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Daily Associations Between Sleep and Physical Activity

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Abstract

Background Research has demonstrated a correlational relationship between sleep and physical activity, though this work has been largely cross sectional and fails to demonstrate temporal relationships. The purpose of this study was to test the daily, bidirectional relationships between sleep and physical activity, and whether this varied between weekdays and weekend days.
Method Fifty-four healthy, young adults wore a Fitbit Flex to measure sleep and physical activity during a 6-day study period.
Results Mixed linear models revealed that physical activity did not predict subsequent night's sleep. However, on nights when participants had longer than their own average total sleep time, and greater than their own average wake after sleep onset, this predicted less physical activity the following day.
Conclusion Results suggest that, in healthy young adults, physical activity may not promote healthier subsequent sleep, but sleep duration and continuity influence physical activity in their own way. Young adults may respond differently to health promotion efforts, and a greater understanding of these temporal associations can enhance the efficacy of these efforts.

Keywords Sleep · Physical activity · 24-h health behavior · Fitbit

Introduction

Both insufficient sleep and low physical activity are associated with poor health outcomes [1, 2], and individuals who are more physically active tend to have healthier sleep [3–5]. In fact, physical activity may lead to better sleep quality, and sleep may promote more physical activity, but the direction of these relationships is not well established [6–8]. Meta-analyses have demonstrated that exercise training programs subsequently improve sleep [9, 10], but prospective studies testing the effects of sleep interventions on subsequent physical activity are rare, and the few studies to date have not demonstrated that sleep interventions promote greater physical activity levels [3]. More recently, research has begun to examine how daily fluctuations in physical activity and sleep may relate to one another. Measuring daily fluctuations of physical activity and sleep over multiple days provides a more effective framework for examining temporal relationships between physical activity and sleep. In fact, Irish et al. [11] proposed a 24-h health behavior framework that allows researchers to more effectively examine the daily, temporal relationships between waking health behaviors (i.e., physical activity) and sleep. They posit that by collecting daily data over an extended period of time, it allows researchers to use statistical analyses that test temporal relationships between sleep and waking health behaviors. While this framework does not allow the testing of causal relationships, it provides a greater understanding of how health behaviors may influence one another. Studying these temporal relationships can identify facilitators and barriers to behavior change and maintenance, providing insight that can improve the efficacy of behavioral interventions.

While this framework provides an opportunity to better understand temporal relationships between physical activity and sleep, the research on this topic is limited. Two studies have tested and found significant, bidirectional relationships between sleep and physical activity. A study of middle-aged women found actigraphy-assessed sleep efficiency, which is the percent of time spent asleep while trying to sleep at night, predicted

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more daily activity counts and moderate to vigorous intensity physical activity (MVPA) minutes. Further, while smaller in magnitude, physical activity was associated with a shorter sleep duration that night [12]. In another sample of older adults, Dzierzewski et al. [13] found that MVPA did not lead to greater sleep duration, but did reduce time spent awake during the night. Further, better sleep quality was associated with more MVPA the following day. Two additional studies have assessed bidirectional relationships between physical activity and sleep, but only found significant associations between sleep and next day physical activity. A study of patients with chronic pain found that greater subjective sleep quality, and not actigraphy-assessed sleep, was associated with more participation in exercise the following day [14], and a study conducted among older adults with insomnia reported that longer sleep onset latency predicted shorter exercise duration the following day [15]. Lastly, two studies conducted in middle-aged women did not find any significant, daily relationships between physical activity and sleep [11, 16].

Taken together, these findings demonstrate some support for the 24-h health model, but the research has several limitations. First, the majority of these studies do not differentiate within- and between-person differences in their statistical models. Not differentiating these effects does not allow researchers to determine whether changes in health behavior are determined by intra-individual (daily fluctuations within each person) or inter-individual (differences in mean level study variables) factors. Identifying whether physical activity and sleep are determined by stable or state factors can improve health promotion efforts by identifying targets for behavior change. To our knowledge, only two studies have used this approach to examine the relationships between sleep and physical activity [13, 14].

