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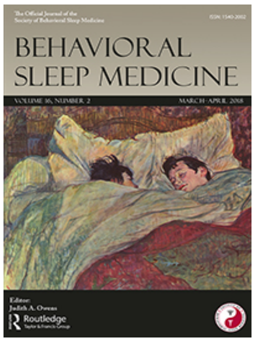

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The Temporal Order of Changes in Physical Activity and Subjective Sleep in Depressed Versus Nondepressed Individuals: Findings From the MOOVD Study

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Epidemiological studies have shown an association between physical activity and sleep, but it is unclear what the temporal order of this association is and whether it differs for depressed patients and healthy controls. Using a multiple repeated observations design, 27 depressed and 27 pair-matched nondepressed participants completed daily measurements of subjective sleep quality and duration during 30 consecutive days while an accelerometer continuously registered their physical activity. Changes in sleep duration, not quality, predicted next-day changes in physical activity (B = –0.21, $p < .001$), but not the

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other way around. Significant heterogeneity between individuals was observed, but the effect was not different for depressed and nondepressed participants. The findings underline the strength of a multiple repeated observations design in observational sleep research.

Physical activity and sleep play an important role in the etiology, maintenance, and treatment of major depression (Lopresti, Hood, & Drummond, 2013; Schmid et al., 2009a). The amount of physical activity and sleep can influence each other, although this bidirectional relationship is not fully understood (Lopresti et al., 2013; Youngstedt, 2005). To clarify this relationship and its role in depression, it is important to further investigate the relationship between physical activity and sleep in depressed and nondepressed people. Since sleep and physical activity are both altered in major depressive disorder (Da Silva et al., 2012; Tsuno, Besset, & Ritchie, 2005; Wielopolski et al., 2015), it would be valuable to investigate if and in what order they affect each other in daily life. To the best of our knowledge, this was not investigated before in depressed patients.

Every opportunity to improve the treatment of depression should be seized, because treatment is not always sufficient, while the recurrence rate of depression increases with every new episode (Solomon et al., 2000). Health care professionals in the Netherlands use a multidisciplinary guideline for the treatment of depression (Spijker et al., 2013). Though sleep is seen as an important factor in depression, interventions concerning the improvement of sleep are not included nor mentioned in the treatment guidelines and protocols for depression (Keijsers, Minnen, & Hoogduin, 2011; Spijker et al., 2013). In contrast, advice with regard to physical activity is commonly accepted in the treatment (and prevention) of depression and is included as a basic intervention in the multidisciplinary guideline. A better understanding of the bidirectional relationship between sleep and activity in depressed patients could be used as a first incentive to improve depression treatment linked to activity or sleep.

The effect of exercise interventions on sleep has been investigated in depressed patients. Adults with depression and adults with chronic sleep complaints experienced a positive impact of exercise programs on subjective sleep quality, which also led to a decrease of depressive symptoms (Gebhart, Erlacher, & Schredl, 2011; Rethorst et al., 2013; Singh, Clements, & Fiatarone, 1997; Singh et al., 2005). An improved subjective quality and duration of sleep ameliorated mood in both depressed and nondepressed people (Bower, Bylsma, Morris, & Rottenberg, 2010; de Wild-Hartmann et al., 2013). We could not find studies that investigate the influence of sleep on physical activity in depressed people. In intervention studies with healthy people and people with sleep complaints, improved sleep quality and duration were associated with an increase in physical activity (Driver & Taylor, 2000; Gebhart et al., 2011; Holfeld & Ruthig, 2014; Rethorst et al., 2013; Schmid et al., 2009b; Youngstedt et al., 2003).

