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Daily reciprocal relationships between affect, physical activity, and sleep in middle and later life

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Abstract

Background: The daily dynamics among affect, physical activity, and sleep are often explored by taking a unidirectional approach. Yet, obtaining a comprehensive understanding of the reciprocal dynamics among affect and health behaviors is crucial for promoting daily well-being.

Purpose: This study examined the reciprocal associations among affect, physical activity, and sleep in daily life in a U.S. national sample of mid- and later-life adults.

Methods: The study sample included 1,171 participants (mean age = 62.61 years, SD = 10.26 years, 57% female, 82% White) with 9,033 daily interview days from the daily diary project of the third wave of the Midlife in the United States study (MIDUS III). Participants reported their daily experiences across eight consecutive days. Using a dynamic structural equation modeling, we examined day-to-day autoregressive and cross-lagged associations among positive and negative affect, physical activity, and sleep.

Results: Results revealed that higher positive affect predicted a greater likelihood of engaging in moderate-to-vigorous physical activity (MVPA) and better sleep quality the following day. Higher sleep quality predicted increased positive affect, reduced negative affect, and a greater likelihood of MVPA engagement the next day. Longer sleep duration predicted lower negative affect the following day. However, MVPA engagement predicted subsequent higher negative affect.

Conclusions: Findings underscore the importance of simultaneously considering affect, physical activity, and sleep in studying their day-to-day dynamics, and the protective role of positive affect and sleep quality in daily life. Maintaining high positive affect and managing sleep quality may be important intervention targets for enhancing daily well-being.

Lay Summary

Health behaviors and emotions exhibit complex dynamics in daily life. Previous research has often taken a unidirectional approach when examining the relationships between these factors. Adopting a more comprehensive approach, this study investigated the reciprocal relationships between affect, physical activity, and sleep in the daily lives of US middle-aged and older adults. The study sample was 1,171 adults who completed daily diary assessments across eight consecutive days. During the daily interviews, participants reported their positive and negative affect, physical activity, and sleep duration and quality. Dynamic structural equation models showed that higher positive affect predicted a greater likelihood of engaging in moderate-to-vigorous physical activity (MVPA) and better sleep quality the following day. Higher sleep quality was associated with increased positive affect, reduced negative affect, and a greater likelihood of MVPA engagement the next day. Longer sleep duration predicted lower negative affect the following day. However, MVPA engagement predicted subsequent higher negative affect. The results highlight the importance of simultaneously considering affect, physical activity, and sleep in studying their day-to-day dynamics, and the protective role of positive affect and sleep quality in daily life. Maintaining high positive affect and managing sleep quality may be important intervention targets for enhancing daily well-being.

Key words: dynamic structural equation modeling; daily diary design; physical activity; positive affect; negative affect; sleep.

Introduction

Exploring the dynamic interplay between physical activity, sleep, and affect has been receiving increased attention. Physical activity and sleep are key modifiable behavioral factors that exert both proximal and persistent impacts on affective well-being.[1–3] Experimental studies have consistently shown that negative affect was reduced and positive affect was enhanced after engaging in a physical activity session.[4,5] Laboratory-based sleep deprivation has also been associated with increased negative affect and decreased positive affect the following morning.[6,7] Moreover, the reciprocal nature of these relationships has been evidenced by findings indicating that experimentally-induced negative affect induced sleep deterioration, such as decreases in sleep efficiency and total sleep time and altered patterning of rapid eye movement (REM) sleep.[8,9]

Despite the experimental evidence supporting the reciprocal relationships among affect, physical activity, and sleep, these factors may demonstrate distinct day-to-day dynamics in naturalistic settings as they fluctuate within individuals from one day to the next. A recent surge in intensive longitudinal research designs, such as ecological momentary assessment (EMA) and daily diary assessment, show promise for better characterizing the relationships between health behaviors and affect in naturalistic settings, allowing for the generalization of findings across person, place, and time.[10–12] Using these techniques, a growing body of research has examined physical activity and sleep as important correlates of affect in daily life.[13–26] Some of these studies observed increased positive affect[14–16,18,19] and reduced negative affect[16,27] following physical activity, whereas others found no linkage with positive[17,20] and negative affect.[14,17,18,20] A recent review of twelve studies conducted in naturalistic settings in non-clinical populations revealed consistent evidence that physical activity predicted higher positive affect but mixed findings on physical activity reducing negative affect.[28] On the other hand, studies have consistently observed elevated positive affect and decreased negative affect following nights with adequate sleep quality[21–25,29] and sufficient sleep duration.[22,26]

The consideration of affect as a predictor of physical activity and sleep has been studied less frequently. Studies have generally agreed that positive affect was predictive of increased physical activity over the next few hours,[17,30–32] whereas negative affect was associated with a decrease or no change in subsequent physical activity.[14,18,30,31] In addition, studies have reported mixed findings on the impact of daily affect on sleep. Some research has indicated that higher positive and lower negative affect predicted subsequent better sleep quality, longer sleep duration, and shorter sleep-onset latency,[23,33] whereas others found no significant relations[21,22] or shorter sleep duration following higher prior positive affect.[34]

