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The relationship of daily physical activity and sleep in adults: variations by age, sex, and race

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Abstract
Prior work suggests physical activity (PA) is related to quantity and quality of sleep. Questions remain regarding directionality, and whether relationships vary by age, sex, and race. We examined daily bidirectional associations between PA and sleep over one week. Participants were 427 adults from the MIDUS Biomarker study, with a mean age of 54.21 ± 11.67 (61% female, 30% non-white). PA (total activity) and sleep (total sleep time; TST and waking after sleep onset; WASO) were measured with an ActiWatch 64. Multilevel mixed-effects models showed differences in the relationships between PA and sleep by age, race, and sex. Following a day with increased PA, younger and nonwhite participants had significantly shorter TST. Days with higher PA were also associated with less WASO for younger participants. Bidirectional effects also emerged; following a night with shorter TST, men, not women, engaged in less next-day PA. Like other studies of daily PA and sleep, effect sizes were small. Future studies should assess potential mechanisms that could explain these demographic differences.

Keywords Aging · Accelerometry · Gender · Health behavior

Introduction

Despite the fact that both physical activity (PA) and sleep are integral to a healthy lifestyle, more than half of adults are physically inactive, and about one-third of adults do not get enough sleep (Schoenborn et al., 2013). While previous work suggests that PA and sleep are related (Chennaoui et al., 2015; Kredlow et al., 2015; Kubitz et al., 1996), there are still many questions with regard to the nature of their relationship. Sleep improvements have often been observed following structured exercise, however, it is worth noting that exercise is distinct from physical activity (Caspersen et al., 1985). While exercise is a planned structured PA that is typically done for the purpose of maintaining physical health, PA can include any movements that occur during the day across multiple domains (work, home, leisure) (Caspersen et al., 1985).

It has been suggested that PA and sleep may compete for time, as the amount of time available in one day is finite (Yao & Basner, 2019). The longer one sleeps, the less time one has available to engage in physical activity. The 24-h movement guidelines give specific recommendations for how sleep, PA, and sedentary behavior could be distributed throughout the day (Rollo et al., 2020; Tremblay, 2020). Generally, guidelines for adults include moderate to vigorous PA that accumulate to 150 min per week, several hours of light PA including standing, 7–8 h of sleep per night, and limited sedentary time (8 h or less) (Ross et al., 2020). Such 24-h guidelines support the examination of total PA accumulated throughout the day, rather than specific exercise bouts. More work is needed to explore the nature of the day-to-day relationships between PA and sleep. Another open question is whether relationships vary across demographic characteristics including age, sex, or race. This knowledge could lead to the development of targeted sleep interventions for groups disposed to poor sleep, including older adults or racial/ethnic minoritized groups.

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Interrelationships between physical activity and sleep

Previous review articles and meta analyses have shown that, generally, PA and/or exercise is beneficial to sleep (Kredlow et al., 2015; Kubitz et al., 1996; Youngstedt et al., 1997). Studies have shown the effects of PA on sleep are both acute (short-term; typically one day of measuring physical activity and sleep), or chronic (long-term, multiple days of assessment). Physical activity could affect sleep by inducing changes in body temperature, heart rate, mood, along with secretions of brain derived neurotrophic factor and growth hormone (Buman & King, 2010; Uchida et al., 2012). Many studies have examined effects of different structured exercise modalities on sleep (e.g., running, cycling, swimming, walking), however, there has yet to be a clear consensus on which types or intensities of exercise are best. Some have shown that high-intensity exercise like cycling or running improve sleep (Herring et al., 2015; Yang et al., 2012), while others find low-intensity activity like walking or yoga can be sufficient (Chen et al., 2009; Chiu et al., 2015; Halpern et al., 2014; Sullivan Bisson et al., 2019).

Recent work has begun to examine how these behaviors interact within-person, over multiple days of assessment. A recently published meta-analysis reported that daily physical activity can affect multiple sleep variables (e.g., sleep latency, wake after sleep onset; WASO, total sleep time; TST), with some caveats (Atoui et al., 2021). Nevertheless, there were many inconsistencies in findings across studies included in the meta-analysis, likely due to differing populations, measurement type, or analyses conducted. Moreover, effect sizes were small to medium (Atoui et al., 2021), suggesting the need for additional research in this area to provide further clarification. Within-person variations in PA have been linked to sleep timing, duration, and efficiency (Master et al., 2019). Reciprocal effects have also been reported; not only does PA impact sleep, but sleep can affect next-day PA (Atoui et al., 2021; Chennaoui et al., 2015; Chevance et al., 2022). At the between-person level, individuals with insomnia or symptoms of disordered sleep are less likely to engage in sufficient PA (Haario et al., 2013). Studies have pointed to negative relationships between sleep variables and next-day PA; following nights with more sleep, longer latencies, or less WASO, next-day PA is decreased (Atoui et al., 2021; Ávila-García et al., 2020; Pettee Gabriel et al., 2017).

Individual differences in PA and sleep

There are large individual differences in both PA and sleep, especially with regard to characteristics such as age, sex, and race (Chen et al., 2015; Mander et al., 2017; Santhi et al., 2016; Schoenborn et al., 2013; Unruh et al., 2008). Those who are older, women, and racial/ethnic minorities are less likely to meet the Centers for Disease Control and Prevention (CDC) PA guidelines (Schoenborn et al., 2013). In general, aging is associated with decreases in total sleep time, along with increases sleep latency, awakenings, and complaints about sleep quality (Helfrich et al., 2018; Scullin, 2012). With regard to sex differences in sleep, while women tend to sleep better according to objective measures, they report sleep problems more frequently than similarly-aged men (Mong & Cusmano, 2016; Santhi et al., 2016). A recent review article reported that compared to white adults, racial/ethnic minorities have shorter TST, poorer self-reported sleep quality, and increased daytime sleepiness (Johnson et al., 2019). Racial differences in TST are observed even in populations as young as four (Parsons et al., 2018). Minority adult populations are also at a higher risk for conditions like sleep disordered breathing or insomnia (Kingsbury et al., 2013).