The relationship between sleep and physical activity has been investigated mostly by means of intervention studies, as the above paragraph shows. An alternative approach to investigate the relationship between sleep and activity is by using multiple repeated observations in daily life. One diary study examined whether the amount of exercise predicted changes in subsequent sleep self-reports and vice versa, in a sample of 79 older adults with a sedentary lifestyle during a lifestyle intervention study (Dzierzewski et al., 2014). An increase in exercise during the day was found to predict an increase in sleep quality, and vice versa. Strenous exercise such as running, hockey, or squash, and moderate exercise such as tennis, volleyball, or badminton, but not the amount of regular physical activity, was used as a predictor in this study. To the best of our knowledge, no observational studies with repeated measurements were done yet to investigate the temporal dynamics between sleep and regular physical activity in adult depressed and nondepressed participants. Observational studies with multiple repeated measurements have high ecological validity because the observations are a better representation of the daily life of the participant (Trull & Ebner-Priemer, 2009). Studies with multiple repeated observations can give information about the short-term dynamics (from day to day) between physical activity and sleep. Besides, they allow researchers to estimate group-level effects while taking into account interindividual heterogeneity. The use of multiple repeated observations therefore provides the appropriate design to get a closer look at the bidirectional relationship between activity and sleep in the heterogeneous population of depressed patients (Lamers et al., 2010).

The aim of the current study is to assess the bidirectional relationship between physical activity and subjective quality and duration of sleep in the daily life of depressed and nondepressed people. Using multiple repeated observations within depressed and matched nondepressed people, we were able to investigate the temporal order of this relationship and to disaggregate effects between and within subjects. We expected a bidirectional relationship, meaning that subjective sleep measures influence subsequent physical activity and vice versa. Second, we wanted to find out whether the relationship is different for depressed and nondepressed people. Lack of earlier studies prevented us from forming a well-argued hypothesis on this research aim.

METHODS

We used data from the MOOVD (Mood and Movement in Daily Life) study, a longitudinal time-series design in which participants were monitored 3 times a day for 30 consecutive days in their natural environment (Bouwmans et al., 2015). Depressed ($N = 27$) and nondepressed participants ($N = 27$) were included and pair-matched based on gender, age, smoking, and body mass index (BMI).

Participants

Participants were recruited between January 2012 and May 2014. Depressed individuals were recruited from three outpatient centers for psychiatry; nondepressed individuals were recruited from the general population in the Netherlands. Interested people aged 20 to 50, who could wear an accelerometer for 30 days and could complete a questionnaire on an electronic diary three times a day while collecting saliva samples, were informed with written information. In the first part of the screening procedure, three self-report questionnaires were assessed: (a) a health questionnaire with questions about health complaints, sleep, amount of weekly exercise, medication use, and substance (ab)use; (b) the Munich Chronotype Questionnaire (MCTQ; Roenneberg et al., 2007) to assess the sleep-wake rhythm of the participant; and (c) the Beck Depression Inventory-II (BDI-II; Beck, Erbaugh, Ward, Mock, & Mendelsohn, 1961) to assess the severity of depression symptoms in the past seven days. A BDI-II score ≤ 9 for the controls and ≥ 14 for the depressed participants was sufficient to get invited for the second screening part. In the second part of the screening, the Composite International Diagnostic Interview (CIDI; World Health Organization, 1995) was administered to investigate the absence or presence of a diagnosis of depression according to the *Diagnostic and Statistical Manual of Mental Disorders* (4th ed., text rev.; DSM-IV; American Psychiatric Association, 2000). Depressed and nondepressed participants were interviewed by a trained researcher using the CIDI, who specifically paid attention to the sections on major depressive disorder, bipolar disorder, and psychotic disorder. Depressed participants had to suffer from a major depression episode at the time of the interview or within two months prior to the interview. Nondepressed participants were excluded if they had a current or recent (< 2 months) depressive episode. Somatic disorders or medication use influencing the HPA-axis or the autonomic nervous system, severe visual or auditory difficulties, pregnancy, and a bipolar or psychotic disorder in the past two years were additional exclusion criteria. All participants gave written informed consent prior to the screening procedure.

Design

Participants started the thrice-daily assessments immediately following the screening interview. The first two days were designed for participants to get used to the electronic device and the procedure, and on the third day the official measurement period of 30 days started. Participants filled out the diary questionnaire for 30 days, three times a day, using an electronic diary (Psymate®, PsyMate BV, Maastricht, The Netherlands), while collecting saliva samples. Further, they wore an accelerometer (Actical®, Respironics, Bend, OR, USA) during the whole study period. The timing of the measurements was adjusted to the individuals' sleep–wake schedule to not interfere with the regular rhythm of the participant (Roenneberg et al., 2007). Participants were asked to complete the BDI questionnaire again during the follow-up meeting at the end of the 30-day diary study.

