Exercise and sleep in community-dwelling older adults: evidence for a reciprocal relationship

JOSEPH M. DZIERZEWSKI 1, 2, MATTHEW P. BUMAN 3, PETER R. GIACOBBI JR 4, BEVERLY L. ROBERTS 5, ADRIENNE T. AIKEN-MORGAN 6, MICHAEL MARSISKE 5 and CHRISTINA S. MCCRAE 5

1Geriatric Research, Education, and Clinical Center, VA Greater Los Angeles Healthcare System, Los Angeles, CA, USA, 2David Geffen School of Medicine, University of California, Los Angeles, CA, USA, 3Arizona State University, Phoenix, AZ, USA, 4West Virginia University, Morgantown, WV, USA, 6University of Florida, Gainesville, FL, USA and 6Duke University Medical Center, Durham, NC, USA

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Correspondence
Joseph M. Dzierzewski, PhD, Advanced Geriatrics Fellow, Geriatric Research, Education, and Clinical Center, Greater Los Angeles Veterans Healthcare System, and Assistant Researcher, David Geffen School of Medicine, University of California, Los Angeles, CA, USA.
Tel.: 818-891-7711 X9164; fax: 818-895-9519; e-mail: Joseph.Dzierzewski@va.gov

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SUMMARY
Exercise behaviour and sleep are both important health indicators that demonstrate significant decreases with age, and remain modifiable well into later life. The current investigation examined both the chronic and acute relationships between exercise behaviour and self-reported sleep in older adults through a secondary analysis of a clinical trial of a lifestyle intervention. Seventy-nine community-dwelling, initially sedentary, older adults (mean age = 63.58 years, SD = 8.66 years) completed daily home-based assessments of exercise behaviour and sleep using daily diary methodology. Assessments were collected weekly and continued for 18 consecutive weeks. Multilevel models revealed a small positive chronic (between-person mean-level) association between exercise and wake time after sleep onset, and a small positive acute (within-person, day-to-day) association between exercise and general sleep quality rating. The within-person exercise and general sleep quality rating relationship was found to be reciprocal (i.e. sleep quality also predicted subsequent exercise behaviour). As such, it appears exercise and sleep are dynamically related in older adults. Efforts to intervene on either sleep or exercise in late-life would be wise to take the other into account. Light exposure, temperature regulation and mood may be potential mechanisms of action through which exercise can impact sleep in older adults.

INTRODUCTION
Exercise and sleep are both important health behaviours in older adults. Exercise level has been linked to cardiovascular disease, metabolic disorders, obesity and mental health (Physical Activity Guidelines Advisory Committee, 2008). Sleep duration and quality has also been linked to many of these outcomes (Dew et al., 2003; Kay and Dzierzewski, in press; Patel et al., 2009). However, both behaviours decline with age. Only 10% of Americans over the age of 65 years meet the national physical activity guidelines needed to receive health benefits (Physical Activity Guidelines Advisory Committee, 2008). Similarly, as an individual increases in age, important metrics of sleep quality and duration decline, including the amount of time it takes one to fall asleep (i.e. sleep-onset latency; SOL), the amount of unwanted time one spends awake during the night (i.e. wake time after sleep onset; WASO; Floyd et al., 2000).

Randomized intervention studies have examined the ‘chronic’ effect of exercise (regular, sustained exercise typically in line with national guidelines) on sleep. A number of trials of exercise, compared with controls, have found modest, yet significant improvements in self-reported sleep quality (King et al., 1997; Singh et al., 1997) and objective sleep parameters via polysomnography (King et al., 2008) in older adults with a sleep complaint, while no such improvements have been found in healthy sleeping older adults (Oudegeest-Sander et al., 2013). Meta-analyses of ‘acute’ exercise studies (typically a single bout) have found that increased exercise is associated with modest improvements in several sleep parameters, including total sleep time, slow-wave sleep and rapid eye movement sleep latency (Driver...
and Taylor, 2000; Youngstedt et al., 1997). These meta-analyses are limited in that they mostly include young, fit subjects lacking sleep complaints (Youngstedt, 2003). Despite the apparent temporal link between increased physical activity and sleep improvements, only one study that we are aware of has explored this relationship temporally. Holfeld and Ruthig (2012) found, in a 2-year cross-lagged panel analysis of community-dwelling older adults, that initial sleep quality predicted physical activity 1 year later, but that initial physical activity did not predict later sleep quality. There are a number of hypotheses that would support a reciprocal relationship between exercise and sleep. Individuals who achieve a restful night of sleep may awaken the next day with sufficient energy to engage in increased levels of exercise (Holfeld and Ruthig, 2012). Alternatively, enhanced sleep may impact other health systems, such as mood (McCrae et al., 2008) or pain (Dzierzewski et al., 2011), which in turn may impact physical activity.