It has been suggested that an important next step in this line of work is assessing whether the relationships between physical activity and sleep are moderated by demographic characteristics (Atoui et al., 2021). It is possible that age, sex, or race, could impact the amount or type of PA one is able to engage in, or their motivation for doing so (Hickey & Mason, 2017). These demographic factors also have marked impacts on sleep (Redline et al., 2004), which could lead to floor or ceiling effects, by which PA can only do so much to improve sleep. One meta-analysis reported that increases in PA are more closely linked to sleep latency in younger than older participants, but age differences were not seen when other sleep variables were examined (Kredlow et al., 2015). Findings regarding sex differences are inconclusive; some have shown that PA and sleep are more closely linked in males than females (Kredlow et al., 2015), while others have found stronger relationships in females than males (Kubitz et al., 1996; Sullivan Bisson et al., 2019).

Few studies have directly examined racial differences in the relationships between PA and sleep. Using self-reported PA and sleep, one study found that relationships between healthy sleep duration and PA engagement were consistent among black and white college students (Towne et al., 2017). Others suggest that the type of PA matters when examining racial differences. White adults who self-reported engaging in recreational PA had healthier TST (6–9 h per night), whereas black participants who engaged in more occupational PA were more likely to report shorter TST (Murillo et al., 2017). While prior work suggests that PA and sleep are interrelated, results vary as a function of the type of sample, measures, or exercise modality. Further, many studies linking PA and sleep only test relationships within one day without assessing moderators.

Current study

In this study, both physical activity (PA) and sleep were measured objectively over one week with an ActiWatch 64 (Philips USA). The ActiWatch provided estimates of total daily activity and activity intensity, along with total sleep time (TST), minutes of wake after sleep onset (WASO), and latency (amount of time it takes to fall asleep). It was predicted that at the between-person level, more active individuals would sleep objectively better (longer TST, less WASO, and shorter sleep latency). Within-person, it was predicted that on days in which participants were more active than average, they would also have better sleep, that is, longer TST, less WASO, and shorter sleep latency that corresponding night. Alternative lagged models were examined to determine whether sleep predicted next-day PA within-person. It was predicted that following a night of sleep that is better than average (longer TST, less WASO, shorter latency), participants would engage in more next-day PA. Exploratory analyses tested whether any of these relationships were moderated by age, sex, or race.

Method

Participants

Adults who came to the University of Wisconsin (UW), Madison for the Midlife in the United States (MIDUS) Biomarker Study were included in the analyses (n = 441). The Biomarker sample was part of the larger MIDUS study, which was conducted over a 20-year period, in three waves of data collection (Brim et al., 2020). The Biomarker Study was conducted at Wave 2 of data collection and involved an overnight stay at the UW clinic. Participants in the Biomarker sample were originally recruited either from the main national MIDUS longitudinal survey (Brim et al., 2004), or from the MIDUS Milwaukee sample. Probability sampling was used in the MIDUS Milwaukee sample to recruit higher proportions of racial or ethnic minorities to increase diversity of the Biomarker subsample. Of note, prior work has shown that participants in the Biomarker subsample did not significantly differ from the main MIDUS sample when comparing most demographic (e.g., age, sex, income) and health (physical health, BMI, instrumental activities of daily living) characteristics (Dienberg Love et al., 2010). The average education of the Biomarker subsample was, however, slightly lower than the main MIDUS sample.

Analyses were conducted with those who have both sleep and physical activity data (N = 436). Six individuals displayed an idiosyncratic sleep pattern, flagged by MIDUS researchers, and were excluded from data analyses. Three other individuals were excluded due to incomplete data, leaving a final sample of 427. Participants (61% female) ranged in age between 34 and 83, with a mean age of 54.21 (*SD* = 11.67). Participants had an average of 14.37 years of education (SD = 2.62), and an average BMI of 30.68 (SD = 7.36). 30% of the sample was non-white; with 113 participants out of 427 self-reported being black or African American, 6 were Native American or Alaska Native, 2 were Asian, 6 reported being 'other', and 1 did not know.

Measures

Physical activity (PA)

The ActiWatch data was collected in 30-s epochs, with a wake threshold of 40 (medium). MIDUS collaborators from the UW-Madison used Actiware 5 software to generate the summary statistics. A more detailed account of data collection procedures, scoring, and imputation methods is publicly available on the Interuniversity Consortium for Political and Social Research (ICPSR) website (https://www.icpsr.umich.edu/web/NACDA/studies/29282/datadocumentation). The summary statistics used in the current analyses were obtained from www.midus.colectica.org.

The Actiwatch-64 recorded daily PA over a period of 6 days, beginning the day after participants returned home from the University clinic (Wednesday through the following Monday). Both daily *total PA* (the sum of all valid PA activity counts during waking hours), and *PA intensity* (the highest of all valid activity counts during waking hours) were examined. Total PA and PA intensity were averaged over the week for between person analyses. Outliers that fell within the bottom 2% or top 98% of the distribution were winsorized.

Sleep

Sleep was measured objectively with the ActiWatch over 7 days, beginning the night participants returned home from UW (Tuesday). Daily *total sleep time (TST)* was measured in minutes spent asleep, which was transformed into hours. Sleep was also measured using metrics including *wake after sleep onset* (WASO; number of minutes spent awake after falling asleep) and *sleep latency* (minutes it takes to fall asleep). For TST, outliers that fell within the bottom 2% or top 98% of the distribution were winsorized. For WASO and latency, outliers that were within the top 98% of the distribution were winsorized.