Another limitation of the current literature is the lack of research examining potential moderators of the daily associations between physical activity and sleep. For instance, schedule demands may differ during weekdays when compared with weekend days. Specifically, individuals are more likely to follow their rhythms during the weekend when there are fewer schedule constraints, while on weekdays they may be restrained by work and social demands [17]. Thus, these differences may lead to different patterns of sleep and physical activity on the weekend when compared with weekdays. For example, if an individual feels rested on weekdays, they still may not have time to be physically active due to work, social, or school obligations. In contrast, feeling rested on weekend days may lead to more physical activity because they have the energy for it *and* have the time to do so. Thus, individuals may have more time to obtain adequate exercise and sleep during the weekend. To our knowledge, this has not yet been tested as a moderating influence between daily physical activity and sleep. Lastly, research has yet to examine daily associations of sleep and physical activity among healthy, young adults. To date, this research has only been conducted in clinical and/or older populations. As noted by Irish et al. [11], it is important to replicate this research in other populations, as it is unclear whether the daily associations between physical activity and sleep would differ between various populations.

The present study extends the current literature in several ways. We evaluated the daily, bidirectional relationship between physical activity and sleep using objective assessment in a sample of healthy, young adults. We also tested whether the relationships between sleep and physical activity differ between weekdays and weekend days. Lastly, we teased apart the between-subject and within-subject effects to determine whether the bidirectional influences exist at an inter-individual or intra-individual level. A significant between-subject effect would indicate that individuals who, on average, are more physically active would experience better sleep than individuals who are less physically active. In contrast, a significant within-subject effect would indicate that, within an individual, a day with greater physical activity would be followed by a better night of sleep compared with days of less physical activity. It was hypothesized that days of greater physical activity would be significantly associated with longer total sleep time and shorter wake after sleep onset that night, and that longer total sleep time and shorter wake after sleep onset would be significantly associated with higher levels of physical activity the next day. Lastly, it was hypothesized that physical activity and sleep would be more strongly related on the weekend.

Methods

Participants

Participants were recruited from a Midwestern university through an undergraduate subject pool and were eligible to participate if they were non-smokers, were not currently being treated for a sleep disorder, had any medical conditions (e.g., migraines, diabetes, rheumatoid arthritis, hypertension) that could affect sleep or engaging in physical activity, did not have shift work, and self-reported that they were able to engage in physical activity.

Procedure

The present study was part of a larger project that also examined the relationships between sleep and academic performance, and was approved by the university IRB. Participants were recruited throughout the fall and spring semesters of an academic school year, and scheduled an appointment with a research assistant through an online research scheduling system. During this initial lab session, participants provided written informed consent and completed a questionnaire assessing sociodemographics.

Following this, participants were instructed on the proper use and care of the Fitbit Flex device, and were told to sync their Fitbit each night to ensure complete collection of sleep and physical activity data. If participants failed to sync data on any study day, they received an email reminder from the research team to sync their Fitbit. After completing this in home assessment for 1 week, participants returned to the lab and their data was downloaded from the Fitbit website. Sleep and physical activity from the final day of the study were not used in present analyses due to parent study procedures that could influence participant behaviors, and therefore the present study was based on the first 6 days and nights of data collection.

Measures

Sleep Fitbit Flex devices were used to assess objective sleep each night of the study period. This commercially available wrist-worn accelerometer uses movement to infer sleep and wake states. Sleep was measured with both total sleep time and wake after sleep onset. Total sleep time is the amount of minutes spent asleep, and wake after sleep onset is the number of minutes spent awake after initially falling asleep. Fitbits are a cost-effective tool for estimating sleep measurement, particularly among healthy sleepers [18], and have been found to accurately measure sleep duration and continuity when compared with polysomnography [19]. Fitbit provides other sleep parameters (i.e., number of nighttime awakenings) but total sleep time and wake after sleep onset were chosen prior to analyses because they are the best measures of sleep duration and continuity.