Outcome Measures

Subjective sleep measurements

Both sleep measures were obtained during the first diary assessment of each day. Subjective quality of sleep was assessed with the item, "Did you sleep well?" from the Pittsburgh Sleep Diary (Monk et al., 1994), with response categories ranging from 1 (not good) to 7 (very well). A similar single item to assess subjective sleep quality was used in a previous study (Fung, Nguyen, Moineddin, Colantonio, & Wiseman-Hakes, 2014) and showed sufficient internal consistency and criterion validity compared to the commonly used Pittsburgh Sleep Quality Index (PSQI). Subjective instead of objective measurement of sleep was chosen because there are indications that the subjective negative experience of sleep duration can influence mood and behavior, even when the objective amount of sleep was sufficient (Lauderdale, Knutson, Yan, Liu, & Rathouz, 2008; Regestein et al., 2004). We expected that this psychological effect would influence the amount of physical activity as well. Subjective duration of sleep was measured with the item, "How long did you sleep?" with 12 response categories: < 30 min; ½–1 hr; 1–2 hr; 2–4 hr; 4–6 hr; 6–7 hr; 7–8 hr; 8–9 hr; 9–10 hr; 10–11 hr; 11–12 hr; > 12 hr. Subjective sleep duration was operationalized as a continuous variable with range 1–12 representing these categories.

Physical activity

The Actical®, an omnidirectional accelerometer, was worn on the wrist of the nondominant hand during the whole measurement period for the objective measurement of physical activity. Output of the Actical® was presented as energy expenditure per minute. Energy expenditure reflects the amount of kilocalories used for physical activity per kilogram body weight. The obtained value was multiplied with the body weight (in kilogram) of the participant, to obtain the amount of kilocalories used for physical activity. Physical activity was monitored continuously, but we used only the activity data assessed during the 12 hr between the first and last diary assessment of each day for our physical activity measure. This prevented overlap between sleep and physical activity measures. The sum score of energy expenditure during each day was calculated for each participant, and expressed as physical activity (Heil, 2006). Research shows that longer-term physical activity has more predictive capacity compared with short-term physical activity (e.g., 1 hr of exercise) with regard to sleep (Youngstedt, OConnor, & Dishman, 1997; Youngstedt et al., 2003). It is also shown that physical activity due to exercise appears to be compensated by a decrease in physical activity during the remaining part of the same day (Goran & Poehlman, 1992). This means that the total amount of daily physical activity may stay the same compared to nonexercise days. For this reason we used the total amount of physical activity over the whole day.

Statistical Analysis

Baseline characteristics were compared between the depressed and nondepressed group with an independent samples *t*-test by means of IBM SPSS Statistics 20 (IBM, SPSS Inc., Chicago, IL). We investigated whether changes in physical activity preceded and predicted a change in sleep quality or duration, and vice versa, in four separate analyses. We also assessed whether this relationship differed between depressed and nondepressed people. Four autoregressive multilevel analyses were performed using Stata 13 (StataCorp LP, College Station, TX) by means of the XTMIXED command. Every subject of the final sample was included in the analyses, regardless the amount of missing data. We checked for nonlinearity by means of quadratic predictor terms, and used bootstrapped confidence intervals. Bootstrapped confidence intervals do not rely on potentially problematic distributional assumptions (Neal & Simons, 2007). We first tested whether a change in sleep quality (t) last night predicted a change in subsequent physical activity (t). The italic *t* refers to the current measurement day, *t*-1 to the previous day, and so forth. Sleep quality last night was assessed in the morning of the day (t), and subsequent physical activity was assessed from that point on the same day (t). To take autocorrelation into account, a lagged value of sleep quality, that is, sleep quality in the previous night $(t-1)$ was incorporated into the model. Next, the reverse relationship was tested to find out whether a change in physical activity the previous day $(t-1)$ predicted a change in sleep quality the subsequent night (t). Again, we incorporated a lagged value of physical activity $(t-1)$ to estimate the effect of autoregression. Similar models were built for sleep duration. In every model an interaction term was included to test whether the relationship differed between the depressed and nondepressed group.