Covariates

Age, sex, race, education, season, body mass index (BMI), and depression were included as covariates in the subsequent models. These covariates were selected because they have been found to be related to physical activity and/or sleep in previous research. Age and education were measured in years. Sex was coded as 0 = female, 1 = male, and race was coded as 0 = white, 1 = non-white. Season was dummy coded, with winter as the comparison season. Body mass index was calculated using the formula kg/m^2. Depression was measured by the Center for Epidemiological Studies-Depression scale (CES-D). CES-D scores could range from 0 to 60, with a higher score indicating greater depressive symptoms. Because assessments occurred over the course of one week, we controlled for whether the day was a weekday or weekend (0 = weekday; 1 = weekend).

Data analysis

Descriptive and bivariate analyses

First, we examined means and standard deviations of the PA and sleep variables over the course of the week. Bivariate relationships were tested with zero-order correlations at the between person level. Correlations were estimated between the covariates, average PA, and average sleep across the week.

Within-person relationships between daily PA and sleep

To test daily relationships between PA and sleep, multilevel models were conducted using the lme4 package (Bates et al., 2015) in RStudio (RStudio team, 2020). Multilevel tables were created using sjPlot in RStudio (Lüdecke, 2022). R squared values for each of the models were calculated using the MuMIn package (Barton & Barton, 2020) in R. Taking model 1 as an example, both total PA and PA intensity were examined as predictors of the sleep variables in the same model to examine the adjusted effects. To reduce item variance and make data more amenable to modeling, total PA was divided by 100,000 and PA intensity was divided by 1,000 when used as predictors in subsequent analyses. Both within-person fluctuations in PA (deviation from one's own average; Level 1) and between-person averages of PA across the study (Level 2) were included as predictors. Thus, it was possible to examine effects of average PA on sleep and daily, within-person fluctuations in PA on nightly sleep. Control variables included demographics and health indicators previously linked to sleep; age, sex, race, education, depressive symptoms (CES-D), BMI, and day. The general multilevel model presented here was conducted separately with each of the three sleep variables as outcomes (TST, WASO, and latency). Exploratory analyses were run to determine whether effects of PA on sleep were moderated by age, sex, or race. Only significant moderations are reported.

Model 1:

$$\text{Level 1(within - person)}: \text{Sleep Variable}_{ij} = \beta_{0j} + \beta_{1j}(\text{Total PA}_i) + \beta_{2j}(\text{PA Intensity}_i) + r_{ij}\beta_{1j} = \gamma_{10} + u_{1j}$$

$$\text{Level 2(between} - \text{person)}: \beta_{0j} = \gamma_{00} + \gamma_{01}(\text{Average Total PA}_j) + \gamma_{02}(\text{Average PA Intensity}_j) + \gamma_{0N}(\text{Covariates}_j) + u_{0j}$$

Alternative directional lagged models were tested next, predicting next-day PA from the previous night's sleep. Taking Model 2 as an example, next-day PA was predicted by both within-person fluctuations in daily sleep (deviation from one's own average sleep; Level 1), and between-person average sleep across the study (Level 2). The same covariates were included in the lagged models, with the addition of prior-day PA. This allowed us to examine whether sleep predicted next-day PA above and beyond prior day PA engagement. The general multilevel model shown here was conducted separately with each of our sleep variables as predictors (TST, WASO, and latency), and each of our PA variables as outcomes (total PA and PA intensity). Again, exploratory analyses examined whether age, sex, or race moderated these effects.

Model 2:

$$\text{Level 1 (within - person)}: \text{Next - day PA Variable}_{ij} = \beta_{0j} + \beta_{1j}(\text{Nightly Sleep Variable}_i) + r_{ij}\beta_{1j} = \gamma_{10} + u_{1j}$$

$$\text{Level 2(between} - \text{person)}: \beta_{0j} = \gamma_{00} + \gamma_{01}(\text{Average Sleep Variable}_j) + \gamma_{02}(\text{Prior} - \text{day PA Variable}_j) + \gamma_{0N}(\text{Covariates}_j) + u_{0j}$$

Results

Univariate analyses and correlations between variables of interest

Means and standard deviations for all variables of interest are presented by day of the week in Table 1. Zero-order correlations showing the bivariate relationships between covariates, physical activity (PA) and sleep variables are shown in Table 2. Older adults engaged in less total PA and less intense PA. Age was not significantly correlated with any of the sleep variables. Sex was negatively correlated with objective PA intensity, such that males engaged in

Table 1 Means and SDs for variables of interest over the course of the week

	Day 1 (Tuesday)		Day 2 (Wednesday)		Day 3 (Thursday)		Day 4 (Friday)		Day 5 (Saturday)		Day 6 (Sunday)		Day 7 (Monday)	
Physical activity (PA)														
Total PA	0	NA	416	3.23 (1.23)	426	3.28 (1.23)	421	3.28 (1.26)	417	3.15 (1.25)	413	2.95 (1.19)	408	3.19 (1.18)
PA Intensity	0	NA	416	1.32 (0.47)	426	1.35 (0.51)	421	1.37 (0.51)	417	1.39 (0.54)	413	1.4 (0.56)	408	1.31 (0.48)
Sleep														
TST	414	6.19 (1.35)	425	6.11 (1.3)	426	6.13 (1.43)	420	6.3 (1.46)	415	6.27 (1.53)	412	6.15 (1.41)	407	6.17 (1.36)
Latency	413	26.79 (32.06)	424	26.7 (34.42)	423	26.2 (36.05)	420	29.06 (36.96)	415	28.75 (38.15)	409	26.98 (32.76)	406	30.17 (37.36)
WASO	414	46.92 (29.77)	424	46.47 (30.64)	426	46.98 (29.96)	420	48.74 (30.42)	415	47.94 (29.02)	411	47.13 (28.69)	407	48.11 (27.71)