Although many of these studies have addressed the bidirectionality of the relationships in isolation, a limitation lies in their predominant use of analytic approaches such as multilevel modeling (MLM) or hierarchical modeling (HLM), which typically handles bidirectional relations separately. An advantage of employing dynamic structural equation modeling (DSEM) for temporal dynamics is its capability to estimate within- and between-person reciprocal associations across multiple outcomes. This is accomplished by integrating the features of MLM/HLM, structural equation modeling (SEM), and time-series analysis within a single modeling framework.[35] Indeed, several recent studies have highlighted the importance of shifting towards advanced modeling approaches, such as continuous-time structural equation models (CT-SEM) or network analysis, which can better capture dynamic processes occurring at the within-person level.[19,29,32]

While physical activity and sleep have been independently examined as correlates of affect, they also likely influence each other in daily life. It is equally important to consider the daily dynamics of these two behavioral factors in research, as this may provide a more comprehensive understanding of how physical activity and sleep relate to daily affective well-being and they can promote each other. Empirical findings vary across studies. A review of 33 EMA studies did not find bidirectional sleep-physical activity daily association, but they found weak effects of sleep parameters predicting physical activity the following day and physical activity predicting lower total sleep time the following night.[36] Recent studies have added evidence on the bidirectional associations between sleep quality and physical activity, generally supporting that adequate sleep quality promotes physical activity and vice versa.[37–39] On the other hand, the relationship between daily sleep duration and physical activity appears less consistent, with some evidence suggesting that longer sleep duration predicted lower physical activity the next day[37,39,40] while higher physical activity predicted an increase,[39] decrease,[37] or no changes in sleep duration.[40]

Given the dynamic nature of behavioral and affective factors that fluctuate in everyday life, this study aimed to examine the reciprocal associations between daily affect, physical activity, and sleep using daily diary data from a national sample of US adults in their mid- to later life. Studying these dynamics in mid and later life is crucial for several reasons. First, these life stages often coincide with significant changes in physical health, sleep patterns, and affective well-being,[41,42] making it pertinent to understand how they interact. Secondly, insights gained from such research can inform targeted interventions aimed at promoting healthier lifestyles and enhancing overall quality of life in these populations. Finally, given the increasing prevalence of chronic health conditions and age-related declines in physical function, understanding the relationships between physical activity, sleep, and affect in mid and later life can offer valuable insights for preventive healthcare strategies and interventions. We leveraged the strengths of DSEM to elucidate within- and between-person, as well as within- and across-day components of these associations. Specifically, we included estimations of (1) autoregressive and cross-lagged paths at the within-person level and (2) within-person and between-person correlations among variables in the models.

Methods

Data and study sample

The data for the current study were drawn from the third wave of the Midlife in the United States (MIDUS) study. MIDUS is a national study investigating age-related changes in health and well-being and their associated factors across the adult life span.[43] MIDUS I recruited a sample of 7,108 English-speaking adults aged 25-74 using random digit dialing (RDD) in 1995-1996. Participants were first interviewed over the phone for the baseline survey, followed by the completion of self-administered questionnaires (SAQs) via mail (SAQs response rate = 89%). A longitudinal follow-up was conducted (MIDUS II) in 2004-2005, which included 4,963 participants (SAQs response rate = 81%). A supplemental sample of 592 adults, mostly consisting of Black or African American participants was additionally recruited from Milwaukee County, Wisconsin in 2005-2006 to improve the racial composition of the MIDUS II sample (SAQs response rate = 67.2%). A third wave of survey data (MIDUS III) was collected on a longitudinal sample of 3,294 participants in 2013-2014 (SAQs response rate = 83%). This wave of data collection featured an expanded array of daily measures, including more comprehensive assessments of daily sleep and physical activity. The current study used the data from the daily diary project of MIDUS III, the National Study of Daily Experiences (NSDE) III. The sample of NSDE III consisted of a random subsample of the MIDUS III participants who completed the main survey. Participants completed telephone interviews about their daily experiences across eight consecutive days. 75.5% of the participants completed all eight interview days, resulting in 94.0% completion rate (9,301 days out of a possible 9,888 days).

The current analyses used data from 1,171 participants with 9,033 daily interview days who did not have complete missing data on sociodemographic measures and daily diary variables. The studies were approved by the Institutional Review Boards of the University of Wisconsin-Madison and Pennsylvania State University. Additional details are available at https://doi.org/10.3886/ICPSR36346.v7 and https://doi.org/10.3886/ICPSR38529.v1.

Measures

Daily affect

Participants reported the frequency of items assessing positive and negative affect during daily interviews.[44,45] The assessment of positive affect included 13 items (feeling in good spirits, cheerful, extremely happy, calm and peaceful, satisfied, full of life, close to others, like you belong, enthusiastic, attentive, active, proud, and confident) and negative affect included 14 items (feeling restless or fidgety, nervous, worthless, so sad nothing could cheer you up, everything was an effort, hopeless, lonely, afraid, jittery, irritable, ashamed, upset, angry, and frustrated). Responses for each item ranged from 0 (*none of the time*) to 4 (*all of the time*). Daily positive and negative affect scores were calculated by averaging across the items. Within-person reliability for positive affect was 0.855 and negative affect was 0.802. Between-person reliability for positive affect was 0.971 and negative affect was 0.936.[46]

