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Physical activity, sleep and affective wellbeing on the following day: An experience sampling study

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Summary

This study aims to investigate the temporal links between physical activity, sleep and affective wellbeing in young adults. In particular, the aim was to examine whether physical activity is associated with sleep indicators in subsequent nights and, in turn, whether sleep was associated with improved affective wellbeing the next morning. Relatedly, moderation by baseline levels of depressive symptoms, sleep quality, habitual physical activity and gender was analysed. One-hundred and forty-seven individuals (85.7% female) aged 18–25 years old participated in an experience sampling study over 14 consecutive days. Participants received seven prompts per day, and answered questions about their physical activity and affective states. Every morning, participants also reported their sleep. Physical activity throughout the day was not related to sleep during the following night or to affective wellbeing the next morning. An exception to that pattern was that physical activity before 14:00 hours was associated with longer subsequent sleep duration. Better subjective sleep quality predicted affective wellbeing the next morning. Associations of physical activity, sleep and affective wellbeing were not moderated by baseline depressive symptoms, sleep quality or habitual physical activity. However, investigation of gender as a moderator revealed that moderate physical activity was associated with better subsequent sleep quality for males, but not for females. Overall, we found that physical activity is associated with better subsequent sleep for males, but not for females. Also, our study provides further evidence that better sleep quality is associated with the next morning's affective wellbeing.

KEYWORDS

experience sampling, International Physical Activity Questionnaire, multilevel models, Patient Health Questionnaire-9, Pittsburgh Sleep Quality Index

1 | INTRODUCTION

A large body of evidence suggests that physical activity has a positive effect on sleep quality (Lang et al., 2016; Kline et al., 2021; Kredlow et al., 2015) and affective wellbeing (Cooney et al., 2013; Liao et al., 2015). Relatedly, both a lack of physical activity and disturbed sleep are associated with an increased risk of the onset of mental illness (Firth et al., 2019; Firth et al., 2020), and physical activity is generally recommended for the treatment of depression (National Institute for Health and Care Excellence [NICE], 2009).

While several studies have examined acute within-day temporal associations between physical activity and positive and negative affect (Li et al., 2022; Mata et al., 2012; Schultchen et al., 2019; Stavrakakis et al., 2015; Wichers et al., 2012), no studies to date have examined another potential mechanism behind the association of physical activity and affective wellbeing, namely whether physical activity is associated with the next day's positive and negative affect via the potentially mediating role of improved sleep during the night in between. In line with such a mediation model, experimental and intervention studies show that exercise has an acute beneficial effect on sleep duration, sleep quality and sleep continuity the following night (Kline et al., 2021; Kredlow et al., 2015). Furthermore, analyses of time series data using experience sampling methods (ESMs) show that indicators of sleep quality are positively associated with positive affect and negatively with negative affect the next day (Das-Friebel et al., 2020; Konjarski et al., 2018; Lenneis et al., under review). Thus, based on these two lines of evidence, it is possible that physical activity exerts its positive effect on mental health at least partly via improved sleep quality as a mediator.

While the knowledge about the acute effects of physical activity on sleep mainly comes from experimental and intervention research, studies on the association between naturally occurring physical activity in people's everyday lives and sleep the subsequent night are scarce. In particular, studies examining within-subject day-to-day variation in physical activity and its association with variation in sleep indicators could complement our knowledge about the interplay between physical activity in everyday life, sleep and affective wellbeing. Existing ESM studies that investigated daily associations between physical activity and subsequent sleep provided inconsistent results (Atoui et al., 2021). Two studies with healthy young adults found no association between subjectively and objectively assessed physical activity and subsequent sleep (Mead et al., 2019; Youngstedt et al., 2003). Another study found that objectively measured physical activity and sleep are interrelated, but only for sleep duration and vigorous physical activity (Pesonen et al., 2022). However, several potential moderators could play a role in this relation, including characteristics of physical activity itself (e.g. duration, intensity, type and time of day of the physical activity) and characteristics of the individual (e.g. level of habitual physical activity, sleep disturbance, emotional vulnerability or gender). The American Sleep Association recommends physical activity before 14:00 hours to improve sleep (American Sleep Association, 2022). In accordance, it is often claimed that physical activity in the late evening has negative effects on sleep. However, existing research has not yet found support for the latter, nor has it identified an optimal time for physical activity during the day to benefit subsequent sleep (Kline et al., 2021), while the effects of acute physical activity on sleep have been reported to be moderated by duration, type and habitual baseline levels of physical activity, but not by the intensity of physical activity (Kline et al., 2021; Kredlow et al., 2015), which has not been examined by ESM studies to date.