Participants were given the ActiWatch to begin wearing before departing the University clinic on Tuesday. Thus, it was not worn consistently until the evening and PA data from Tuesday was not included in the dataset

Total PA: Total activity counts (/100,000)

PA Intensity: Max activity counts (intensity; /1,000)

TST: Total sleep time (hours)

Latency: Sleep onset latency (minutes)

WASO: Waking after sleep onset (minutes)

Table 2 Zero-order correlations between variables of interest

Variable	1	2	3	4	5	6	7	8	9	10	11
1. Age											
2. Male	.11*										
3. Race	− .08	− .17**									
4. Education	− .10*	.04	− .20**								
5. CESD	− .11*	− .04	.28**	− .14**							
6. BMI	− .02	− .07	.25**	− .09	.07						
7. Weekend	.04	− .02	.01	.03	− .03	.03					
8. Total PA	− .27**	− .06	− .02	.00	− .05	− .23**	− .09				
9. PA Intensity	− .28**	.11*	.02	.11*	− .14**	− .14**	− .05	.62**			
10. TST	.06	− .19**	− .25**	.02	− .08	− .18**	.06	− .21**	− .12*		
11. Sleep latency	.02	.17**	.23**	− .10*	.21**	.08	.03	− .10*	− .06	− .33**	
12. WASO	.04	.08	.25**	− .05	.16**	.12*	− .03	− .02	− .03	− .11*	.32**

*Indicates $p < .05$; **indicates $p < .01$

more intense activity. Sex was correlated with TST and sleep latency; females had longer TST and shorter sleep latencies. Non-white participants had shorter TST, longer sleep latencies, and more WASO compared to white participants. Education was correlated with PA intensity and sleep latency, such that those who were more educated engaged in less intense PA but fell asleep more quickly. Those with more depressive symptoms engaged in less intense PA, had longer sleep latency, and more WASO. Those with higher BMI engaged in less PA, less intense PA, had longer sleep latencies, and spent more time awake overnight.

Between-person relationships between daily PA and sleep

Average *total PA* across the week significantly predicted TST ($B = -0.25$, 95% CI [−0.34, −0.16], $p < 0.001$; Table 3). Those who engaged in more daily activity, on average, slept less. Average total PA did not significantly predict minutes of WASO, or sleep latency (Table 3). Average *PA intensity* across the week was not a significant predictor of any of the sleep variables (Table 3).

Table 3 Effects of daily and average PA on sleep

	TST			Latency			WASO		
Predictors	Estimates	CI	*p*	Estimates	CI	*p*	Estimates	CI	*p*
Within-person effects									
PA intensity°	0.03	−0.01 to 0.06	0.105	0.01	−0.02 to 0.05	0.504	0.02	−0.01 to 0.05	0.256
Total PA°	−0.05	−0.08 to −0.02	**0.001**	−0.02	−0.05 to 0.02	0.373	−0.04	−0.07 to −0.01	**0.017**
Between-person effects									
Average PA intensity	0.08	−0.01 to 0.16	0.076	−0.01	−0.09 to 0.07	0.753	−0.02	−0.11 to 0.06	0.592
Average total PA	−0.25	−0.34 to 0.16	**< 0.001**	−0.04	−0.11 to 0.04	0.389	0.05	−0.04 to 0.14	0.274
Random effects									
σ^2	0.55			0.70			0.59		
τ_{00}	0.34 $_{\text{M2ID}}$			0.26 $_{\text{M2ID}}$			0.36 $_{\text{M2ID}}$		
ICC	0.39			0.27			0.38		
N	423 $_{\text{M2ID}}$			423 $_{\text{M2ID}}$			423 $_{\text{M2ID}}$		
Observations	2468			2461			2466		
Marginal R^2 /conditional R^2	0.122 / 0.460			0.064/0.320			0.052/0.411		

°Indicates person-centered variable

Within-person relationships between daily PA and sleep

PA and same-night sleep

Daily *total PA* was a significant negative predictor of both TST (*B* = −0.05, 95% CI [−0.08, −0.02], *p* = 0.001) and WASO (*B* = −0.04, 95% CI [−0.07, −0.01], *p* = 0.017) (Table 3; Fig. 1a and b). Following a day in which one was more active than they were on average, they slept less and spent less time awake overnight. The effects of PA on TST were consistent across sex (Table 3). There was a significant interaction between daily total PA and age in predicting nightly TST (*B* = 0.03, 95% CI [0.00, 0.06], *p* = 0.039 Table 4, Fig. 2a). More daily total PA predicted shorter TST in younger adults (*B* = −0.07, 95% CI [−0.12, −0.03], *p* = 0.001), but not older adults (*B* = 0.03, 95% CI [−0.04, 0.04], *p* = 0.862). There was also a significant interaction between daily total PA and race in predicting nightly TST (*B* = −0.09, 95% CI [−0.15, −0.03, *p* = 0.006; Table 4, Fig. 2b). More daily total PA predicted shorter TST in non-white participants (*B* = −0.10, 95% CI [−0.16, −0.05], *p* < 0.001), but not in white participants (*B* = −0.02, 95% CI [−0.05, 0.02], *p* = 0.352).