Physical Activity Fitbit Flex devices were also used to collect objective physical activity data. Physical activity was measured by number of steps taken during the day, total minutes active during the day (metabolic equivalents at or above 3 for at least 10 consecutive minutes), and total calories burned during the day. Fitbit Flex devices are an acceptable tool for measuring step counts and energy expenditure [20, 21]. Fitbit provides other measures of physical activity, but these three were chosen prior to analyses because they best represent levels of physical activity and energy expenditure.

Data Analysis

Using SPSS version 22, mixed linear models were conducted to test the daily influences of both physical activity on subsequent night's sleep and sleep on next day's physical activity. Eight participants were removed from all analyses due to having incomplete study data. All remaining participants had 6 consecutive days and nights of objectively assessed physical activity and sleep data. All physical activity and sleep variables were tested separately as predictors, resulting in 12 main effect models and 12 interaction models. Age and gender were included as covariates in every model. Within-subject (participant's mean subtracted from their daily score) and between-subject (sample mean subtracted from participant's mean) effects for each predictor variable were entered as fixed effects into the same model. Thus, each main effect model had four predictors (e.g., age, gender, steps between subject, steps within subject). A binary variable of weekday vs. weekend day (this will be referred to as "day type") was tested as a moderator of the relationships between the physical activity and sleep variables. Given recommendations for multilevel modeling [22], we were adequately powered to detect both level 1 (within-person) and level 2 (between-person) effects.

Results

Demographics

Sample characteristics for the participants ($N = 54$) are displayed in Table 1. The majority of participants were white (77.4%), were female (70.4%), and were on average 19.35(1.5) years old. Participants were, on average, moderately active and obtained at least 7 h of sleep per night.

Models Testing Bidirectional Effects

Between-Subject Effects The intraclass correlation coefficients indicated that 17% of the variance in steps, 38% in total minutes active, 74% in calories burned, 23% in total sleep time, and 34% in wake after sleep onset existed between participants. There were no significant between-subject associations between physical activity and sleep (see Tables 2 and 3). Days on which participants varied from sample mean steps, calories burned, and total minutes active did not significantly predict subsequent night's sleep, and variation from sample mean

Table 1 Demographic and health characteristics ($N = 54$)

Gender, *n* (%)	
Male	16 (29.6%)
Female	38 (70.4%)
Age, mean (SD), years	19.35 (1.52)
Race, *n*(%)	
White	41 (75.9%)
American Indian	6 (11.1%)
Other	6 (13%)
Steps, mean (SD)	9768.19 (2694.29)
Calories burned, mean (SD)	2446.90 (396.38)
Total minutes active, mean (SD)	258.03 (65.44)
Total sleep time, mean (SD), min	439.43 (64.41)
Wake after sleep onset, mean(SD), min	24.47 (11.13)

Table 2 Physical activity predicting sleep

	Total sleep time			Wake after sleep onset		
Predictor	*B*	SE	*t*	*B*	SE	*t*
Steps						
Age	− 3.37	7.44	− .45	2.03	1.13	1.80
Gender	14.32	24.19	− .45	.95	3.68	.26
Within	− .00	.00	− .22	.00	.00	1.20
Between	− .00	.003	− 1.69	− .00	.00	− 1.26
Calories burned						
Age	.03	7.5	.00	2.29	1.14	2.00
Gender	25.83	26.91	.92	1.01	4.09	.25
Within	− .00	.03	− .06	.00	.00	1.06
Between	− .04	.03	− 1.18	− .00	.00	− .20
Total minutes active						
Age	1.54	7.26	.21	2.22	1.13	1.96
Gender	4.16	4.16	.17	1.11	3.74	.30
Within	.12	.12	1.22	.03	.01	2.23*
Between	− .39	− .39	− 2.37	.02	.03	.72

*$p < .05$

total sleep time and wake after sleep onset did not significantly predict next day physical activity. Thus, inter-individual differences in physical activity did not predict sleep and inter-individual differences in sleep did not predict physical activity.