Daily physical activity

Daily physical activity was assessed with the short form of the International Physical Activity Questionnaire (IPAQ)[47] adapted for daily use. As a part of daily interviews, participants reported whether they undertook any of three physical activities (i.e., light, moderate-intensity, and vigorous-intensity activity) and the duration of each activity. Days with cases in which the summed minutes of three activities greater than 960 minutes were considered outliers and excluded in the analyses based on the IPAQ scoring procedure.[48] A dichotomous variable indicating whether the participant engaged in any of moderate-to-vigorous physical activity (MVPA) on a given day (1 = *days with any of moderate or vigorous physical activity*; 0 = *days without any of moderate or vigorous physical activity*) were used for the analyses. We decided to use a dichotomized MVPA variable for the primary analyses for several reasons. First, the current study sample is relatively healthy and active; on days when participants engaged in any MVPA, the average duration was 110.4 minutes (SD = 117.4). This duration is close to the weekly, rather than daily, recommendation of minimum 150 minutes of moderate-intensity activity or 75 minutes of vigorous-intensity activity.[49] In addition, our study focused on middle-aged and older adults, who may benefit more from engaging in any physical activity, compared to younger adults, who often require greater doses of activity for similar health benefits.[50,51] Thus, evaluating whether participants engaged in any MVPA may better represent the active status of a given day, rather than focusing on the total minutes spent in MVPA. Lastly, given the highly zero-inflated distribution of MVPA in our data, using a dichotomized variable may help address this analytic challenge.[52] We additionally conducted a sensitivity analysis where physical activity levels were examined using the total duration (minutes) of MVPA.

Daily sleep duration and quality

During the daily diary telephone interviews, participants were asked to report their previous-night sleep duration (hours and minutes) by asking, "Since this time yesterday, how much time did you spend sleeping, not including time you may have spent napping?" Total daily sleep duration was calculated in hours. They were also asked to rate their previous-night sleep quality on a 4-point scale (1 = *very bad*; 2 = *bad*; 3 = *good*; 4 = *very good*).

Analytic plan

For the current study, we utilized the dynamic structural equation model (DSEM) to examine the dynamic and reciprocal associations among daily affect, physical activity, and sleep. DSEM is an appropriate analytic tool for intensive longitudinal data where repeated measurement occasions are nested within individuals.[35,53] DSEM integrates the features of time-series analysis, multilevel modeling, and structural question modeling to address modeling of autoregressive and cross-lagged effects and multiple outcomes using nested data structure.[54] DSEM decomposes the total variance across individuals and time points into within-person and between-person parts and constructs separate models for each of these parts.[53] Since the current data set has a structure where days were nested within individuals, we estimated two-level DSEMs. In the two-level DSEM models, the between-person (i.e., trait-level, interindividual) variance is modeled on level 2 using individual-specific random effects and within-person (i.e., state-level, intraindividual) variance is modeled on level 1.[35,53]

DSEM analyses were conducted in Mplus Version 8.8[55] which accommodates the DSEM with categorical outcomes using a probit link function.[54] The models were estimated using Bayesian Monte Carlo Markov Chain (MCMC) estimation with a minimum of 5,000 and maximum of 50 000 iterations and two chains.[53,54,56] At level 1, autoregressive and cross-lagged paths were estimated among daily MVPA, affect, and sleep. Concurrent-day correlations between daily MVPA and affect, as well as between sleep duration and quality, were also included at level-1. However, given the distinct temporal precedence inherent in sleep variables, concurrent-day correlations between sleep and other features were not specified. At level 2, correlations of between-person (i.e., individual-specific) intercepts correlations between MVPA, affect, sleep duration, and sleep quality were estimated. Level-1 covariates included weekdays (vs. weekend) and level-2 covariates included age (centered at grand mean), gender (1 = *female*; 0 = *male*), race (1 = *White*; 0 = *others*), and education level (1 = *Less than 4- or 5-year college or Bachelor's degree*; 0 = *Graduate from 4- or 5-year college or Bachelor's degree or higher*). Both unstandardized and standardized coefficients were reported since standardized results enable the comparison of the magnitude of the cross-lagged paths.

Results

Descriptive statistics

Sample characteristics are presented in Table 1 and descriptive statistics and correlations are presented in Table 2. The mean age was 62.61 years (SD = 10.26, range = 43-90). About a half (57%) of the sample was female. Participants were predominantly White (82%), followed by Black or African

American (11%), and other races (7%). For education level, 44% of the sample graduated from 4- or 5-year college or Bachelor's degree or had a higher degree. The mean level of daily positive affect was 2.68 (SD = 0.77) and negative affect was 0.18 (SD = 0.29). Out of total interview days, 56% (N_{days} = 4,869 days) were days when participants engaged in any MVPA. Participants slept 7.14 hours on average (SD = 1.49 hours) and reported generally good sleep quality (*M* = 3.11. SD = 0.68).

Daily positive affect was negatively correlated with daily negative affect and positively correlated with daily MVPA engagement, sleep duration, and sleep quality at both within- and between-person levels. Daily negative affect was negatively correlated with daily sleep duration and quality, and daily sleep quality was positively correlated with MVPA and sleep duration at the between and within person levels. Daily MVPA was negatively correlated with sleep duration only at between-person level.