The majority of exercise behaviour is conducted outdoors (Youngstedt et al., 1997), where exposure to bright sunlight is likely. Properly timed exposure to daytime bright light has strong known sleep-promoting effects (Hood et al., 2004). As such, it has been suggested that some of the effects of exercise on sleep may be the result of circadian mechanisms (O’Connor and Youngstedt, 1997). In fact, the lack of control regarding exposure to daylight inherent in exercise trials and measurement of location of exercise behaviour has been cited as a major limitation in randomized-controlled trials examining the effects of exercise on sleep in older adults (O’Connor and Youngstedt, 1997).

The current study

The potentially complex relationship between sleep and exercise has been characterized as ‘difficult to answer from the current literature’ (Driver and Taylor, 2000). None of the aforementioned studies has examined how exercise behaviour and sleep may be related over time (across consecutive days) within individuals. Questions concerning the ‘chronic’ and ‘acute’ effects of exercise on sleep remain unanswered. Rather than averaging measurements to generate aggregate estimates or collecting reconstructive single estimates, the current study assumes the variations in exercise behaviour and sleep represent natural fluctuations in the individual’s physiological/psychological condition. This study sought to address four main questions, as follows: (i) Is chronic level of exercise behaviour (i.e. average level of exercise behaviour) associated with self-reported sleep in older adults? (ii) Does the prior day’s exercise (or acute exercise) affect the subsequent night’s self-report of sleep? (iii) Is the exercise-sleep relationship uni-directional or reciprocal in nature among older adults? (iv) Does the location in which the exercise was conducted (indoor versus outdoor) impact the relationship between exercise and sleep?

MATERIALS AND METHODS

General study design

This study represents a secondary analysis of the Active Adult Mentoring Program (Project AAMP). The primary objective of Project AAMP was to test the efficacy of a social-cognitive lifestyle intervention to increase moderate-intensity exercise in older adults. The full study methods are presented elsewhere (Buman et al., 2011), and are briefly summarized here. Project AAMP included an Active Lifestyle intervention arm that received weekly, group-based behavioural counselling focused on physical activity delivered by trained peer counsellors, and a Health Education arm that received appropriately matched health education regarding issues pertinent to late-life. Both arms received access to an exercise facility during the intervention period. The results presented here were from the initial 18 weeks of the study, including a baseline week of observation prior to group assignment, 16 weeks of intervention, and a subsequent week of observation following the intervention period.

Potential enrollees responded to community-based health promotion recruitment strategies delivered through local media outlets. The primary eligibility criteria included: (i) age 50 years or older; (ii) a self-reported sedentary lifestyle [defined as not currently meeting minimum physical activity guidelines of ≥150 min week of moderate or vigorous physical activity (Physical Activity Guidelines Advisory Committee, 2008) during the previous 6 months]; (iii) free of factors with potential for adverse effects on the safety of older adults participating in an exercise intervention; and (iv) free of factors affecting compliance with study protocols. The study protocol was approved by the appropriate university institutional review boards, and written informed consent was obtained. During the entire study period (18 consecutive weeks), study participants provided self-report information, via paper daily diaries, regarding their daily (i) exercise behaviours; (ii) sleep behaviours; and (iii) whether the exercise behaviour was performed indoors or outdoors.

Measures

Exercise behaviour

The Leisure-Time Exercise Questionnaire (LTEQ) is a three-item scale that asks participants to rate how often they engaged in 20-min bouts of mild, moderate and strenuous leisure-time exercise (Godin et al., 1986). Although typically used as a 7-day recall of exercise behaviour, in the present study the LTEQ was used daily to reduce recall bias and examine daily associations between exercise and sleep. Upon awakening each morning, study participants completed the LTEQ based on their previous day’s exercise behaviour. Minutes of moderate-to-vigorous physical activity (from here forward simply referred to as physical activity) were computed from the LTEQ by adding the number of moderate and
strenuous bouts reported, and multiplying by 20. The LTEQ is a valid and reliable measure of physical activity in adults (Godin et al., 1986). To verify the validity of the LTEQ given the modified recall time-frame (from 7 days to daily), a random subsample of AAMP participants concurrently wore an accelerometer and completed the LTEQ. LTEQ scores were significantly correlated with accelerometry at \( r = 0.48 \) (\( P < 0.001 \); see Buman et al., 2011), a value higher than previously reported for the 7-day recall of this measure. Subsequent to completion of the daily LTEQ, participants responded to the following cue, ‘please indicate how many exercise bouts occurred indoors and how many occurred outdoors.’

