 (47%)
PR Spectrum Series	66 (28%)
Tracking Days	6.59 (0.84)
Weekdays	4.51 (0.92)
Weekend Days	2.08 (0.52)
Season	
Spring	43 (18%)
Summer	100 (42%)
Fall	52 (22%)
Winter	45 (19%)
Sleep Duration (min)	417.96 (63.52)
Wake After Sleep Onset (minutes)	56.19 (26.83)
Midsleep (minutes from midnight)	289.99 (76.59)
Midsleep Variability (minutes)	63.66 (44.06)

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819 **Table 2**. Main effects and interactions between age, sex, and neuroimaging measures on
820 actigraphic sleep dimensions. Model weights are reported as standardized regression
821 coefficients.

A. Sleep Duration (Total Sleep Time)

Type of Effect	Variable	Model Weight
Demographic Variable Main Effects	Sex	0.0403
	Age	-0.0732
Subcortical Volume Main Effects	Pallidum	-0.0122
	Hippocampus	-0.0529
	Amygdala	-0.0032
	Lateral Ventricles	0.0221
Cortical Thickness Main Effects	Medial Orbitofrontal Cortex	0.1090
	Parahippocampal Cortex	0.0022
	Posterior Cingulate	0.0576
	Isthmus Cingulate	0.0196
	Superior Parietal Cortex	0.0067
	Cuneus	0.0277
Sex Interactions	Sex x Parahippocampal Cortex	0.0054
	Sex by Posterior Cingulate Cortex	-0.0219
Age Interactions	Age x Lateral Ventricles	0.0234
	Age x Cuneus	-0.0332
	Age x Superior Parietal Cortex	-0.0072
Variance Accounted for by demographic measures only: R^2=0.22		
Variance Accounted for by neuroimaging and demographic measures, and their interactions: R^2=0.25		

B. Sleep Timing (Midsleep)

Type of Effect	Variable	Model Weight
Demographic Variable Main Effects	Sex	-0.0601
	Age	0.1315
Subcortical Volume Main Effects	Thalamus	-0.0009
	Pallidum	0.0120
	Lateral Ventricles	0.0057
Cortical Thickness Main Effects	Medial Orbitofrontal Cortex	-0.0002
	Pars Orbitalis	-0.0136
	Rostral Middle Frontal Cortex	-0.0200
	Posterior Cingulate Cortex	-0.0089
	Superior Parietal Cortex	-0.0051
	Lateral Occipital Cortex	-0.1115
Sex Interactions	Sex x Lateral Ventricles	0.0342
	Sex x Thalamus	0.0010
Age Interactions	Age x Pallidum	-0.0431
	Age x Medial Orbitofrontal Cortex	0.0002
	Age x Pars Orbitalis	0.0187
	Age x Rostral Middle Frontal Cortex	0.0267
	Age x Posterior Cingulate Cortex	0.0189
Variance Accounted for by demographic measures only: R^2=0.10		
Variance Account for by neuroimaging and demographic measures, and their interactions: R^2=0.20		

C. Sleep Continuity (WASO)

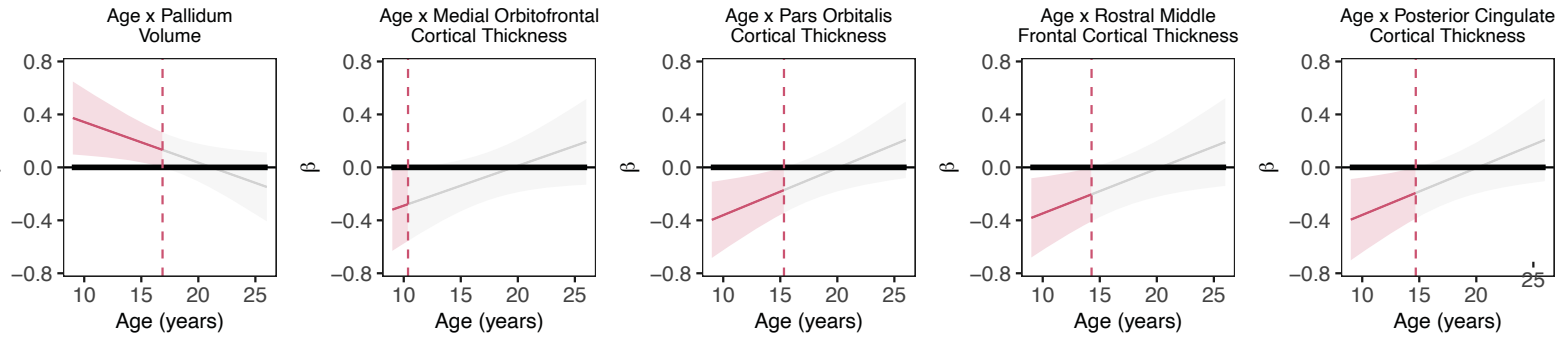| Type of Effect	Variable	Model Weight
Demographic Variable Main Effects	Sex	-0.0444
	Age	0.0244
Subcortical Volume Main Effects	Thalamus	0.0065
	Pallidum	0.0260
	Caudate	0.0083
Cortical Thickness Main Effects	Entorhinal Cortex	0.0009
	Parahippocampal Cortex	-0.0192
	Middle Temporal Cortex	-0.0086
	Precentral Cortex	-0.0283
	Superior Parietal Cortex	-0.0243
	Lateral Occipital Cortex	-0.0149
Sex Interactions	Sex x Caudate	-0.0117
	Sex x Entorhinal Cortex	-0.0021
	Sex x Precentral Cortex	-0.0151
Age Interactions	Age x Parahippocampal Cortex	0.0533
	Age x Superior Parietal Cortex	0.0622
Variance Accounted for by demographic measures only: R^2=0.05		
Variance Account for by neuroimaging and demographic measures, and their interactions: R^2=0.16		