Results from DSEM models

Unstandardized and standardized estimates for autoregressive and cross-lagged paths at within-person level and correlations at within- and between-person levels are presented in Table 3 and Figure 1.

Daily positive affect model

Daily positive affect (*b* = 0.170, 95% BCI [0.148, 0.195]), engagement in MVPA (*b* = 0.384, 95% BCI [0.296, 0.481]), and sleep quality (*b* = 0.032, 95% BCI [0.011, 0.056]) all showed credible autoregressive effects (i.e., day to day associations), but not sleep duration. Cross-lagged paths indicated that higher positive affect on the previous day predicted greater likelihood of engaging in following day MVPA (*b* = 0.107, 95% BCI [0.009, 0.186]) and better sleep quality (*b* = 0.025, 95% BCI [0.002, 0.056]). Higher previous-night sleep quality predicted following day higher positive affect (*b* = 0.072, 95% BCI [0.054, 0.090]) and greater likelihood of MVPA (*b* = 0.074, 95% BCI [0.022, 0.141]). The standardized estimates revealed that the magnitude of the cross-lagged associations was the greatest in sleep quality predicting subsequent MVPA, followed by positive affect predicting subsequent MVPA, sleep quality predicting subsequent positive affect, and positive affect predicting subsequent sleep quality. The within-person correlations indicated that there were concurrent-day positive correlations between daily positive affect and MVPA (*r* = 0.036, 95% BCI [0.028, 0.045]; *r* = 0.039, 95% BCI [0.027, 0.051]) and daily sleep duration and quality (*r* = 0.273, 95% BCI [0.250, 0.297]; *r* = 0.195, 95% BCI [0.180, 0.210]). The between-person correlations showed that positive affect was positively correlated with sleep duration (*r* = 0.061, 95% BCI [0.017, 0.106]) and quality (*r* = 0.065, 95% BCI [0.048, 0.082]) at between-person level. Between-person sleep duration and sleep quality were also positively correlated (*r* = 0.077, 95% BCI [0.051, 0.105]).

Daily negative affect model

The results showed that there were credible autoregressive associations in daily negative affect and MVPA, indicating that previous-day negative affect (*b* = 0.075, 95% BCI [0.045, 0.105]) and MVPA engagement (*b* = 0.373, 95% BCI [0.282, 0.468]) were positively associated with themselves on the following day. For the cross-lagged paths, engagement in MVPA predicted higher negative affect the following day (*b* = 0.018, 95% BCI [0.004, 0.032]). Longer sleep duration predicted next-day lower negative affect (*b* = −0.010, 95% BCI [−0.016, −0.004]). Higher sleep quality predicted lower negative affect (*b* = −0.034, 95% BCI [−0.043, −0.026]) and greater likelihood of MVPA engagement (*b* = 0.080, 95% BCI [0.014, 0.146]) the following day. The standardized estimates indicated that the cross-lagged associations were the strongest in daily sleep quality predicting subsequent negative affect, followed by daily sleep quality predicting subsequent MVPA, daily sleep duration predicting subsequent negative affect, and MVPA predicting subsequent negative affect. At the within-person level, daily negative affect was negatively correlated with concurrent-day MVPA engagement (*r* = −0.007, 95% BCI [−0.013, −0.000]), and sleep duration was positively

Table 1. Sample characteristics (*N* = 1,171).

	M (SD) or *n* (%)
Age	62.61 (10.26)
Gender	
Female	670 (57.22%)
Male	501 (42.78%)
Race	
White	964 (82.32%)
Black or African American	124 (10.59%)
Others	83 (7.09%)
Education level	
Graduate from 2-year college, vocational school, or associate degree	654 (55.85%)
Graduate from 4- or 5-year college or Bachelor's degree or higher	517 (44.15%)

Table 2. Descriptive statistics and correlations of daily affect, physical activity, and sleep (N_{person} = 1,171; N_{days} = 9,033).

	M (SD)/*Ndays* (%)	1	2	3	4	5
1. Daily positive affect	2.68 (0.77)	*0.77*	**−.54**[a]	**.11**[a]	**.08**[a]	**.34**[a]
2. Daily negative affect	0.18 (0.29)	**−.47**[a]	*0.57*	0.00	**−.10**[a]	**−.26**[a]
3. Daily MVPA	4,869 (55.79%)	**.09**[a]	−0.01	*0.52*	**−.02**[a]	**.06**[a]
4. Daily sleep duration	7.14 (1.49)	**.07**[a]	**−.09**[a]	0.00	*0.44*	**.24**[a]
5. Daily sleep quality	3.11 (0.68)	**.23**[a]	**−.19**[a]	**.04**[a]	**.27**[a]	*0.29*

Means and standard deviations are calculated based on 9,033 daily observations. Between-person correlations are reported above the diagonal, within-person correlations are reported below the diagonal, intraclass correlations are reported on the diagonal and are italicized.
[a]Bolded values are statistically significant at $P < .05$.

Table 3. Summary of DSEMS models examining autoregressive and cross-lagged paths among daily affect, MVPA, and sleep.