There was a significant interaction between daily total PA and age in predicting nightly WASO (*B* = 0.03, 95% CI [0.00, 0.07], *p* = 0.042; Table 5, Fig. 2c). More daily total PA predicted less WASO in younger adults (*B* = −0.05, 95% CI [−0.09, −0.01], *p* = 0.018), but not older adults (*B* = −0.01, 95% CI [−0.06, 0.03], *p* = 0.579). The effects of daily total PA on WASO were consistent across sex and race (Table 5). Daily total PA did not significantly predict nightly sleep latency, nor were there any interactions with age, sex, or race (Supplemental Tables 3 & 4).

Daily *PA intensity* was not a significant predictor of any of the sleep variables (TST, WASO, or sleep latency; Table 3). There were no significant interactions between daily PA intensity and age, sex, or race in predicting nightly TST (Supplemental Table 1), WASO (Supplemental Table 2), or latency (Supplemental Table 4).

Sleep and next-day PA

Nightly TST that significantly predicted next-day *total PA* (*B* = −0.04, 95% CI [−0.06, −0.01], *p* = 0.010; Fig. 1c, Table 6). There was also a significant interaction between nightly TST and sex in predicting next-day total PA (*B* = −0.06, 95% CI [−0.11, −0.00], *p* = 0.038; Fig. 2d, Supplemental Table 5). Following a night with more TST than average, males engaged in significantly less total PA (*B* = −0.07, 95% CI [−0.12, −0.03], *p* = 0.002). This relationship was not significant in females (*B* = −0.001, 95% CI [−0.05, 0.02], *p* = 0.468). The effects of TST on next-day total PA were consistent across age and race (Supplemental Table 5). Neither WASO nor sleep latency significantly predicted next-day total PA, nor were there significant age, sex, or race interactions (Supplemental Tables 6 & 7).

There was a significant interaction between WASO and sex on next-day PA intensity (*B* = −0.11, 95% CI [−0.18, −0.03], *p* = 0.004; Fig. 1d, Supplemental Table 8). Following a night with more WASO than average, females engaged in significantly more intense next-day PA (*B* = 0.07, 95% CI [0.02, 0.11], *p* = 0.005). This relationship was not significant in males (*B* = −0.04, 95% CI [−0.10, 0.02], *p* = 0.180). None

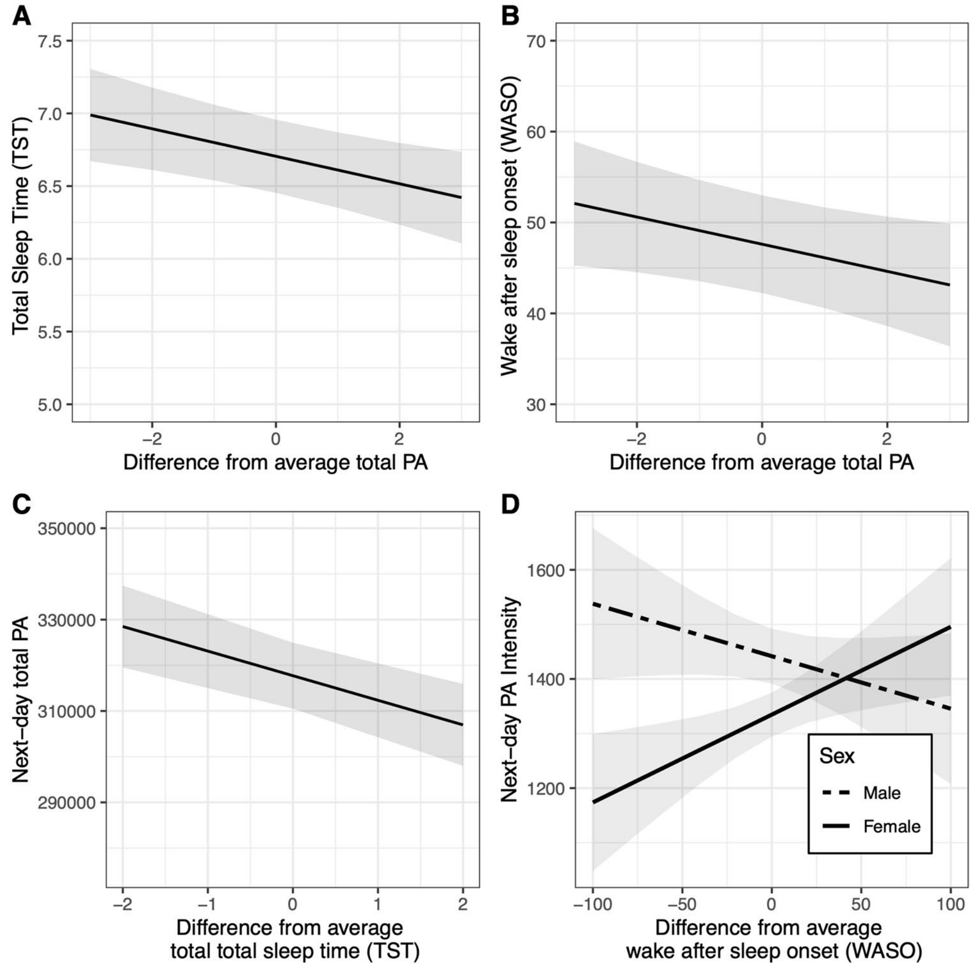

Fig. 1 Sign ificant main effectrs and interactions. Main effect of daily total PA on TST. **a** Main effect of daily total PA on WASO, **b** Main effect of daily TST on next-day total PA, **c** Interaction between daily WASO and sex in predicting next-day PA. *Note* Shaded areas represent 95% confidence intervals

of the other sleep variables predicted next-day *PA intensity,* nor were there any interactions with age, sex, or race. (Supplemental Tables 5, 8, & 9).