The present study aims to examine whether the duration of moderate to vigorous physical activity predicts the next morning's positive and negative affect, and whether this association is mediated by sleep quality, sleep duration and sleep-onset latency. It does so by using an experience sampling protocol applying subjective reports of physical activity, sleep, and positive and negative affect. While objective sleep measurement is generally considered the gold-standard and some disparities on subjective measures can be found (Aili et al., 2017; Jackowska et al., 2011; Lockley et al., 1999), subjectively measured sleep has the advantage of providing a general sense of how people feel about their sleep and how satisfied they are with it. Objective measurement of physical activity also has some drawbacks, such as not adequately detecting stationary activities (e.g. weight lifting), which can be assessed with subjective reports (Skender et al., 2016).

The following hypotheses were tested: (a) increased physical activity is associated with better sleep quality, longer sleep duration and shorter sleep-onset latency; (b) better sleep quality/longer sleep duration/shorter sleep-onset latency at night is associated with higher positive affect/lower negative affect on the following day; (c) increased physical activity is associated with higher positive affect/lower negative affect on the following day; and (d) the positive/negative association between increased physical activity and higher positive affect/lower negative affect the following day is mediated by sleep quality/sleep duration/sleep-onset latency. Furthermore, the present study explores whether associations between physical activity, sleep quality, and positive and negative affect differ between individuals according to their baseline levels of depressive symptoms, general sleep quality and habitual physical activity in moderation analyses. Moreover, the role of the timepoint of physical activity within the day and the intensity of physical activity (i.e. moderate versus vigorous physical activity) are examined.

2 | METHODS

2.1 | Procedure

This study was approved by the Ethics Committee of Bielefeld University (file no. 2020–138). Participants were recruited on-line via social media, e-mail distribution lists of various German universities and the portal of study participation management of the Department of Psychology at Bielefeld University. First, participants were informed about the procedure and conditions of the study, data handling (including their legal rights regarding data protection and withdrawing from the study), and the conditions for receiving a compensation. All participants provided informed consent and confirmed that they fulfilled prerequisite criteria for study participation. These criteria were being aged between 18 and 25 years, and having a smartphone with an Android operating system available for the duration of the study. Data collection occurred in two batches: batch 1 from 23 March to 6 April 2021; and batch 2 from 30 March to 13 April 2021. For each batch, the data collection lasted 15 consecutive days and always began on a Tuesday. The data collection occurred during the COVID-19 (coronavirus disease 2019) pandemic and a so-called “partial lockdown” in Germany. People could go out for buying groceries, going for walks or doing individual outdoor sports. Gyms and sports clubs were closed, a majority of people worked remotely from

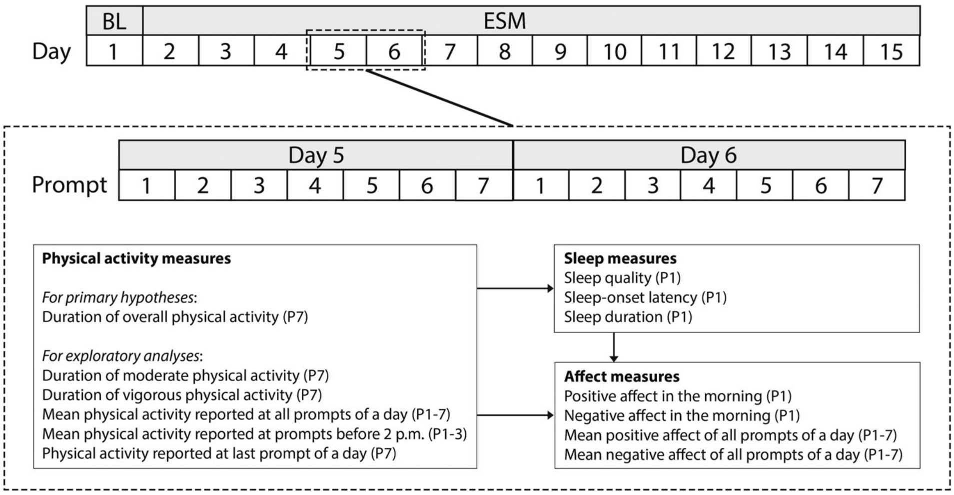

FIGURE 1 Study design with exemplary presentation of the associations investigated for days 5 and 6 (can be generalized to all other days). BL, baseline questionnaire; ESM, experience sampling methodology; P, prompt. Participants received the prompt for the first questionnaire of the day at random times between 08:00 hours and 09:00 hours on weekdays, and between 09:00 hours and 10:00 hours on weekends. For the next five questionnaires during the day, prompts were sent out between 10:30 hours and 19:30 hours on weekdays, and between 11:30 hours and 19:30 hours on weekends. Each day's last prompt was sent out between 21:00 hours and 22:00 hours on weekdays and weekends.

their homes, and University students attended classes online (Bundesministerium für Gesundheit, 2022).