	Positive affect		Negative affect	
	Unstandardized Est. [95% BCI]	Standardized Est. [95% BCI]	Unstandardized Est. [95% BCI]	Standardized Est. [95% BCI]
Autoregressive paths				
Affect $_{t-1}$ → Affect $_t$	**0.170 [0.148, 0.195]**[a]	**2.770 [1.935, 4.392]**[a]	**0.075 [0.045, 0.105]**[a]	**0.352 [0.208, 0.507]**[a]
MVPA $_{t-1}$ → MVPA $_t$	**0.384 [0.296, 0.481]**[a]	**1.322 [0.820, 2.435]**[a]	**0.373 [0.282, 0.468]**[a]	**1.397 [0.849, 2.597]**[a]
Sleep duration $_{t-1}$ → Sleep duration $_t$	0.025 [−0.001, 0.048]	0.320 [−0.010, 0.617]	−0.011 [−0.034, 0.015]	−0.162 [−0.527, 0.210]
Sleep quality $_{t-1}$ → Sleep quality $_t$	**0.032 [0.011, 0.056]**[a]	**0.630 [0.189, 1.248]**[a]	0.014 [−0.010, 0.042]	0.224 [−0.174, 0.664]
Cross-lagged paths				
Affect $_{t-1}$ → MVPA $_t$	**0.107 [0.009, 0.186]**[a]	**0.696 [0.081, 1.361]**[a]	−0.039 [−0.250, 0.177]	−0.044 [−0.298, 0.190]
Affect $_{t-1}$ → Sleep duration $_t$	−0.037 [−0.094, 0.034]	−0.533 [−1.580, 0.528]	−0.094 [−0.278, 0.079]	−0.072 [−0.211, 0.060]
Affect $_{t-1}$ → Sleep quality $_t$	**0.025 [0.002, 0.056]**[a]	**0.616 [0.049, 1.464]**[a]	−0.060 [−0.135, 0.015]	−0.183 [−0.446, 0.045]
MVPA $_{t-1}$ → Affect $_t$	0.006 [−0.018, 0.029]	0.073 [−0.279, 0.403]	**0.018 [0.004, 0.032]**[a]	**0.124 [0.024, 0.218]**[a]
MVPA $_{t-1}$ → Sleep duration $_t$	0.007 [−0.072, 0.086]	0.012 [−0.127, 0.158]	0.029 [−0.033, 0.096]	0.130 [−0.157, 0.579]
MVPA $_{t-1}$ → Sleep quality $_t$	−0.004 [−0.041, 0.028]	−0.049 [−0.823, 0.461]	−0.012 [−0.044, 0.022]	−0.178 [−0.821, 0.381]
Sleep duration $_{t-1}$ → Affect $_t$	0.008 [−0.002, 0.018]	0.122 [−0.025, 0.279]	**−0.010 [−0.016, −0.004]**[a]	**−0.178 [−0.287, −0.075]**[a]
Sleep duration $_{t-1}$ → MVPA $_t$	−0.001 [−0.035, 0.032]	−0.006 [−0.468, 0.422]	−0.002 [−0.036, 0.036]	−0.013 [−0.483, 0.336]
Sleep quality $_{t-1}$ → Affect $_t$	**0.072 [0.054, 0.090]**[a]	**0.681 [0.457, 0.965]**[a]	**−0.034 [−0.043, −0.026]**[a]	**−0.652 [−0.951, −0.450]**[a]
Sleep quality $_{t-1}$ → MVPA $_t$	**0.074 [0.022, 0.141]**[a]	**0.831 [0.135, 3.456]**[a]	**0.080 [0.014, 0.146]**[a]	**0.672 [0.086, 2.364]**[a]
Correlations				
Within-person components				
Affect $_{t-1}$ ↔ MVPA $_{t-1}$	**0.036 [0.028, 0.045]**[a]	**0.094 [0.072, 0.115]**[a]	−0.001 [−0.005, 0.002]	−0.007 [−0.030, 0.016]
Affect $_t$ ↔ MVPA $_t$	**0.039 [0.027, 0.051]**[a]	**0.111 [0.076, 0.147]**[a]	**−0.007 [−0.013, 0.000]**[a]	**−0.042 [−0.084, −0.004]**[a]
Sleep duration $_{t-1}$ ↔ Sleep quality $_{t-1}$	**0.273 [0.250, 0.297]**[a]	**0.270 [0.250, 0.291]**[a]	**0.273 [0.250, 0.297]**[a]	**0.270 [0.249, 0.290]**[a]
Sleep duration $_t$ ↔ Sleep quality $_t$	**0.195 [0.180, 0.210]**[a]	**0.314 [0.292, 0.336]**[a]	**0.192 [0.177, 0.207]**[a]	**0.330 [0.294, 0.339]**[a]
Between-person components				
Affect $_i$ ↔ MVPA $_i$	0.037 [−0.011, 0.086]	0.078 [−0.022, 0.178]	**0.015 [0.001, 0.030]**[a]	**0.116 [0.010, 0.222]**[a]
Affect $_i$ ↔ Sleep duration $_i$	**0.061 [0.017, 0.106]**[a]	**0.224 [0.113, 0.333]**[a]	−0.004 [−0.017, 0.008]	−0.037 [−0.141, 0.069]
Affect $_i$ ↔ Sleep quality $_i$	**0.065 [0.048, 0.082]**[a]	**0.145 [0.040, 0.253]**[a]	**−0.009 [−0.014, −0.004]**[a]	**−0.227 [−0.340, −0.110]**[a]
MVPA $_i$ ↔ Sleep duration $_i$	−0.052 [−0.130, 0.025]	−0.080 [−0.202, 0.039]	−0.074 [−0.156, 0.005]	−0.091 [−0.187, 0.006]
MVPA $_i$ ↔ Sleep quality $_i$	0.010 [−0.020, 0.039]	0.041 [−0.082, 0.163]	0.021 [−0.010, 0.052]	0.076 [−0.037, 0.186]
Sleep duration $_i$ ↔ Sleep quality $_i$	**0.077 [0.051, 0.105]**[a]	**0.366 [0.246, 0.492]**[a]	**0.079 [0.052, 0.106]**[a]	**0.326 [0.220, 0.427]**[a]