**Self-report sleep**

Participants completed sleep diaries upon awakening each morning for 126 days, providing subjective estimates of the following sleep parameters: (i) SOL: estimated by participants as the time it took them to fall asleep after laying down with the intention of going to sleep; (ii) WASO: estimated by participants as the total amount of time spent awake during the night; and (iii) sleep quality rating (SQR): participants overall rating of the quality of their night’s sleep (from 1 = very poor to 5 = excellent). These sleep parameters were chosen for inclusion in the present study due to known age-related changes based on meta-analysis (Floyd et al., 2000), while other indicators of sleep (i.e. sleep efficiency and total sleep time) were not included to reduce potential family-wise error and due to lack of associations with exercise behaviour in other studies (Oudegeest-Sander et al., 2013).

**Demographic data**

Each study participant provided demographic data by a telephone screening instrument at baseline. Information regarding participant age, gender, education level and body mass index (BMI) was collected. During the telephone screening all participants were also administered the Telephone Interview for Cognitive Status (TICS; Brandt et al., 1988) for a standardized assessment of cognitive status. A cut-off score of 27 points was used to exclude individuals with dementia from the study.

**Analysis**

Daily ratings of physical activity were used to predict sleep (SOL, WASO and SQR), applying a multilevel model (MLM) approach. This provided the opportunity to examine whether exercise behaviour predicted sleep both within- (level 1: across days/acute) and between- (level 2: across persons/ chronic) persons. Final models predicted daily sleep with: average level of sleep; demographic variables (experimental group, age, gender, education, BMI and TICS score); mean-level physical activity (between-person, chronic exercise); person-centred physical activity (within-person, acute exercise); random error term; and random residual component. Three separate MLMs were parameterized (one for SOL, one for WASO and one for SQR).

To examine the potential of reciprocal relationships between physical activity and sleep (i.e. that sleep may predict exercise behaviour), three additional MLMs were parameterized such that physical activity was the dependent variable, and chronic and acute sleep variables (mean-level and person-centred SOL, WASO, SQR) were the independent variables. Models predicting physical activity were estimated in a similar fashion as models predicting sleep. Mathematical equations estimated (for mixed/combined models) as follows:

\[
\text{Sleep}_i = \beta_{00} + \beta_{01}(\text{Group}_i) + \beta_{02}(\text{Age}_i) + \beta_{03}(\text{Gender}_i) + \beta_{04}(\text{Education}_i) + \beta_{05}(\text{BMI}_i) + \beta_{06}(\text{TICS}_i) + \beta_{07}(\text{Physical Activity}_i) + \beta_{08}(\text{Physical Activity}_i - \text{Physical Activity}_i) + \gamma_i(\text{MVPA}_i - \text{Physical Activity}_i) + \delta_i + \epsilon_i
\]

\[
\text{Physical Activity}_i = \beta_{00} + \beta_{01}(\text{Group}_i) + \beta_{02}(\text{Age}_i) + \beta_{03}(\text{Gender}_i) + \beta_{04}(\text{Education}_i) + \beta_{05}(\text{BMI}_i) + \beta_{06}(\text{TICS}_i) + \beta_{07}(\text{Sleep}_i) + \beta_{08}(\text{Sleep}_i - \text{Sleep}_i) + \gamma_i(\text{Physical Activity}_i - \text{Sleep}_i) + \delta_i + \epsilon_i
\]

To examine the effects of location of exercise (indoor versus outdoor) on any observed exercise-sleep relationships, the number of outdoor and indoor exercise bouts were summed on a day-to-day basis, and mean-level and person-centred number of outdoor exercise bouts were entered into the models. Levels and patterns of significance were examined to inspect for any changes as a result of including location of exercise in the models.

All variables were standardized into \( Z \)-score metrics between- and within-participants (thus, the average participant on the average day would have a mean of 0.0, standard deviation of 1.0) prior to parameterization of the MLM. This approach preserved both between- and within-person differences, while facilitating interpretation of model parameters. As such, the model-produced coefficients are similar to traditional standardized regression coefficients in ordinary least squares regressions. The specifics of MLM are beyond the scope of this paper. Interested readers are referred to other sources (Bryk and Raudenbush, 1992).

**RESULTS**

**Sample characteristics**

The final sample included 79 older adults \( (\text{M}_{\text{age}} = 63.58 \text{ years}, \text{SD}_{\text{age}} = 8.66 \text{ years}) \). In general, the sample was comprised of young-old, highly educated and
predominantly female Caucasians. To test the assumption that we could treat our participant sample as one homogenous group (and not as two distinct arms of an intervention), \( t \)-tests and \( \chi^2 \)-tests were employed to examine any group (i.e. Active Lifestyle versus Health Education) differences in descriptive characteristics, mean-level sleep and mean-level physical activity across the 18-week study period. All tests of group differences resulted in non-significant results; thus, the sample was treated as a homogenous whole in subsequent analyses. As a precaution, we included a dummy code for intervention group in all MLMs. Specific sample descriptive characteristics (including demographics, sleep and exercise information) can be found in Table 1.