On the first day of the study, participants completed a baseline questionnaire (approximately 35 min), where information regarding demographics, sleep habits, physical activity habits, mental well-being, and somatic, anxiety and depressive symptoms were collected (see section 2.3 "Measures and instruments"). On the second day (a Wednesday), experience sampling questionnaires presented on movisensXS (version 1.5.13; library version 7365; movisens GmbH, Karlsruhe, Germany) started. Participants received short questionnaires (taking approximately 2–3 min) seven times per day for 14 consecutive days (maximum 98 questionnaires per participant; see Figure 1 for an overview of the ESM protocol). Participants received a prompt for the first questionnaire of the day at random times between 08:00 hours and 09:00 hours on weekdays, and between 09:00 hours and 10:00 hours on weekends. The first questionnaire assessed participants' current affective states and information about their previous night's sleep. For the next five questionnaires during the day, prompts were sent out between 10:30 hours and 19:30 hours on weekdays, and between 11:30 hours and 19:30 hours on weekends. These five questionnaires asked about participants' current affective states and their physical activity during the preceding 90 min. Each day's last prompt was sent out between 21:00 hours and 22:00 hours on weekdays and weekends. The last questionnaire of a day assessed participants' current affective states and their physical activity across the whole day. All prompts were sent out at random times within the respective time interval. Also, there was a gap of at least 90 min between two adjacent prompts. Participants could respond to the questionnaires within 30 min after receiving the prompts. If participants did not respond within 30 min, this questionnaire was marked as missing. Participants were instructed to ignore prompts in situations that could cause danger to themselves or others (e.g. while driving).

Participants who completed at least 72% of all questionnaires received either a 40€ voucher or research participation credits. In addition, three 100€ vouchers were raffled among the participants qualified for receiving monetary compensation.

2.2 | Participants

In total, 200 participants signed up for the study, but 42 participants did not start the study (e.g. due to personal reasons or technical incompatibility). Among the remaining 158 participants, 11 were excluded from further analysis because they provided fewer than two complete sets of measurements (see section 2.4 "Statistical analyses"). The final sample of 147 participants completed the study and provided sufficient measurements (126 females, 20 males, and one person did not indicate their gender; mean age = 22.6 years, *SD* = 1.9).

2.3 | Measures and instruments

2.3.1 | Baseline questionnaire

The baseline questionnaire included demographic questions as well as standardized questionnaires measuring sleep quality, depressive symptoms and habitual physical activity. Depressive symptoms were measured by using the depressiveness subscale of the German version of the Patient Health Questionnaire (PHQ-D; Löwe et al., 2002) on a four-point scale (0 = not at all; 1 = several days; 2 = more than half the days; 3 = nearly every day). This subscale, PHQ-9, measures how often the nine depressive symptoms occurred the preceding week, which differed from the original version of the PHQ-9 that measured the symptom frequency during the preceding 2 weeks. Out of all items, a sum score was computed (0–27 points). The internal consistency for the present sample was $\alpha = 0.83$. To assess sleep quality at baseline, a German version of the Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989) was used. Habitual physical activity was measured with the International Physical Activity Questionnaire (IPAQ; Craig et al., 2003), and the total metabolic equivalent of task (MET) of the reported week was calculated for each participant according to the official scoring protocol (see http://ipaq.ki.se).

2.3.2 | Experience sampling

Physical activity

To assess physical activity at each prompt of experience sampling, participants were asked to report their recent physical activity ("How physically active have you been during the last 90 min?") on a visual analogue scale (0 = not at all; 100 = very much).

Furthermore, in the last questionnaire of each day, participants were asked to indicate how long (in hours and minutes) they had engaged in moderate and vigorous physical activity that day ("How long did you engage in moderate physical activity today [e.g. carrying light things, riding a bicycle at a normal speed, or playing light sports]? "; "How long did you engage in vigorous physical activity [e.g. strenuous physical work or strenuous sports such as riding a bike fast, playing soccer, or jogging] today?"). The durations of all items were summed to calculate total physical activity of each day.

Sleep indicators

In the first questionnaire of each day, participants were asked about different sleep indicators of the previous night. These included sleep-onset latency ("How long did it take you to fall asleep last night?"), sleep duration (time difference between items "When did you turn off the light to sleep?" and "When did you wake up this morning?"), and two sleep quality indicators on a visual analogue scale (0 = not at all; 100 = very much) – "How satisfied are you with your sleep last night?" and "I tossed and turned constantly last night". The second item was adopted from the Groningen Sleep Quality Scale (Mulder-Hajonides van der Meulen et al., 1981). Before computing a sum score of both sleep quality indicators, the second sleep quality indicator was reversed. The sleep quality scale had good internal consistency ($\alpha = 0.77$).