Abbreviations: Est, estimate; BCI, Bayesian credible interval.
[a]Bolded values are credible based on the 95% Bayesian credible interval.

correlated with concurrent-day sleep quality (r = 0.273, 95% BCI [0.250, 0.297]; r = 0.192, 95% BCI [0.177, 0.207]). At the between-person level, daily negative affect was positively correlated with MVPA (r = 0.015, 95% BCI [0.001, 0.030]) and negatively correlated with sleep quality (r = −0.009, 95% BCI [−0.014, −0.004]). Sleep duration and quality were positively correlated at the between-person level (r = 0.079, 95% BCI [0.052, 0.106]).

Sensitivity analysis

A sensitivity analysis was conducted among 4,888 days with 1,027 participants when they engaged in any MVPA (active day), in which the total minutes of MVPA were included in the DSEM models (see Supplementary material). The MVPA duration was log-transformed to adjust for the skewness of the distribution. In the positive affect model, the cross-lag coefficients indicated that, consistent with the main analyses, better sleep quality was associated with higher positive affect. Longer MVPA duration was associated with shorter sleep duration and lower sleep quality the following night. In the negative affect model, longer MVPA duration and lower sleep quality were associated with higher negative affect the following day. Longer MVPA duration was associated with lower sleep quality and sleep duration on the next day.

Discussion

Though prior research has explored the linkages between affect, physical activity, and sleep in daily life, it has predominantly focused on the unidirectionality of these relationships without fully considering these factors simultaneously. The current study aimed to disentangle these intricate relationships by applying a novel statistical approach, DSEM, to daily diary data in a US national sample of middle-aged and older adults. Using this approach, we simultaneously estimated the within-person contemporaneous and lagged associations and between-person associations among affect, physical activity, and sleep in naturalistic real-world settings.