A trend in the variables can lead to spurious associations between the variables (Rovine & Walls, 2006). Therefore, trends were removed from the variables using ordinary least squares (OLS) regression, for each individual separately, before the analyses were performed. In order to distinguish effects *within* participants from effects *between* participants, the recommended approach of "person-mean centering of the predictor variables" was used by calculating the daily deviation from the participants' mean values for the predictors (Bolger & Laurenceau, 2013; Curran & Bauer, 2011). As a result the mean value of each predictor equaled zero for all participants, canceling out all between-subjects differences in levels. Consequently, the regression coefficients could be interpreted as within-subjects effects. We also allowed the coefficient of these predictors to vary among individuals (random slope), to take into account possible heterogeneity of the effects among participants. Significance of random slopes was estimated by means of likelihood-ratio tests. When significant random slopes were found, we predicted the effect per individual based on Best Linear Unbiased Prediction (Rabe-Hesketh & Skrondal, 2008). The individual effects were then visualized with a histogram. Further, a random intercept was included in all models. Various covariance structures were tested for the random effects and the residuals. The best-fitting model was chosen based on Akaike and Bayesian Information Criteria. In most models, the best-fitting covariance structure for the random effects and for the residuals was independent.

The season and day of the week were included in the models as covariates, because they are seen as a factor of influence on sleep quality and the amount of physical activity (Levin, Dubose, Bowles, & Ainsworth, 2003; Pereira & Elfering, 2014; Sigmon, Schartel, Boulard, & Thorpe, 2010). The dates at which participants monitored themselves were classified based on the astronomical seasons spring, summer, autumn, and winter (winter used as reference category), and as the respective weekdays (Sunday used as a reference category).

Sensitivity Analysis

A sensitivity analysis was performed to examine whether low levels of physical activity may have been responsible for some of the results. Therefore, the four autoregressive multilevel analyses were repeated in the subsample of participants whose energy expenditure was higher than the average ($\geq$ 756 kcal per day).

RESULTS

Baseline Statistics

The study period of 30 days was started by 62 participants. Four participants dropped out before the end of the study. Another four participants completed the study but did not have enough valid measurements ($T < 60$) with regard to physical activity or diary observations, and were therefore removed from the final sample. Most of the remaining 54 participants were matched based on gender, age, smoking, and BMI ($N = 50$). Four participants could not be matched. Table 1 summarizes the baseline characteristics for both groups. Depressed participants reported a significantly lower quality of sleep on working days compared with the nondepressed participants as measured with the MCTQ, $t(42) = 6.79$, 95% CI of the difference 2.0 to 3.6, $p < 0.01$. During days off, the depressed group also scored significantly lower on sleep quality compared with the nondepressed group, $t(40) = 6.40$, 95% CI of the difference 1.8 to 3.4, $p < 0.01$. Sleep duration on days off reported at baseline was significantly shorter for depressed participants compared with nondepressed participants ($t(50) = 2.10$, 95% CI of the difference 2 to 91, $p = 0.04$). At working days, no difference was found between the groups. There was no significant difference between the groups in the amount of participants that played sports at the baseline measurement of the study ($p > 0.05$). The reported amount of exercise per week at the baseline measurement also did not differ between the depressed and the nondepressed participants ($p > 0.05$). Out of the 17 participants with depression that reported medication use, 14 used antidepressants. One

TABLE 1
Demographic and Clinical Characteristics of MOOVD Participants

	Depressed (N = 27)	*Nondepressed (N = 27)*
Age, years (*SD*)	34.7 (9.9)	34.0 (9.0)
Female, *n*	20	20
BMI, kg/m^2 (*SD*)	24.2 (6.0)	22.5 (2.6)
Smoker, *n*	7	6
Level of education, *n*		
Low	0	0
Middle	14	13
High	11	13
Missing	2	1
Employment, *n*		
Employed	8	14
Student	6	8
Unemployed	8	3
Other	4	2
Missing	1	0
BDI score (*SD*)		
Baseline measurement	31.3 (10.0)***	2.3 (2.7)
Follow-up measurement	24.1 (14.7)***	2.6 (3.6)
Baseline quality night's rest (MCTQ) score range: 1 "lowest" to 10 "highest" (*SD*)		
Workday	4.4 (1.8)***	7.2 (1.1)
Free day	5.0 (1.8)***	7.5 (1.0)
Baseline sleep duration (MCTQ), minutes (*SD*)		
Workday	430 (92)	451 (49)
Free day	450 (95)*	497 (63)
Total amount of exercise as measured with baseline health questionnaire, minutes per week (*SD*)	103 (95)	144 (150)
Daily physical activity during study period, kilocalories (*SD*)	718 (226)**	793 (234)
Medication use, *n*	17***	3
Antidepressants use, *n*	14***	1