Affective states

Following Das-Friebel et al. (2020), positive affect was measured with five positive items including attentive, content, enthusiastic, happy and relaxed, whereas negative affect was measured with five negative items including annoyed, bored, sad, upset and worried. These items were originally taken from the Positive and Negative Affect Scale (PANAS; Watson et al., 1988) and Russell's Circumplex Model of Affect (Russell, 1980). At each prompt of experience sampling, participants were asked to indicate on a visual analogue scale to what extent they felt each affective state ("How … do you feel at the moment?", 0 = not at all; 100 = very much). Principal axis factoring with varimax rotation revealed a two-factor. Internal consistency was found to be good for positive affect ($\alpha = 0.82$) and acceptable for negative affect ($\alpha = 0.75$). Sum scores for positive and negative affects were computed. Higher sum scores indicate higher levels of positive and negative affect.

2.4 | Statistical analyses

The data processing and analysis plan was preregistered on the Open Science Framework on 22 March 2021 (https://osf.io/rntuc/). Changes made to the analysis plan were described in Supplement 1. Data pre-processing and all statistical analyses were performed using R (version 4.1.2; R Core Team, 2021). The hypothesized relationships were tested by using multilevel models with R-package *lme4* (version 1.1–27.1; Bates et al., 2015). Day of participation and a dichotomous variable indicating whether the respective day was a weekday or weekend were included as covariates in all models.

For each participant, we only included the days with complete information of: (1) duration of moderate and vigorous physical activity of the previous day; (2) sleep indicators; and (3) positive and negative affects measured in the first ESM questionnaire on each sampling day. For missing values, list-wise deletion was applied ($n_{measurements} = 654$). In addition, days when participants reported having engaged in moderate or vigorous physical activity combined for more than 600 min (10 hr; $n_{measurements} = 5$) or a sleep-onset latency of more than 480 min (8 hr; $n_{measurements} = 8$) were excluded from the analysis.

All relevant numerical variables were within-person standardized before analysis, to facilitate classification and comparison of the effect sizes and the interpretation of the results, and to account for within-subject effects (Wang et al., 2019). Maximum likelihood estimation was used to obtain parameters of the multilevel models. A significance threshold of $\alpha = 0.05$ was determined. To address the problem of alpha error accumulation in multiple comparisons, all *p*-values of the multilevel models were adjusted using false discovery rate (FDR; Benjamini & Hochberg, 1995). The *p*-values of all predictors and interactions tested in multilevel models for all primary analyses and exploratory analyses were included in the FDR correction (a total of 326 *p*-values). This excludes the sensitivity analyses that are reported solely in the Supplementary materials (Tables S2 and S3).

2.4.1 | Moderator analyses

To explore whether the relations between physical activity, sleep and affective wellbeing are moderated by depressive symptoms (PHQ-9), sleep quality (PSQI) or habitual physical activity (total MET; IPAQ), the respective variable was included as a cross-level interaction term to each model. Furthermore, for each interaction term, Johnson–Neyman intervals (Bauer & Curran, 2005) were computed using FDR-adjusted critical *t*-values (Esarey & Sumner, 2018) with R-package *interactions* (Long, 2019).

In case of a significant cross-level interaction or limited regions of significance, additional sensitivity analyses testing group differences were conducted. For this purpose, a grouping variable was included into the interaction term of the respective multilevel model instead of the continuous moderator variable. For depressive symptoms, three subgroups were defined by established cut-off scores (Kroenke et al., 2001): participants with no depressive symptoms (PHQ-9 score ≤ 4); mild depressive symptoms (PHQ-9 score = 5–9); and moderate/severe depressive symptoms (PHQ-9 score ≥ 10). Sleep quality subgroups were defined by their PSQI scores (≤ 5 as good sleep quality; > 5 as poor sleep quality; Buysse et al., 1989). The IPAQ scoring protocol (see http://ipaq.ki.se) was used for categorization into subgroups of low, moderate and high habitual physical activity. For the latter, three participants were excluded due to erroneous or incomplete data according to the procedure described in the scoring protocol.

Additionally, gender was investigated as a moderator. Data from one participant who self-identified as "other" were excluded from the moderation analyses. In this analysis, males were coded as 1, and females were coded as 0. In the case of a significant moderation, stratified analyses of the respective association were run separately for females and males.

2.4.2 | Exploratory analyses

In exploratory analyses, we repeated the main analyses and used other physical activity indicators, including: (1) the duration of moderate physical activity the entire day (physical activity since getting out of bed, which was asked in the last questionnaire of the day at random times between 21:00 hours and 22:00 hours); (2) the duration of vigorous physical activity the entire day (this was asked in the last questionnaire in the evening, too); (3) the average physical activity reported in all available daily prompts (maximum seven prompts per day, and each question assessing physical activity within 90 min before the prompt); (4) the average physical activity reported in all the prompts before 14:00 hours (including the first, the second and some of the third prompts of each day, with each question assessing the physical activity within the 90 min before the respective prompt); and (5) physical activity in the 90 min before the seventh/last prompt of each day (the last prompt was between 21:00 hours and 22:00 hours).