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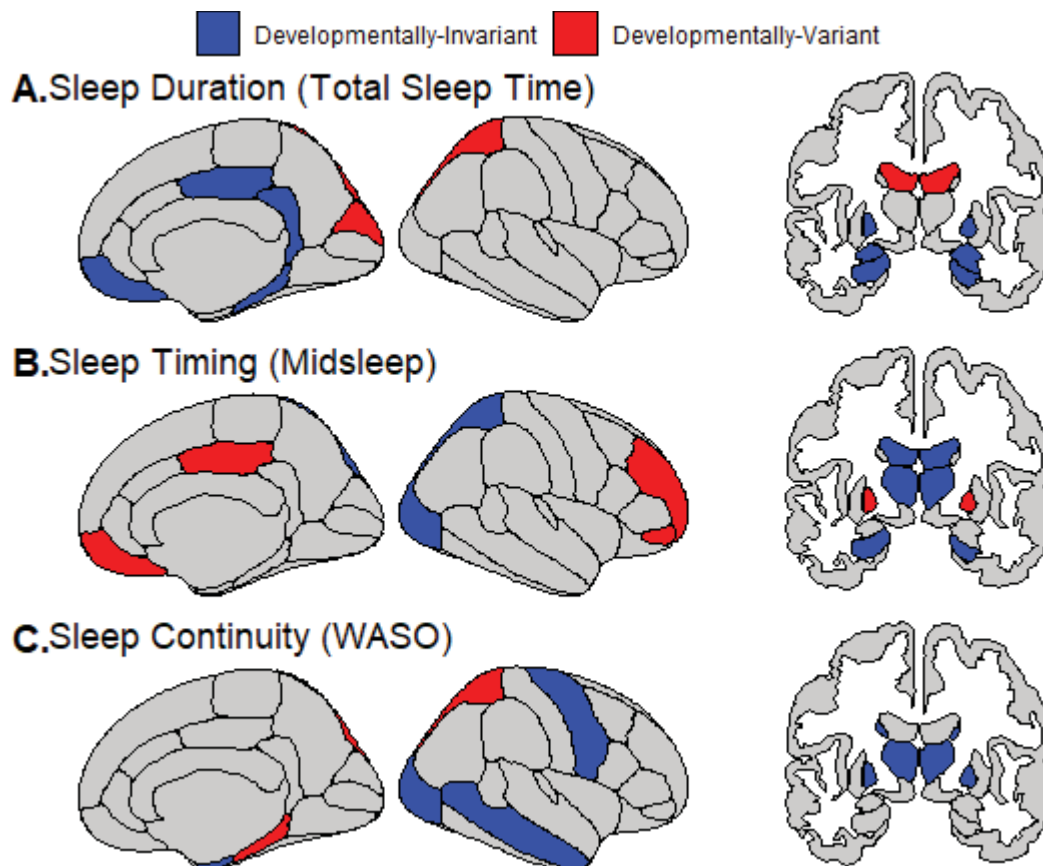
A. Sleep Duration (Total Sleep Time)
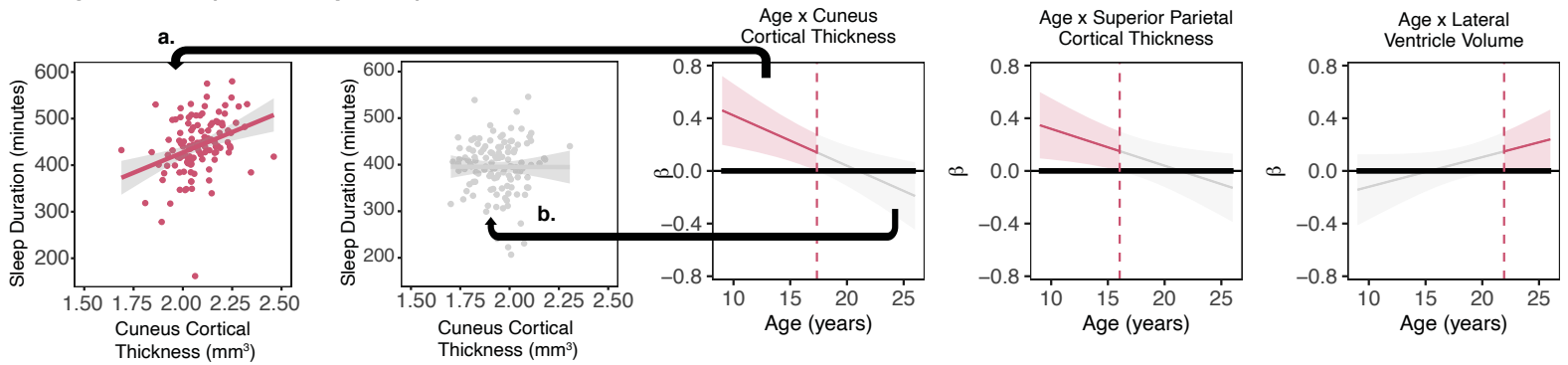
B. Sleep Timing (Midsleep)

C. Sleep Continuity (WASO)