Sensitivity analyses

The fact that both total PA and PA intensity were included as predictors in the same model could have led to issues of multicollinearity, given that total PA and intensity were significantly and positively correlated. To assess this, we conducted sensitivity analyses predicting sleep with one PA variable in the model at a time. Results were consistent whether models included one or both PA variables predicting sleep; total PA but not PA intensity predicted nightly sleep.

Discussion

In the current study, we found evidence for bidirectional relationships between daily physical activity (PA) and sleep in a diverse sample of American adults over the course of one week. We also found evidence that these relationships differ based on demographic characteristics including age, sex, and race. While the effect sizes in this study are small, they are similar to other studies of daily PA and sleep (e.g., Atoui et al., 2021) and suggest the need for further research to examine additional factors involved in the relationship. Contrary to predictions, we found that more active individuals slept less. These findings were consistent at both the between-person and within-person levels, suggesting the effects are both short-term and cumulative. While this finding is in contrast to prior work that showed increases in PA were related to *more hours of* sleep (Kishida & Elavsky, 2016; Kredlow et al., 2015; Richards et al., 2011; Sullivan Bisson et al., 2019), the findings are consistent with some recent studies using Actigraphy (Atoui et al., 2021; Ávila-García et al., 2020; Chevance et al., 2022; Pettee Gabriel et al., 2017). The negative relationship between PA and sleep may be more apparent when examining whole-day PA engagement, as opposed to structured exercise. Because there are only 24 h in a day, the more one sleeps, the less time there is for exercise (Yao & Basner, 2019). More sophisticated analytical techniques such as compositional

Table 4 Effects of daily and average PA on total sleep time (TST)

Predictors	Total sleep time		Total sleep time		Total sleep time		Total sleep time	
	Estimates	*p*	Estimates	*p*	Estimates	*p*	Estimates	*p*
(Intercept)	0.37	**< 0.001**	0.37	**< 0.001**	0.37	**< 0.001**	0.37	**< 0.001**
Total PA°	−0.04	**0.004**	−0.07	**0.001**	−0.04	**0.022**	−0.02	0.377
Male	−0.38	**< 0.001**	−0.38	**< 0.001**	−0.38	**< 0.001**	−0.39	**< 0.001**
Age	−0.00	0.984	−0.00	0.982	−0.00	0.986	−0.00	0.988
BMI	−0.15	**< 0.001**	−0.15	**< 0.001**	−0.15	**< 0.001**	−0.15	**< 0.001**
CESD	−0.03	0.430	−0.03	0.429	−0.03	0.431	−0.03	0.436
Weekend	−0.06	0.069	−0.06	0.068	−0.06	0.060	−0.06	0.062
Race (NW)	−0.41	**< 0.001**	−0.41	**< 0.001**	−0.41	**< 0.001**	−0.41	**< 0.001**
Education	−0.02	0.552	−0.02	0.550	−0.02	0.553	−0.02	0.554
Spring	−0.03	0.730	−0.03	0.730	−0.03	0.734	−0.03	0.737
Summer	−0.20	0.057	−0.20	0.057	−0.20	0.058	−0.19	0.058
Fall	−0.05	0.639	−0.05	0.638	−0.05	0.643	−0.05	0.645
Average total PA	−0.20	**< 0.001**	−0.20	**< 0.001**	−0.20	**< 0.001**	−0.20	**< 0.001**
Total PA°*sex			0.06	0.065				
Total PA°*age					0.03	**0.039**		
Total PA°*race							−0.09	**0.006**
Random effects								
σ^2	0.55		0.55		0.55		0.55	
τ_{00}	0.35 $_{M2ID}$		0.35 $_{M2ID}$		0.35 $_{M2ID}$		0.35 $_{M2ID}$	
ICC	0.39		0.39		0.39		0.39	
Observations	2468		2468		2468		2468	
Marginal/conditional R^2	0.118 / 0.459		0.119 / 0.460		0.119 / 0.461		0.120 / 0.461	

°Indicates person−centered variable

data analysis (CoDA) could address these challenges in future research (Fallmann & Chen, 2019). Alternatively, it is possible that more active individuals need less sleep because they are waking up fewer times during the night and getting a better-quality sleep.

Moderators

While other studies examined homogeneous samples, like samples primarily composed of women (Kishida & Elavsky, 2016) or older adults (Richards et al., 2011), the current study was racially diverse and varied in age throughout the adult lifespan. This allowed us to assess differences between white and non-white participants. We found that the negative relationship between total PA and TST was significant for non-white, but not white, participants. This could be because the type of PA is different for different participants. Others have reported racial differences in PA engagement; while white adults are more likely to engage in leisure time PA, black adults are more likely to engage in work-related PA (He & Baker, 2005). Recently, Murillo and colleagues reported that increased PA at work was associated with shorter sleep in African American participants, but not white participants (Murillo et al., 2017). While we did not have specific information about the type of PA recorded by the ActiWatch, this is an important point of future study.

We also found evidence that negative relationships between daily total PA and TST, and PA and WASO were only significant for younger participants. Kredlow and colleagues reported that age moderated the relationship between PA and sleep latency, with older adults having a weaker link between the two. While they did not report significant age moderations for TST or WASO, our findings are in the same direction, with weaker links between PA and sleep in older compared to younger participants. This could be because sleep in older adults is less variable from one day to the next. Indeed, intra-class correlations for the TST of older adults in our study is higher than younger adults (0.45 vs 0.28, respectively). It's also possible that changes to sleep homeostatic mechanisms or circadian processes could explain why sleep is not as affected by PA in older adulthood (Li et al., 2018).