For further sensitivity analyses, we also investigated: (1) the mean affective wellbeing of a whole day as an outcome variable; and (2) the previous night's sleep duration as a covariate for all models that include sleep measures as outcome variables. Previous research has shown that sleep duration is both predictor and outcome of vigorous physical activity – shorter sleep duration was followed by less vigorous activity, while more vigorous activity was followed by a longer sleep duration (Pesonen et al., 2022). This means that following a night with shorter sleep duration, a person might be less vigorously active during the day and sleep longer the subsequent night. Controlling for the previous night's sleep duration could therefore test the actual effect of physical activity on sleep.

3 | RESULTS

3.1 | Demographic characteristics

The demographic characteristics and descriptive statistics of the baseline questionnaires and experience sampling items of the entire sample as well as the subgroups are shown in Table 1.

3.2 | Association between physical activity, sleep the following night, and affective states the next day

After removing missing data and outliers, a total of 1244 measurements (65.1% of 1911 possible measurements) from 147 participants were included in the analyses. The number of missed questionnaires per participant was uncorrelated with baseline measures of PHQ-9, PSQI and IPAQ (all p-values > 0.05). All results of primary and exploratory analyses are displayed in Figure 2.

The results of multilevel models showed that physical activity was not associated with subsequent sleep indicators. Exploratory analyses showed that increased physical activity before 14:00 hours was associated with longer sleep duration the following night ($\beta = 0.09$, $p < 0.05$). Better sleep quality ($\beta = 0.22$, $p < 0.001$) and longer sleep duration ($\beta = 0.09$, $p < 0.05$) were associated with higher positive affect the next morning. Also, better sleep quality was followed by lower negative affect the next morning ($\beta = -0.18$, $p < 0.001$). Physical activity was not associated with the next morning's affective states. Therefore, the hypothesis of sleep mediating the association between physical activity and the next day's mood was not tested. All results are displayed in Table S1.

In an additional sensitivity analysis, we also tested the mean values of the affective states over the entire day as an outcome variable. The estimates of the associations described above were slightly weaker or the same, but still significant. The results are displayed in Table S2. Also, for models testing sleep variables as the outcome, we conducted a further sensitivity analysis in which the previous night's sleep duration was included as a covariate. Again, the estimates of respective associations changed slightly, but the overall findings were the same. The results are displayed in Table S3.

3.2.1 | Moderator analyses: Differences between subgroups with diverging levels of depressive symptoms, sleep quality and habitual physical activity

No significant interactions were found when depressive symptom levels (baseline PHQ-9 score), sleep quality (baseline PSQI scores) and habitual physical activity levels (baseline MET reported in IPAQ) were

TABLE 1 Sample characteristics for the full sample and all subgroups based on gender, PHQ-9, PSQI and IPAQ scores