Note. Education level "low" = primary school/education, vocational education, preparatory secondary vocational education; "middle" = senior general secondary school, pre-university education; "high" = higher professional education, scientific education; * $p < .05$; ** $p < .01$; *** $p < .001$.

nondepressed participant reported antidepressant use out of the three nondepressed participants that reported medication use.

Multilevel Analyses

Model 1: Do changes in sleep quality precede changes in physical activity?

The multilevel model for physical activity shows that changes in quality of sleep did not precede changes in physical activity (B = 0.03, 95% CI –0.07 to 0.12, p = 0.60; see Table 2, Model 1). Participants' physical activity was not significantly different between seasons. Average physical activity was significantly higher on all days compared with Sundays (p <

TABLE 2
Multilevel Models Predicting Physical Activity From Sleep Quality/Duration, and Vice Versa

	Model 1 Physical activity	*Model 2 Physical activity*	*Model 3 Sleep quality*	*Model 4 Sleep duration*
Fixed effects				
Intercept	6.58 (0.22)	6.68 (0.24)	4.99 (0.13)	6.03 (0.15)
Physical activity$_{t-1}$	–0.003 (0.04)	0.004 (0.03)	–0.001 (0.02)	0.02 (0.02)
Sleep quality$_t$	0.03 (0.05)			
Sleep quality$_{t-1}$			–0.01 (0.02)	
Sleep duration$_t$		–0.21 (0.05)***		
Sleep duration$_{t-1}$				–0.10 (0.03)***
Day of the week				
Monday	0.86 (0.19)***	0.74 (0.22)**	–0.05 (0.10)	–0.31 (0.11)**
Tuesday	0.77 (0.17)***	0.65 (0.20)**	–0.10 (0.13)	–0.32 (0.12)**
Wednesday	0.98 (0.20)***	0.91 (0.24)***	–0.08 (0.11)	–0.18 (0.10)
Thursday	0.94 (0.18)***	0.82 (0.19)***	–0.16 (0.12)	–0.43 (0.11)***
Friday	0.79 (0.20)***	0.62 (0.22)**	–0.18 (0.13)	–0.42 (0.11)***
Saturday	0.97 (0.17)***	0.91 (0.17)***	–0.14 (0.12)	–0.00 (0.09)
Sunday	(reference)	(reference)	(reference)	(reference)
Season				
Spring	0.29 (0.23)	0.30 (0.21)	–0.08 (0.15)	0.04 (0.13)
Summer	0.34 (0.44)	0.32 (0.41)	–0.37 (0.23)	–0.33 (0.36)
Autumn	0.29 (0.47)	0.26 (0.42)	–0.12 (0.15)	–0.29 (0.28)
Winter	(reference)	(reference)	(reference)	(reference)
Random Effects				
Intercept	2.26 (0.07)	2.26 (0.07)	0.77 (0.02)	1.10 (0.03)
Slope				
Physical activity	n.s. (omitted)	n.s. (omitted)	n.s. (omitted)	n.s. (omitted)
Sleep quality	0.23 (0.07)***		n.s. (omitted)	
Sleep duration		0.31 (0.06)***		0.12 (0.03)***
Residual	1.84 (0.06)	1.81 (0.06)	1.13 (0.03)	1.06 (0.04)
N/observations	54/1425	54/1423	54/1353	54/1349

Note. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. N = number of participants. Fixed effects are estimated coefficients (B). Values for *Physical activity*$_t$ and *Physical activity*$_{t-1}$ are 100 times smaller than observed values (rescaled for the sake of clarity). Between parentheses: standard error (*SE*) of the observed coefficient. Random effects are variances. Moderation effects were not significant and therefore removed from the final models.