Our findings also add to a growing line of work on sex differences in the relationship between PA and sleep. In some cases, stronger relationships have been found for males (Kredlow et al., 2015) and others have found stronger relationships in females (Kubitz et al., 1996; Sullivan Bisson

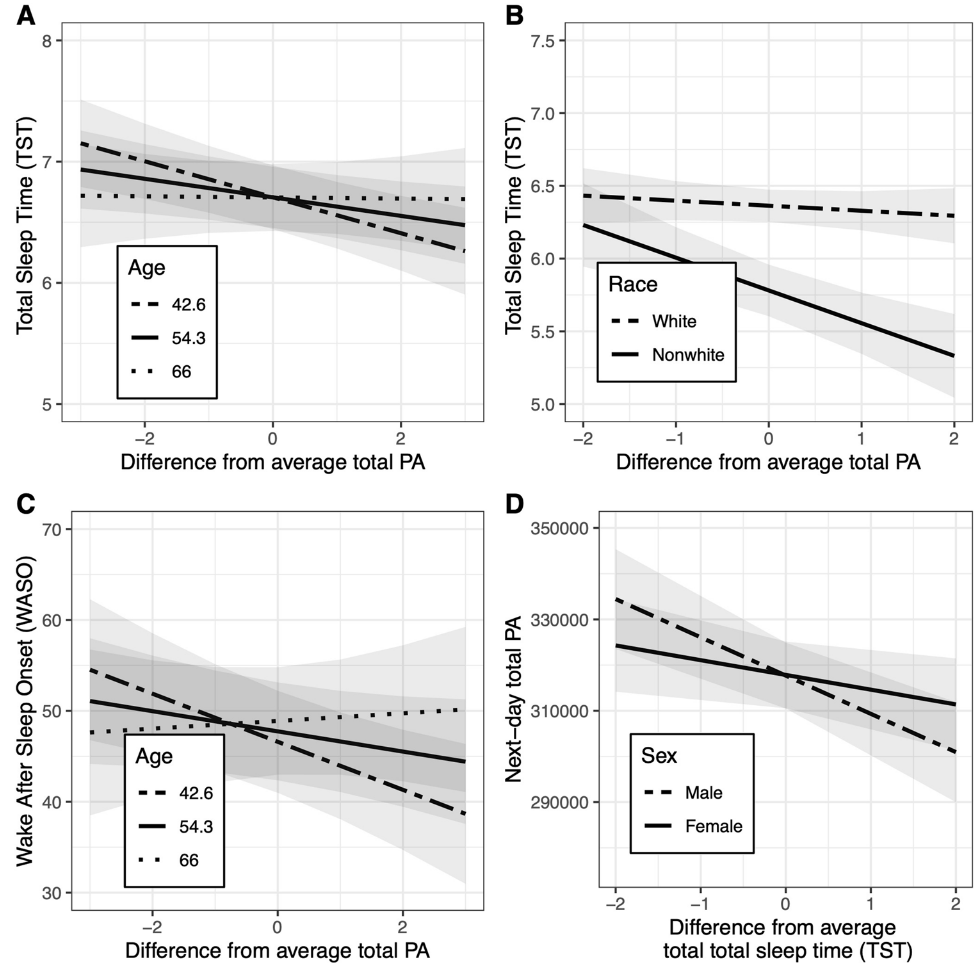

Fig. 2 Results from significant interactions. Interaction between daily PA and age in predicting TST. **a** Interaction between daily PA and race in predicting TST, **b** Interaction between daily PA and age in predicting WASO, **c** Interaction between daily TST and sex in predicting next-day total PA. *Note*: Shaded areas represent 95% confidence intervals

et al., 2019). There are some potential mechanisms that could explain why PA and sleep are differentially related in men and women. First, there is evidence that compared to men, women are more aware of their internal states (Pennebaker, 1982). Thus, it is possible that women are more perceptive of changes in their PA and/or sleep, which could in-turn affect their subsequent behaviors. Both PA and sleep also have the potential to change one's mood or affect, and these pathways could differ by sex (Bhui & Fletcher, 2000; Bisson et al., 2021). Differing thresholds of PA may need to be met for men and women to experience sleep improvements. Because prior work has shown that men typically engage in more PA in total, and more intense PA than women (Aoyagi & Shephard, 2013; Centers for Disease Control (CDC), 2020), women could possibly experience sleep improvements with smaller increases in total PA or PA intensity compared to men.

Limitations

While the sample was diverse with regard to age and race, the majority of the non-white participants were a probability sample from the same geographical area (Milwaukee, Wisconsin). Moreover, participants in this study were those who were able to come to the University of Wisconsin, Madison for an overnight stay. Thus, even though the participants in the Biomarker substudy did not differ from the overall MIDUS sample on key measures, the generalizability of findings is limited somewhat by selective attrition of the longitudinal samples. Also, important to note is that we did not have information as to whether participants had been diagnosed with a sleep disorder, such as obstructive sleep apnea (OSA). It is possible that a sleep disorder like OSA could play a role in the interrelationships between PA and sleep. Future work could examine this question by comparing a sample of healthy controls with OSA patients. Other potential moderators such as BMI or depression are also of interest for consideration in future research.

Another consideration is that participants may have behaved differently during the week they were monitored compared to their normal day to day life. Although we did not have access to the raw Actigraphy data, it is possible that different algorithms for sleep wake threshold could have yielded different estimates of objective nightly sleep.