	Full sample ($N = 147$)	Gender[a]		Depressive symptoms (PHQ-9)			Sleep quality (PSQI)		Physical activity (IPAQ)[b]		
		Female ($n = 126$)	Male ($n = 20$)	None ($n = 47$)	Mild ($n = 59$)	Moderate/severe ($n = 41$)	Good ($n = 93$)	Poor ($n = 54$)	Low ($n = 25$)	Moderate ($n = 50$)	High ($n = 69$)
	n (%)/M (SD)	n (%)/M (SD)	n (%)/M (SD)	n (%)/M (SD)	n (%)/M (SD)	n (%)/M (SD)	n (%)/M (SD)	n (%)/M (SD)	n (%)/M (SD)	n (%)/M (SD)	n (%)/M (SD)
Demographics											
Age	22.6 (1.9)	22.5 (1.9)	23.4 (1.9)	23.1 (1.8)	22.4 (2.0)	22.4 (2.1)	22.6 (1.8)	22.6 (2.1)	22.4 (1.9)	22.9 (1.9)	22.4 (2.0)
Gender											
Female	126.0 (85.7%)			33.0 (70.2%)	54.0 (91.5%)	39.0 (95.1%)	77.0 (82.8%)	49.0 (90.7%)	21.0 (84.0%)	42.0 (84.0%)	61.0 (88.4%)
Male	20.0 (13.6%)			14.0 (29.8%)	5.0 (8.5%)	1.0 (2.4%)	16.0 (17.2%)	4.0 (7.4%)	4.0 (16.0%)	7.0 (14.0%)	8.0 (11.6%)
Other	1.0 (0.7%)			0.0 (0.0%)	0.0 (0.0%)	1.0 (2.4%)	0.0 (0.0%)	1.0 (1.9%)	0.0 (0.0%)	1.0 (2.0%)	0.0 (0.0%)
Baseline											
PHQ-9	7.8 (5.2)	8.3 (5.0)	4.2 (3.7)	2.7 (1.5)	7.0 (1.5)	14.9 (3.1)	5.7 (3.9)	11.5 (5.0)	9.2 (6.6)	7.2 (5.0)	7.6 (4.7)
PSQI	4.9 (2.5)	5.1 (2.5)	3.7 (2.2)	3.2 (2.0)	5.0 (2.1)	6.9 (2.2)	3.4 (1.4)	7.6 (1.6)	5.2 (3.2)	5.0 (2.5)	4.7 (2.3)
IPAQ (total MET)	3180 (2483)	3183 (2472)	3258 (2648)	3158 (2646)	3263 (2293)	3084 (2610)	3307 (2353)	2950 (2712)	608 (495)	1689 (725)	5193 (2078)
ESM											
Overall PhA (min)	84.6 (57.2)	82.5 (54.2)	99.1 (74.4)	86.5 (61.3)	80.8 (53.2)	87.7 (59.0)	85.3 (54.0)	83.3 (62.9)	58.7 (50.6)	70.4 (49.1)	101.6[c,d] (58.7)
Moderate PhA (min)[e]	58.7 (41.2)	58.4 (39.9)	61.3 (50.2)	56.5 (41.2)	57.7 (41.6)	62.7 (41.3)	60.8 (40.7)	55.0 (42.0)	47.5 (40.8)	52.3 (35.8)	67.1[c,d] (43.6)
Vigorous PhA (min)[e]	25.9 (34.0)	24.1 (30.0)	37.8 (52.6)	30.0 (45.4)	23.1 (23.1)	25.1 (32.3)	24.5 (27.7)	28.2 (42.9)	11.2 (16.6)	18.2 (36.5)	34.5[c,d] (33.3)
Mean PhA at all prompts[j,e]	18.2 (9.5)	18.5 (9.6)	16.6 (8.9)	17.5 (10.4)	19.5 (8.8)	17.2 (9.4)	18.5 (9.8)	17.7 (9.0)	14.3 (7.6)	15.9 (8.6)	21.3[c,d] (9.7)
PhA before 14:00 hours[j,k,e]	15.5 (10.9)	15.2 (10.2)	17.4 (14.7)	15.8 (11.5)	16.9 (11.2)	13.3 (9.6)	16.2 (9.8)	14.5 (12.5)	13.6 (11.3)	14.2 (10.9)	17.3 (10.7)
PhA at prompt 7[j,e]	12.0 (11.2)	12.3 (11.2)	10.3 (11.0)	10.1 (11.2)	13.2 (8.9)	12.6 (13.8)	12.1 (11.3)	11.8 (11.0)	8.8 (7.7)	9.8 (9.0)	14.6[c,d] (12.4)
Sleep quality	133.2 (30.1)	133.7 (29.7)	133.0 (31.3)	140.7 (35.5)	138.1 (22.2)	117.8[f,g] (28.0)	138.2 (29.8)	124.7[h] (28.8)	130.2 (37.0)	131.3 (31.1)	135.3 (26.4)
Sleep-onset latency (min)	22.1 (21.5)	22.8 (22.6)	17.2 (13.4)	20.9 (17.0)	19.1 (21.5)	27.9 (25.3)	16.5 (14.7)	31.8[h] (27.4)	21.9 (21.8)	23.2 (20.2)	21.4 (22.9)
Sleep duration (hr)	7.9 (0.9)	7.9 (0.9)	7.6 (0.9)	8.0 (0.8)	7.9 (0.8)	7.7 (1.2)	8.0 (0.8)	7.7[h] (1.1)	7.7 (1.2)	8.1 (0.7)	7.8[d] (0.9)
Positive affect	268.6 (66.4)	267.0 (65.7)	281.4 (71.5)	302.1 (69.4)	262.6[f] (48.3)	238.7[f] (69.9)	285.7 (64.9)	239.0[h] (58.7)	251.5 (71.1)	275.0 (72.9)	271.9 (60.3)
Negative affect	103.0 (63.1)	107.3 (64.1)	74.4 (49.7)[i]	73.3 (52.9)	102.9[f] (57.5)	137.3[f,g] (65.2)	94.9 (62.5)	117.0[h] (62.0)	104.9 (72.4)	88.4 (60.1)	110.5 (60.9)

Abbreviations: ESM, experience sampling method; IPAQ, International Physical Activity Questionnaire; *M*, mean; MET, metabolic equivalent of task; *n*, number of participants in subgroup; *N*, total number of participants; PhA, physical activity; PHQ-9, Patient Health Questionnaire-9; PSQI, Pittsburgh Sleep Quality Index; *SD*, standard deviation.

[a]One participant was excluded for descriptive statistics and moderation analyses for gender because this participant identified as other.

[b]Three participants were excluded from the IPAQ classification because they provided erroneous or incomplete data.

[c]Significantly different from IPAQ subgroup with low physical activity.

[d]Significantly different from IPAQ subgroup with moderate physical activity.

[e]Variable used for exploratory analyses.