Within-Subject Effects The intraclass correlation coefficients indicated that 83% of the variance in steps, 62% in total minutes active, 26% in calories burned, 77% in total sleep time, and 66% in wake after sleep onset existed between days and within participants. There was one significant, within-subject effect of physical activity on subsequent night's sleep (see Table 2); days on which participants spent more time active than they do on average predicted greater wake after sleep onset that night ($p = .03$). There were significant, within-subject main effects of sleep on next day's physical activity (see Table 3). Nights in which participants had longer than their average total sleep time predicted fewer next day steps ($p = .001$), fewer calories burned ($p = .004$), and fewer total minutes active ($p = .007$). Nights in which participants had longer than their average wake after sleep onset predicted fewer steps ($p = .004$) and fewer calories burned ($p = .006$) the following day.

Interaction Models

Day type did not moderate any of the relationships between physical activity and sleep (see Tables 4 and 5).

Discussion

The current study sought to examine the temporal relationships between sleep and physical activity in healthy, young adults, and also explore how these relationships differ on weekdays versus weekend days. It was hypothesized that greater physical activity would promote healthier sleep that night, and that greater total sleep time and shorter wake after sleep onset would predict more physical activity the following day. It was also hypothesized that these relationships would be moderated by day type, in that the associations between physical activity and sleep would be stronger over the weekend.

Our study revealed that, overall, physical activity was not associated with subsequent night's sleep. Given the consensus of previous research and the plausible mechanisms in which physical activity could promote healthy sleep, this finding was somewhat unexpected. While unexpected, several other studies have similar results, demonstrating that today's physical

Table 3 Sleep predicting physical activity

	Steps			Calories burned			Total minutes active		
Predictor	*B*	SE	*t*	*B*	SE	*t*	*B*	SE	*t*
Total sleep time									
Age	− 317.51	277.47	− 1.44	33.48	34.48	.97	5.32	6.36	.84
Gender	− 109.37	913.68	− .12	325.33	113.60	2.86**	− 23.17	20.92	− 1.12
Within	− 9.44	2.86	− 3.31**	− .58	.20	− 2.94**	− .15	.05	− 2.75**
Between	− 3.06	6.46	− .29	− .46	.80	− .58	− .28	.15	− 1.86
Wake after sleep onset									
Age	212.47	304.82	− .70	19.89	38.11	.52	2.65	7.24	.37
Gender	− 273.74	919.72	− .30	298.56	114.63	2.61*	− 27.95	21.80	− 27.96
Within	− 60.32	20.58	− 2.93**	− 4.00	1.43	− 2.79**	− .64	.39	− 1.62
Between	− 40.09	41.67	− .96	4.17	5.20	.80	.91	.99	.92