Table 5 Effects of daily and average PA on wake after sleep onset (WASO)

Predictors	WASO		WASO		WASO		WASO	
	Estimates	*p*	Estimates	*p*	Estimates	*p*	Estimates	*p*
(Intercept)	0.01	0.916	0.01	0.917	0.01	0.915	0.01	0.917
Total PA°	−0.03	**0.034**	−0.05	**0.011**	−0.02	0.123	−0.02	0.380
Male	0.19	**0.006**	0.19	**0.006**	0.19	**0.006**	0.19	**0.006**
Age	0.04	0.274	0.04	0.275	0.04	0.273	0.04	0.273
BMI	0.05	0.162	0.05	0.162	0.05	0.162	0.05	0.162
CESD	0.07	0.057	0.07	0.058	0.07	0.057	0.07	0.057
Weekend	0.00	0.928	0.00	0.930	0.00	0.976	0.00	0.946
Race (NW)	0.31	**< 0.001**	0.31	**< 0.001**	0.31	**< 0.001**	0.31	**< 0.001**
Education	0.02	0.613	0.02	0.615	0.02	0.611	0.02	0.611
Spring	−0.25	**0.015**	−0.25	**0.015**	−0.25	**0.015**	−0.25	**0.015**
Summer	−0.22	**0.036**	−0.22	**0.036**	−0.22	**0.037**	−0.22	**0.037**
Fall	−0.16	0.104	−0.16	0.104	−0.16	0.106	−0.16	0.105
Average total PA	0.03	0.334	0.03	0.335	0.03	0.335	0.03	0.336
Total PA°*sex			0.04	0.152				
Total PA°*age					0.03	**0.042**		
Total PA°*race							−0.05	0.114
Random effects								
σ^2	0.59		0.59		0.59		0.59	
τ_{00}	0.36 $_{M2ID}$		0.36 $_{M2ID}$		0.36 $_{M2ID}$		0.36 $_{M2ID}$	
ICC	0.38		0.38		0.38		0.38	
Observations	2466		2466		2466		2466	
Marginal/conditional R^2	0.052 / 0.411		0.052 / 0.411		0.053 / 0.412		0.052 / 0.411	

°Indicates person-centered variable

While the objective measurement of PA is a strength, it is difficult to equate total activity counts or max activity counts from Actigraphy to current public health recommendations. Because this study was a secondary analysis of summarized Actigraphy, we weren't able to transform the raw data to a more meaningful measure, such as minutes of time spent in moderate to vigorous PA. Future work should examine physical activity variables that can be more directly translated to public health guidelines. We ran many different analyses to test the effects of the moderators. It is important to note so many analyses have increased the likelihood of type 1 errors, especially given that some interactions had p-values that were close to 0.05. Future studies should try to replicate these interaction effects in other samples.

Table 6 Effects of sleep on next-day PA

Predictors	Next-day total PA		Next-day PA intensity	
	Estimates	*p*	Estimates	*p*
Within-person effects				
TST°	−0.04	**0.010**	0.02	0.282
WASO°	−0.03	0.074	0.02	0.344
Latency°	0.01	0.592	0.00	0.962
Between-person effects				
TST	−0.18	**< 0.001**	−0.06	0.085
WASO	0.03	0.335	0.00	0.944
Latency	−0.05	0.102	−0.05	0.318
ICC	0.41		0.28	

Note: Results in Table 6 are from 3 separate models, thus, random effects and model fit statistics are not presented. The full models are presented in Supplementary Tables 5–10

°Indicates person-centered variable

Finally, seasonal or geographical variations may have also played a role in these findings, as seasonality and climate have the potential to affect quantity and quality of sleep, along with the amount of PA engagement (Mattingly et al., 2021; Reilly & Peiser, 2006). While we control for season in the current study, we did not have access to information about where participants lived. It is very possible that participants experienced different climates even in the same season. It is important for future work to assess longitudinal patterns of physical activity and sleep across multiple seasons. While we present evidence that the relationship between PA and sleep may be moderated by factors like age, sex, and race, future work should test whether these pathways are moderated by other factors, like depression, BMI, or other indicators of physical or mental health.

Conclusions

The current study adds to a growing line of work that suggests physical activity and sleep are related to one another both daily (within-person) and cumulatively over a week (between-person). A greater number of significant relationships emerged in the within-person models, and the findings differed by age, sex, and race. Thus, future work should assess whether sleep and PA could be linked with different mechanisms in different populations. Our findings also reinforce the notion that relationships between PA and sleep are bidirectional in nature. Future work should continue to assess bidirectional pathways between PA and sleep, and their interdependence in the daily lives of adults.

The study results also have implications for understanding individual differences in PA and sleep, which could inform future sleep interventions. First, the findings regarding age, sex, and race differences suggest that PA and/or sleep may be related differently in certain populations. Thus, interventions may be more successful if they are personalized to the target population. Second, our findings suggest that total daily PA was more closely related to sleep than PA intensity. Thus, sleep interventions may benefit by taking a whole-day approach in encouraging daily PA increases. Interventions of this nature, perhaps via an activity such as walking, could benefit many groups disposed to poor sleep who may not be able to engage in intense forms of physical activity.

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Authors' contribution AB and ML created the analysis plan, AB conducted all analyses, AB and ML wrote the manuscript collaboratively.

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Availability of data and material The data used in the current analyses are publicly available and obtained from www.midus.colectica.org. A detailed account of data collection procedures, scoring, and imputation methods is also publicly available on the Interuniversity Consortium for Political and Social Research (ICPSR) website (https://www.icpsr.umich.edu/web/NACDA/studies/29282/datadocumentation).

Code availability Codes for all analyses will be published as supplemental materials.

Declarations

Conflict of interest All authors declare this research was conducted in the absence of any financial conflicts of interest. The authors have no competing interests to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Consent to participate Written consent was obtained for all participants prior to beginning the study.

Consent for publication Not applicable.

Human and animal rights and informed consent The study was approved by the Institutional Review Board at the UW-Madison. Written consent was obtained for all participants prior to beginning the study.

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