[f]Significantly different from PHQ-9 subgroup with no depressive symptoms.

[g]Significantly different from PHQ-9 subgroup with mild depressive symptoms.

[h]Significantly different from PSQI subgroup with good sleep quality.

[i]Significantly different from females.

[j]At each prompt, physical activity during the preceding 90 min was reported.

[k]Including first, second and partly third prompt of each day.

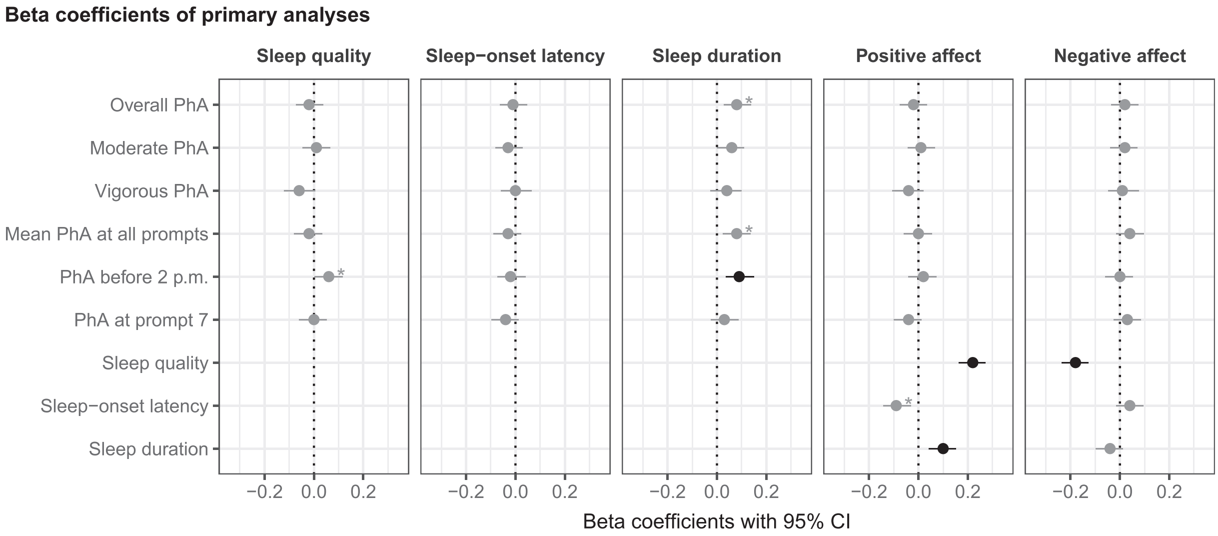

FIGURE 2 Forest plots of standardized beta coefficients for all multilevel models of the full sample. PhA, physical activity. The depicted confidence intervals have not been corrected for multiple comparisons. Interpretations concerning the significance of an association might therefore differ from the false discovery rate (FDR)-corrected *p*-values. Black colour indicates associations that were significant after FDR correction. Asterisks (*) indicate associations that were significant before but not after FDR correction

used as moderators of the tested relations. When testing group differences (i.e. no versus mild depressive symptoms, or no versus moderate/severe depressive symptoms; good versus poor sleep quality; high versus low physical activity), no significant moderation by group was observed either. Johnson–Neyman intervals/regions of significance are displayed in Figures S1–S3.

3.2.2 | Moderator analyses: Gender differences

A significant moderation by gender was found for the association between duration of moderate physical activity and subsequent sleep quality ($\beta = 0.28$, $p < 0.05$). A stratified analysis of the association for females and males separately showed that there was a significant association between moderate physical activity and subsequent sleep quality for males ($\beta = 0.24$, $p < 0.05$), but not for females ($\beta = -0.03$, $p = 0.828$). Gender did not moderate the other associations.

4 | DISCUSSION

Contrary to the hypotheses, the duration of overall physical activity throughout the day did not predict sleep indicators the following night or positive and negative affects the next morning. An exception to that pattern was that physical activity before 14:00 hours was associated with longer subsequent sleep duration. Better subjective sleep quality was followed by higher positive affect and lower negative affect the next morning. Relatedly, longer sleep duration was associated with higher levels of positive affect but not negative affect the next morning. Moderation analysis showed that the hypothesized associations were not moderated by different levels of depressive symptoms, sleep quality or habitual physical activity.

While physical activity has been shown to be associated with acutely improved affective states within the same day (Mata et al., 2012; Wichers et al., 2012), the results of the current study indicate that physical activity is not associated with the next day's affective states anymore. However, our results are consistent with findings of existing experience sampling studies on within-subject associations between physical activity and sleep (Mead et al., 2019; Youngstedt et al., 2003), suggesting that daytime physical activity generally does not predict sleep indicators in young adults. Our finding that physical activity before 14:00 hours was associated with longer subsequent sleep duration is consistent with the recommendation by the American Sleep Association (2022) that physical activity in the morning is beneficial for sleep. It is possible that physical activity earlier in the day is more beneficial for sleep compared with physical activity in the evening as there is more time left for calming down autonomic arousal before going to bed. As that finding comes from an exploratory analysis, it needs to be replicated with independent samples.