0.001). The relationship between sleep quality and physical activity was not significantly moderated by depression status (B = –0.16, 95% CI –0.33 to 0.01, p = .06), and therefore this interaction term was omitted from the final model. A significant random slope was found for sleep quality (SD^2 = 0.23, 95% CI 0.13–0.41). This indicates that the strength of the effect of sleep quality on subsequent physical activity differed substantially between participants. Best Linear Unbiased Prediction (BLUP) was used to estimate the predicted individual effects of sleep quality on physical activity in Figure 1

Model 2: Do changes in sleep duration precede changes in physical activity?

The multilevel model for physical activity (Table 2, Model 2) shows that changes in sleep duration did precede changes in physical activity (B = –0.21, 95% CI –0.31 to –0.12, $p < 0.001$). This means that, when participants slept longer than was typical for them, they were less physically active than usual the following day. Average amount of physical activity was not different between different seasons ($p > 0.05$), and significantly lower on Sundays compared with all other days of the week ($p < 0.001$). The relationship between physical activity and sleep quality was not significantly moderated by depression (B = 0.03, 95% CI –0.15 to 0.21, p = 0.74). A significant random slope was estimated for sleep duration (SD^2 = 0.31, 95% CI 0.22–0.45), indicating individual variability in the magnitude of the effect of sleep duration on

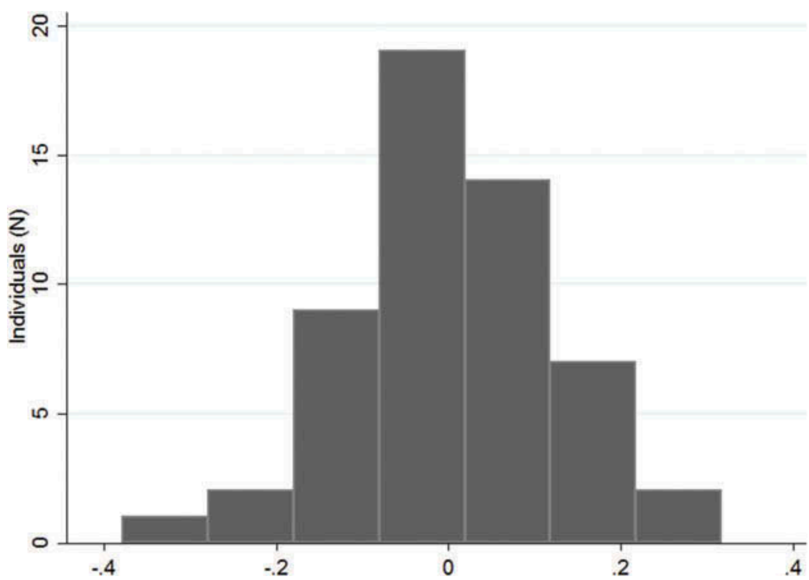

FIGURE 1. We estimated the size and direction of the effect of sleep quality on subsequent physical activity for each individual by means of Best Linear Unbiased Prediction (BLUP). The x-axis represents size and direction of these estimated coefficients, with the number of participants on the y-axis. Example interpretation of the rightmost bar: for n = 2 individuals the predicted coefficient lies between 0.2 and 0.3, which suggests that an increase of 1 unit in sleep quality predicted a subsequent increase between 0.2 and 0.3 unit in physical activity in these individuals.