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

Table 4 Physical activity predicting sleep, moderated by day type

	Total Sleep Time			Wake After Sleep Onset		
Predictor	*B*	SE	*t*	*B*	SE	*t*
Steps						
Age	− 3.41	7.37	− .46	2.05	1.14	1.80
Gender	11.62	23.72	.49	.80	3.70	.22
Within	− .00	.00	− .14	.00	.00	.92
Between	− .00	.00	− 1.80	− .00	.00	− 1.27
Day type	35.86	15.48	2.32*	1.80	2.09	.86
Day type*steps Within	.00	.00	.29	− 3.71	.00	− .06
Day type*steps Between	.00	.00	.40	.00	.00	.28
Calories burned						
Age	− .00	7.51	− .00	2.31	1.15	2.31
Gender	22.13	26.73	.83	.87	.87	.21
Within	− .0	.04	− .03	− .00	.01	.85
Between	− .02	.03	− .65	− 4.58	.01	− .01
Day type	34.23	15.20	2.25*	1.53	2.07	.74
Day type* Calories burned Within	.02	.06	.38	.00	.01	.04
Day type* Calories burned Between	− .06	.04	− 1.38*	− .00	.01	− .56
Total minutes active						
Age	1.60	7.20	.23	2.26	1.15	1.97
Gender	2.00	23.42	.09	1.03	3.75	.28
Within	.07	.15	.48	.03	.02	1.43
Between	− .41	.18	− 2.31*	.02	.03	.57
Day type	32.90	15.59	2.11*	1.08	2.10	.51
Day type*total Minutes active Within	.05	.23	.20	− .00	.03	− .13
Day type*total Minutes active Between	.08	.24	.31	.01	.03	.34

$^*p < .05$

activity may not significantly influence subsequent night's sleep [11, 14–16]. While our sample was predominately white and female, and thus may not generalize to other populations, our results suggest that the positive influence of physical activity on subsequent sleep is complex and may not be as beneficial for young, healthy adults. This study objectively measured both physical activity duration and energy expenditure, but there were aspects that were not measured and could influence this relationship, such as intensity or activity type [4].

We found that the within-subject effects of sleep on next day exercise were significant (with the only exception of wake after sleep onset predicting next day total minutes active), whereas the between-subject effects were not. This suggests that sleep predicts next day physical activity when individuals deviate from their own mean level total sleep time and wake after sleep onset. Specifically, when participant total sleep time was longer than their average night, they had fewer steps, fewer calories burned, and fewer minutes active the following day. This finding contradicted our study hypotheses, but while unexpected, the effect sizes were subtle and may not be clinically significant (e.g., 566 fewer steps for every 1 h of total sleep time greater than their average). It may indicate that certain health behaviors, such as physical activity, may be sacrificed when negotiating a demanding schedule [6]. For instance, an individual may decide to sleep in 1 day instead of getting up early to exercise. Moreover, spending more time asleep naturally reduces the time available during the day to be physically active. Consistent with our hypotheses, greater than an individual's average wake after sleep onset was associated with fewer steps and calories burned the following day, and these effects were of greater clinical significance (e.g., for every 15 min of greater than an individual's average wake after sleep onset, 900 fewer steps the next day). These findings parallel previous research [12–15], which demonstrated that healthier sleep is associated with more physical activity the following day. Perceived fatigue may play a mediating role between sleep fragmentation (wake after sleep onset) and physical activity, though the current study did not measure fatigue and is therefore unable to test this. The discrepant findings that total sleep time and wake after sleep onset have on physical activity highlight that different components of sleep may hold different relationships with subsequent physical activity, and encourage multidimensional assessment methods. It is possible that in order for young, healthy adults to obtain adequate physical activity, sleep may have to be sacrificed, but total sleep time does not strongly influence next day physical activity. In contrast, greater wake after sleep onset is more predictive of lower physical activity levels than total sleep time.

We hypothesized that day type would moderate the daily associations between physical activity and sleep, in that the relationships would be stronger over the weekend. However, our analyses did not support this and all interaction effects were non-significant. We hypothesized that day type would have a moderating effect due to a participant's schedule being less busy over the weekend, but it is possible that weekday and weekend schedules did not significantly differ in this sample. These results suggest that day type may not influence daily associations between physical activity and sleep, but further research is needed to clarify these relationships. Specifically, future studies could test this in a sample with homogenous schedules (i.e., 9am–5pm, Monday through Friday) or measure participants' 7-day schedules.