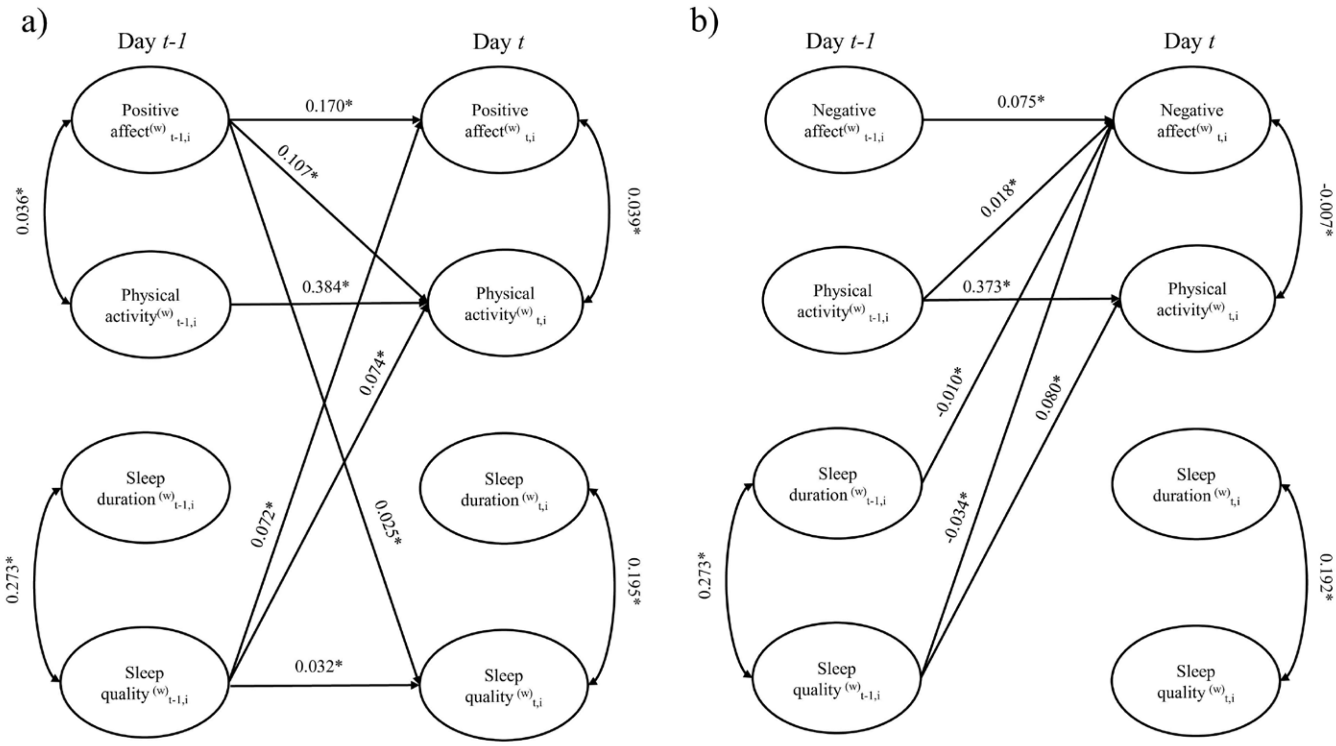

Figure 1. The within-person components of results from DSEM models. The models examined the bidirectional within-person associations between affect, physical activity, and sleep. Unstandardized coefficients were reported. One-sided arrows represent autoregressive and cross-paths coefficients, whereas two-sided arrows represent correlations coefficients. Credible results are presented with solid lines.

The current study found credible positive autoregressive associations of affect and physical activity, which indicates that when individuals experience a certain level of daily affect or engage in MVPA, they are more likely to maintain similar daily affect levels and MVPA engagement. This highlights the continuity and stability in affective states and physical activity engagements across days. Daily sleep quality, on the other hand, exhibited inconsistent positive autoregressive paths which were only credible in the positive affect model, but not in the negative affect model. It may indicate the weaker stability of sleep quality across days compared to other variables.

Findings revealed credible concurrent-day correlations and cross-lagged associations between the daily positive affect and MVPA, such that higher positive affect was associated with greater likelihood of engaging in MVPA on the same day and the subsequent day. In line with the previous research indicating that positive, but not negative, affective states were positively associated with physical activity over the next few hours,[13] our findings suggest that positive affect may offer extensive benefits in promoting physical activity even across multiple days. This is supported by affect congruency theory that posits positive affect will promote engagement with physical activity that foster more similarly valenced affect.[57] Yet, it should be noted that the effect size is small that a one-unit increase in positive affect was associated with 6.91% increase in the likelihood of MVPA engagement, holding all other factors constant. In contrast, MVPA engagement and duration predicted subsequent higher negative affect. This is somewhat contradictory to prior literature that physical activity predicted a decrease or no change in subsequent negative affect,[14,17,18,29] possibly due to the differences in sample characteristics, time scales of assessments, and measures. Indeed, physical activity in free-living settings greatly varies across individuals (e.g., type or social contexts of activity), which thus have different associations with affective status.[13,28] For example, these studies mostly examined moment-to-moment associations between the two by using multiple-time assessments per day, whereas the current study examined day-to-day associations.[14,17,18] Further, some of these studies included participants who were younger than those from the current study, such as college students.[29] It is plausible that fatigue or bodily pain contributes to the heightened negative affect following physical activity, where fatigue is exacerbated in older adults who already experience elevated fatigue symptoms associated with aging or physical conditions.[58] Further, the effects of physical activity on fatigue vary by the level at which these associations are investigated (e.g., within-person vs. between-person levels) and by general health status.[59,60] Although the current data cannot directly test this association, it is possible that physical activity elevated physical tiredness, subsequently leading to increased negative affect the following day. Further, within- and between-person correlations between MVPA and daily negative affect exhibited inverse relations. Specifically, at the within-person level, we observed lower negative affect on days when they engaged in MVPA. However, at the between-person level, individuals with higher overall negative affect engaged in more frequent MVPA. This finding may suggest an important modeling implication that simultaneously addressing within-and between-person components of the relationship may capture varying dynamics between variables. In addition, the positive between-person correlation between MVPA and negative affect may be explained by the affect regulation theory, which proposes that individuals would engage in physical activity that are expected to alter their current affective states.[57] This theory posits that negative affect may prompt engagement in physical activity to modify their current negative affective states. Further investigations are needed to elucidate the applicability of these two contrasting theories (i.e., affect congruency and affect regulation theories) across various study populations, timescales, and levels of analyses.

With respect to the sleep-affect associations, we observed the daily reciprocal associations between sleep quality and positive affect, where higher daily positive affect was associated with improved sleep quality on subsequent nights, and vice versa. While sleep quality predicted reduced negative affect the next day, the reverse relationship was not observed. This result is in line with prior research demonstrating the robust influences of sleep quality on daily affective well-being and the impact of positive affect, but not negative affect, on sleep quality.[21–25,33] In contrast, consistent with prior work,[22,23] sleep duration emerged as a weaker correlate of affect in daily life, as evidenced by unidirectional credible relations of sleep duration predicting a reduction in negative affect the following day. Together, these findings suggest that the associations between daily positive affect and sleep metrics are more pronounced compared to those involving negative affect. This is further substantiated by credible between-person correlations between positive affect and both sleep duration and quality, whereas negative affect correlated only with sleep quality.