We did not find moderation of the association between physical activity and sleep by timepoint or intensity of physical activity, or participants' baseline characteristics including their level of depressive symptoms, habitual physical activity and sleep disturbance. Thus, our and other existing experience sampling studies examining the within-subject variation of physical activity and sleep do not replicate the well-documented finding of an acute beneficial effect of physical activity on subsequent sleep in intervention studies (Kline et al., 2021; Kredlow et al., 2015). A possible reason for this difference between experience sampling and intervention studies is that the naturally occurring day-to-day variation in physical activity observed in this study might be too small to exert an influence on subsequent sleep. Alternative interpretations could be that the sample of the current study was distinct with regard to background characteristics such as habitual physical activity level, age and sex as our sample was rather active, young and predominantly female. However, according to Kredlow et al. (2015), only 23% of the studies included in their meta-analysis were specifically targeting individuals with low physical activity. Moreover, both in Kredlow et al. (2015) as well as in the current study, habitual physical activity was not a moderator of the effect of acute physical activity on sleep indicators such as sleep-onset latency, sleep duration or sleep quality. Therefore, differences in habitual physical activity level appear not as a likely explanation for our diverging results. Furthermore, Kredlow et al. (2015) did not find moderation of the effect of acute exercise on sleep by age. However, they found stronger effects in males compared with females. It is possible that we did not find any association between physical activity and sleep in the models not including gender as a moderator because the participants were predominantly women.

Our findings concerning the associations between sleep indicators and affective states the next morning align with findings from other ESM studies (Das-Friebel et al., 2020; Konjarski et al., 2018; Lenneis et al., under review). The association of sleep quality with the next morning's affective states was found consistently across the full sample, independent of the levels of depressive symptoms, sleep disturbances or habitual physical activity. Thus, consistent with Bouwmans et al. (2017), our results showed no moderation by depressive symptoms.

Overall, it appears that higher physical activity relates to improvements in sleep, even though the association is smaller in the current study than in previous research (Kredlow et al., 2015; Kline et al., 2021) and specific for males. We did not find specific patterns concerning the time of day of physical activity. Future research may also try to find out why people react differently to physical activity. The current study suggests that the baseline measures that were tested as moderators (i.e. depressive symptoms, sleep quality and physical activity) are not among those variables. However, we found that gender is a significant moderator of the association between moderate physical activity and subsequent sleep quality in such a way that the association is only significant in males, but not in females.

4.1 | Limitations and future research

To the best of the authors' knowledge, this study is the first to explore the associations of physical activity with the next day's affective states and the potential mediating effect of sleep in between. Limitations of our study include the following. First, our sample mainly consisted of young female university students, and the findings may therefore not be generalized to other populations. Moreover, while our sample included a large number of individuals scoring above clinical cut-offs of depressive symptoms and/or poor sleep quality, the findings within these subgroups may not necessarily be generalizable to clinical samples. Second, both sleep quality and physical activity were assessed only subjectively, which may have affected our results. In particular, it is conceivable that using self-report for measuring physical activity, sleep and affective wellbeing the next morning may result in the so-called "common-method bias" (Podsakoff et al., 2003), that is that negative mood may taint the perception of all the self-reported variables. In future research, incorporating objective measures of physical activity and sleep using accelerometry could address this issue. Third, the type of physical activity was not considered as a moderating factor. It is possible that the associations of physical activity with affective states (White et al., 2018) or sleep varies depending on the type of physical activity, which could be a topic of future research. Fourth, we did not conduct clinical interviews, therefore we have no information regarding whether participants affected by different types of psychopathologies would behave differently.

5 | CONCLUSION

We found little evidence for an association of duration, intensity or time-point of physical activity during the day with the following night's sleep indicators or the next morning's affective states. An exception to this pattern was that sleep duration was longer after physical activity before 14:00 hours. Also, no major differences in these associations between participants with diverging levels of depressive symptoms, baseline sleep quality and habitual level of physical activity were observed. However, we found that moderate physical activity was associated with sleep quality in males, but not in females. Our study provides further evidence that better sleep quality is associated with higher levels of positive affect and lower negative affect the next morning.

AUTHOR CONTRIBUTIONS

Justin Hachenberger conceptualized the study, collected the data, carried out the analyses, drafted the initial manuscript, and reviewed and revised the manuscript. Yu-Mei Li conceptualized the study, and reviewed and edited the manuscript. Sakari Lemola conceptualized the study, reviewed and edited the manuscript, and supervised the project.

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CONFLICT OF INTEREST

All authors have no known conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. It is planned to make the data available on a repository.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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