There were several strengths to this study. First, we collected six consecutive days of both physical activity and sleep

Table 5 Sleep predicting physical activity, moderated by day type

Predictor	Steps			Calories Burned			Total minutes Active		
	B	SE	*t*	*B*	SE	*t*	*B*	SE	*t*
Total sleep time									
Age	− 301.21	279.04	− 1.08	34.37	34.82	.99	5.24	6.41	.82
Gender	− 84.79	919.75	− .09	325.18	114.78	2.83**	− 24.38	21.11	− 1.16
Within	− 12.05	3.85	− 3.13**	− .77	.27	− 2.85**	− .17	.07	− 2.38*
Between	1.24	7.08	.18	− .15	.83	− .18	− .19	.16	− 1.17
Day type	− 1587.74	557.32	− 2.85**	− 74.55	38.49	− 1.94	4.47	11.18	.40
Day type* TST Within	8.01	5.81	1.38	.56	.41	1.35	.08	.11	.74
Day type* TST Between	− 16.01	9.28	− 1.72	− 1.19	.65	− 1.84	− .32	.19	− 1.67
Wake after sleep onset									
Age	− 188.02	303.91	− .62	20.55	38.15	.54	2.64	7.24	.37
Gender	− 213.95	916.37	− .23	302.77	114.70	2.64*	− 28.42	21.81	− 1.30
Within	− 78.17	29.58	− 2.64**	− 4.09	2.12	− 1.92	− .93	.58	− 1.59
Between	− 70.11	44.85	− 1.56	2.30	5.33	.43	.48	1.04	.46
Day type	− 1532.06	573.28	− 2.67**	− 72.11	39.61	− 1.82	3.45	11.54	.30
Day type* WASO within	48.39	43.75	1.11	.78	3.19	.24	.51	.87	.58
Day type* WASO Between	92.99	51.73	1.80	5.78	3.57	1.62	1.34	1.04	1.20

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

TST total sleep time, *WASO* wake after sleep onset

data. As noted by Youngstedt and Kline [6], a limitation to the physical activity and sleep literature is that a majority of studies record only a couple days' worth of data, which greatly limits the internal validity of daily models. Our data sampling allowed us to more effectively model the daily, bidirectional relationships between physical activity and sleep. Our study also utilized objective data collection for both physical activity and sleep. Fitbit is a moderately valid, cost-effective tool compared with the polysomnography, and is most accurate in the study of healthy sleepers [18, 19]. While Fitbit is a cost-effective tool for measuring objective sleep parameters, it is not the gold standard for objective sleep measurement and future studies should utilize either actigraphy or polysomnography. To our knowledge, there is one study to date that has used actigraphy in multilevel modeling to test the daily relationship between sleep on next day physical activity, while also parsing apart within- and between-subject effects [14]. An additional limitation to this study is that we were unable to include some of the more nuanced factors in our models, such as timing and intensity of exercise, and timing of sleep [23]. Moreover, while our study focused on the relationships between physical activity and sleep, there are a number of other behaviors to consider in future research. For instance, research has demonstrated that health behaviors are related to one another [24], and future studies should consider how other health behaviors (e.g., diet, alcohol, and nicotine use) interact with sleep and physical activity.

In sum, our study makes several important contributions. We provide more support for a 24-h model of health behavior, in that both total sleep time and wake after sleep onset are associated with next day physical activity. Moreover, it was deviation from one's average total sleep time and wake after sleep onset that predicted next day physical activity. The finding that more sleep does not always lead to higher physical activity indicates that healthy, young adults may respond to interventions targeting 24-h health behavior differently than other populations. For instance, these results suggest that increasing physical activity levels would not necessarily promote healthier sleep, and that targeting sleep duration may not lead to greater physical activity levels. Instead, promoting behaviors that enhance sleep continuity may be a more effective avenue for health promotion. Lastly, these results demonstrate that daily associations between physical activity and sleep may vary between different populations, and future research should utilize the 24-h health behavior model to examine these relationships. A greater understanding of the daily relationships between physical activity and sleep can improve the efficacy of behavioral interventions.

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Compliance with Ethical Standards

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institution and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Conflict of Interest The authors declare that they have no conflict of interest.

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