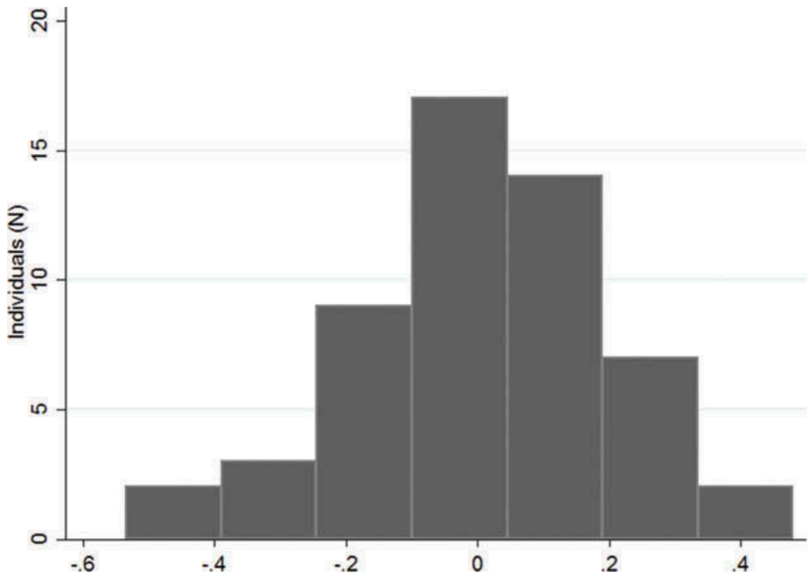

FIGURE 2. We estimated the size and direction of the effect of sleep duration on subsequent physical activity for each individual by means of Best Linear Unbiased Prediction (BLUP). The x-axis represents size and direction of these estimated coefficients, with the number of participants on the y-axis.

physical activity. The predicted individual effects of sleep duration on physical activity were calculated by means of BLUP and visualized in Figure 2

Model 3: Do changes in physical activity precede changes in sleep quality?

The multilevel model for sleep quality (Table 2, Model 3) shows that changes in physical activity did not precede changes in sleep quality (B = –0.001, 95% CI –0.03 to 0.03, $p = 0.93$). Participants' average sleep quality was not different on different days of the week or seasons. The relationship between physical activity and sleep quality did not differ between depressed and nondepressed groups (B = –0.03, 95% CI –0.11 to 0.04, $p = 0.39$). No significant random slopes were found, indicating that there did not exist significant variability between individuals in the magnitude of the relationship between physical activity and sleep quality.

Model 4: Do changes in physical activity precede changes in sleep duration?

The multilevel model for sleep duration (Table 2, Model 4) shows that changes in physical activity did not precede changes in sleep duration (B = 0.02, 95% CI –0.01 to 0.05, $p = 0.17$). Average sleep duration was significantly less on Mondays, Tuesdays, Thursdays, and Fridays compared with Sundays ($p < 0.01$). The relationship between sleep duration and physical activity was not significantly different between the different groups (B = –0.02, 95% CI –0.09 to 0.04, *p*

= 0.50). No significant random slope was found for the effect of physical activity. A significant random slope was found for the autoregressive effect of sleep duration.

Sensitivity Analysis

Eleven depressed and 15 nondepressed participants were included in the sensitivity analysis, based on their mean activity levels during the study period. The results of the autoregressive multilevel models were similar to those of the analyses performed on the complete sample (results not shown).

DISCUSSION

In this study the bidirectional relationship between physical activity and subjective sleep measurements was assessed in depressed and nondepressed participants. The design with multiple repeated measurements enabled us to study this relationship at the group level while taking heterogeneity of individuals into account. The hypothesis that a bidirectional relationship existed was not confirmed, but we found a significant (unidirectional) effect of sleep duration on physical activity. The magnitude of the effect of sleep duration on physical activity differed significantly among individuals. Depression did not moderate the relationship between sleep and physical activity.

Two methodological limitations should be kept in mind while interpreting these findings. The first limitation concerned the operationalization of the subjective sleep measurements. Only one variable was used to define *sleep quality*, and another one was used to define *sleep duration*. Probably, the sleep measures would have been more reliable if multiple variables were used to represent both measures. However, the design hindered us to use multiple variables, because questionnaires in a diary study should be short to keep participants motivated. A second limitation was that subjective but not objective sleep measures were used as a reflection of sleep. Objective sleep measures, such as polysomnography, are mostly used to monitor sleep in an experimental setting. The observational design of the present study prevented the collection of objective sleep measures by means of polysomnography. Though subjective sleep measures have been reported to give an overestimation of objective sleep problems (Lauderdale et al., 2008), these observations were mainly based on studies that used reported sleep over a longer time period (i.e., average sleep duration per month). In the current study subjective sleep was assessed every morning in contrast to every month. Moreover, we were not interested in absolute but in relative levels of sleep duration and quality, and we expect that this recall bias is less for these parameters.