Our results also emphasize sleep quality, but not sleep duration, as a credible predictor of MVPA engagement, but not duration, in everyday life. The effect size was small, with a one-unit increase in sleep quality associated with a 4.80% increase in the likelihood of engaging in MVPA. However, along with the findings indicating sleep quality was associated with enhanced daily affect, it's worth noting that sleep quality may be an important feature that characterizes a favorable and active day. Conversely, MVPA engagement did not predict sleep duration and quality on following nights and was not correlated at the between-person level. This finding is consistent with the review study showing that physical activity was not associated with subsequent sleep quality.[36] The daily dynamics between sleep duration and physical activity may be complex due to the time constraints that position these behaviors at the opposite ends of a continuum where prioritizing one behavior may come at the expense of the other.[29,61] The association may also be influenced by the intensity of physical activity, individuals' regular exercise habits, or the extent of other responsibilities on a given day,[37,62] which could explain conflicting findings. This is supported by the findings from the sensitivity analysis that longer MVPA duration was associated with subsequent shorter sleep duration and lower sleep quality. Further investigations are warranted, particularly with extended time frames (i.e., longer than 24-hour framing),[37] to unravel the mutual dependencies of these two behaviors.

It is worth noting the discrepancies between findings from the main analyses and those from the sensitivity analysis. While higher positive affect and sleep quality were associated with a higher likelihood of MVPA engagement the following day, neither was associated with MVPA duration. In addition, MVPA engagement was associated with higher negative affect the next day, whereas longer MVPA duration was associated with shorter subsequent sleep duration, poorer sleep quality, and higher negative affect. These results should be interpreted with caution, given the characteristics of the current data and sample, where most of the participants were active and in their middle or older age. As the sensitivity analysis was conducted only using data from active days with an average of 110 minutes of MVPA, an increase in MVPA minutes may have different effects on daily affective states or sleep compared to prior findings, where participants were often younger, less active or involved in prevention or intervention programs promoting physical activity engagement.[14,27,29,39] Further, the current study examined MVPA in naturalistic settings, where the types of MVPA varied significantly across individuals or days.

There are limitations to note that warrant further discussion. First, the study sample was primarily White and highly educated, with relatively good affective well-being, evidenced by lower average daily negative affect. This may limit the generalizability of the results to other study populations. Second, although daily diary data have the strength of reducing recall bias, our end-of-day measures are not completely free from recall bias or recency effects. In addition, the daily dynamics among affect, physical activity, and sleep may differ depending on the time scales or intervals of data collection. Future studies may benefit from increasing the number of assessments to reduce the potential biases and identify more intensive (e.g., moment-to-moment) dynamics. Third, the assessments of physical activity and sleep were limited to self-reported and retrospective measures. The use of objective measures, such as wearable devices or actigraphy, would provide additional insights into the understanding of the dynamics among affect, physical activity, and sleep. Additionally, contextual or individual differences in daily dynamics were not investigated in the current study. Examining potential moderating variables, such as age, gender, education level, or weekday, may be an important future step to enhance the current understanding of the daily dynamics of affect, physical activity, and sleep. Furthermore, given the potential longer-lasting effects of one variable on another, such as the accumulation of inadequate sleep across multiple days,[63] future studies could expand on the current study by considering beyond one-day lagged associations. Despite these limitations, this study has several strengths. Using a large sample of data, our study contributes to previous studies on reciprocal dynamics among affect, physical activity, and sleep by investigating their mutual dependencies at the within- and between-person levels. The use of daily diary data collected in real-life naturalistic settings also enhanced the ecological validity of the study. Our study also suggests implementation of DSEM may expand our understanding of the intricate dynamics among health behaviors and affect in daily life.

In summary, the current study contributes to the growing literature on daily dynamics among affect, physical activity, and sleep by examining the concurrent-day and cross-lagged associations at the within-person level. Our findings highlight the importance of positive affect in promoting physical activity and improving sleep quality. The role of sleep quality in shaping a favorable and active day is notable, supported by the results that sleep quality predicted higher positive affect, lower negative affect, and greater likelihood of MVPA engagement the following day. These findings together inform that positive affect and sleep quality may be important targets for interventions/preventions that aim to improve daily well-being. Future work could test whether these associations may vary across different populations and factors, such as age, gender, or regular exercise habits. Such efforts could provide evidence needed to ground the design of tailored interventions by taking a person-specific approach.

Supplementary material

Supplementary material is available at *Annals of Behavioral Medicine* online.

Author contributions

Sun Ah Lee (Conceptualization [lead], Formal analysis [lead], Methodology [lead], Writing—original draft [lead], Writing—review & editing [lead]), Zachary Fisher (Formal analysis [supporting], Methodology [supporting], Writing—review & editing [supporting]), and David M. Almeida (Investigation [lead], Supervision [lead], Writing—review & editing [supporting])

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Conflicts of interest

None declared.

Ethical approval

All procedures were approved by the Institutional Review Boards of the University of Wisconsin-Madison (IRB Protocol number: 2016-1051) and Pennsylvania State University (IRB Protocol number: PRAMS00042558).

Transparency statements

(i) This study is a secondary analysis of publicly available data set. (ii) The analysis plan was not formally preregistered. (iii) De-identified data from this study are available in a public archive. The MIDUS study procedure and data documentation are publicly available at https://doi.org/10.3886/ICPSR36346.v7 and https://doi.org/10.3886/ICPSR38529.v1. (iv) Analytic code used to conduct the analyses presented in this study are not available in a public archive. They may be available by emailing the corresponding author. (v) Materials used to conduct the study are not publicly available.

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