An increase in sleep duration predicted a significant decrease in physical activity the subsequent day in the present study. A negative association was also reported in an observational study with children (Pesonen et al., 2011). This association between sleep duration and next-day exercise duration was not found in an observational study with insomniac patients (Baron, Reid, & Zee, 2013), though the association was stronger for patients with shorter sleep duration at baseline in that study. This contradiction in results is probably due to differences in samples. In our sample, participants showed normal sleep behavior. A possible (Baron, Reid, & Zee, 2013)—but tentative —explanation for the counterintuitive finding that an increase in subjective sleep duration predicted a decrease in subsequent physical activity could be the activation of the parasympathetic nervous system (PSNS). The PSNS is part of the autonomic nervous system and responsible for bodily functions while in rest and while sleeping. Activation of the PSNS results in a decreased heart rate, and increased stomach and intestinal activity (McCorry, 2007). Possibly, the subjective experience of longer sleep results in more relaxation the subsequent day, which might enhance activation of the PSNS. This may in turn result in a decrease in physical activity. Beforehand we expected that a change in sleep quality would influence physical activity the subsequent day as well, but it did not. Dzierzewski and colleagues (Dzierzewski et al., 2014), who included sedentary elderly in their study, did find an association between sleep quality and physical activity. In contrast to those in the Dzierzewski study, the participants in the present study were not sedentary. This might be an explanation for the absence of an effect of sleep quality on subsequent physical activity. We do think that a long-lasting improvement of subjective sleep quality may benefit activity levels, but this is not detectable with the present design. The long-term effect of sleep quality on exercise is still unexplored, and it would therefore be interesting to focus on this in future research (Chennaoui, Arnal, Sauvet, & Leger, 2015).

The nonsignificant finding with regard to the effect of physical activity on subsequent sleep was also found in the study with insomniac patients (Baron et al., 2013), in whom physical activity did not predict changes in sleep duration as well. Contrary to these findings, the earlier diary study in older adults showed a bidirectional relationship between sleep quality and exercise in a lifestyle intervention study (Dzierzewski et al., 2014). This finding might be explained by the nature of the sample: sedentary older people were motivated to enhance the amount of exercise for 16 weeks. This may suggest that physical activity only influences sleep in sedentary people, or that not regular daily physical activity, but moderate and heavy exercise influences sleep. Exercise was recommended as a treatment to improve sleep in a recent review about the reciprocal relationship between exercise and sleep (Chennaoui et al., 2015). Longitudinal intervention studies showed an improvement in sleep quality (Passos et al., 2011; Reid et al., 2010) and duration (Youngstedt et al., 1997) due to physical activity interventions (i.e., exercise for several months 3 times a week) in adults with and also without insomnia. The suggestion that the effect of physical activity on sleep is long-spun instead of short-term (Holfeld & Ruthig, 2014; Lambiase, Gabriel, Kuller, & Matthews, 2013), could be an explanation for this discrepancy.

The heterogeneity in the effects of sleep duration on physical activity emphasizes the importance of tailor-fit approaches in research, but also in clinical settings. Substantial heterogeneity (i.e., significant random effects) was also reported in the earlier mentioned Dzierzewski study (Dzierzewski et al., 2014) on exercise and sleep in older adults. Interindividual variability might explain why treatment based on group averages is ineffective for some, but not all individuals. An appropriate statistical technique to focus on individuals next to group averages would be vector autoregressive modeling (Brandt & Williams, 2007). This technique allows investigating the bidirectional dynamics between multiple variables within individuals (Hamaker, 2012; Rosmalen, Wenting, Roest, de Jonge, & Bos, 2012). By means of this technique, the dynamics between several sleep measures, physical activity, and affect could be estimated simultaneously per individual and give a detailed view of processes between variables within subjects. Techniques like this can be used as a starting point for treatment strategies in which individual differences are taken into account.

In the present observational study the bidirectional dynamic relationship between sleep and physical activity was investigated in depressed and nondepressed individuals. The hypothesis of a bidirectional relationship between sleep and physical activity was not confirmed, but duration of sleep was found to have impact on next day's physical activity negatively. The within-subjects repeated measurements design allowed us to establish the temporal order of the effect and to show the presence of substantial heterogeneity between individuals. This is important, since ultimately depression treatment should target what comes first and what works for whom.

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