MLMs

The intraclass correlation coefficients (ICCs), which serve as an index of within- and between-person variability to be explained (Bryk and Raudenbush, 1992), were 0.46, 0.28 and 0.54, respectively, for SOL, WASO and SQR, indicating that 54, 72 and 46% of the overall variability in SOL, WASO and SQR was a within-person phenomenon. The ICC for physical activity was 0.50. Response rates for our daily measures of exercise and sleep were approximately 80% (from a potential 9954 data points). MLM uses all available data, and is valid for making inferences to the population of origin when data are missing at random (Bryk and Raudenbush, 1992).

Predictor estimates, significance levels and model parameters are presented in Table 2 for all models predicting sleep. In the final MLM predicting SOL, Education Level \( (\beta = -0.17, \ SE = 0.07, \ t_{63.87} = -2.38, \ P = 0.02) \) was a significant between-person (level 2) predictor, suggesting that individuals with above-average educational attainment had lower than average SOL. At the within-person level (level 1) there were no significant predictors of SOL. The model explained approximately 27% of the variance in SOL.

In the final MLM predicting WASO, Age \( (\beta = 0.13, \ SE = 0.06, \ t_{64.25} = 2.22, \ P = 0.03) \) and Physical Activity_\text{mean} \( (\beta = -0.34, \ SE = 0.13, \ t_{64.87} = -2.58, \ P = 0.01) \) were significant between-person (level 2) predictors, suggesting that individuals who reported participating in less physical activity (on average) and were older had more than average WASO. At the within-person level (level 1) there were no significant predictors of WASO. The model explained approximately 19% of the variance in WASO.

In the final MLM predicting SQR, there were no significant between-person (level 2) predictors. At the within-person level (level 1), Physical Activity_\text{centred} \( (\beta = 0.06, \ SE = 0.03, \ t_{65.01} = 2.04, \ P = 0.05) \) was a significant predictor of SQR, suggesting that following a day of above-average physical activity individuals experienced above-average SQR. The model explained approximately 36% of the variance in SQR.

In the final MLM predicting physical activity from SOL, no substantive predictors were significant (Table 3). In the final MLM predicting physical activity from WASO, Age \( (\beta = 0.11, \ SE = 0.05, \ t_{64.81} = 2.00, \ P = 0.05) \) and WASO_\text{mean} \( (\beta = -0.26, \ SE = 0.09, \ t_{62.32} = -2.74, \ P = 0.008) \) were significant between-person (level 2) predictors, suggesting that younger individuals and individuals who experienced more WASO also reported participating in less physical activity (on average). In the final MLM predicting physical activity from SQR, SQR_\text{centred} \( (\beta = 0.04, \ SE = 0.01, \ t_{53.75} = 3.40, \ P = 0.001) \) was a significant predictor of physical activity, suggesting that following a day of above-average sleep

<table>
<thead>
<tr>
<th>Table 1 Sample characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total sample</strong> (N = 79)</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
</tr>
<tr>
<td>Age</td>
</tr>
<tr>
<td>Education</td>
</tr>
<tr>
<td>TICS</td>
</tr>
<tr>
<td>BMI</td>
</tr>
<tr>
<td>Gender (% female)</td>
</tr>
<tr>
<td>Race (% white)</td>
</tr>
<tr>
<td>SOL</td>
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<tr>
<td>WASO</td>
</tr>
<tr>
<td>SQR</td>
</tr>
<tr>
<td>Physical Activity</td>
</tr>
</tbody>
</table>

BMI, body mass index; Physical Activity, minutes of moderate to vigorous physical activity; SOL, sleep-onset latency; SQR, sleep quality rating; TICS, Telephone Interview for Cognitive Status; WASO, wake time after sleep onset.

\( t \)-tests show significance of the comparison between Active Lifestyle and Health Education participants; for gender and race, a corresponding chi-squared test was used. No covariate adjustment was employed.

*Degrees of freedom and \( t \)-statistic were adjusted for non-homogeneity of variance.

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quality individuals reported engaging in above-average levels of physical activity. These models explained between 28 and 30% of variance in physical activity.

When the number of outdoor exercise bouts was included into the models predicting sleep outcomes with exercise behaviour, the pattern of results and significance levels did not substantially change. Acute outdoor exercise bouts did not predict the subsequent night’s SOL, WASO or SQR ($P = 0.69, 0.12$ and $0.85$, respectively). Similarly, individuals who engaged in chronic outdoor exercise did not also experience better/worse average SOL, WASO or SQR ($P = 0.21, 0.27$ and $0.65$, respectively).

**DISCUSSION**

Regarding the four questions posed by this research, we discovered the following: (i) More chronic levels of exercise behaviour were associated with lower self-reported WASO in older adults. (ii) Increased prior day’s exercise (or acute exercise) was associated with higher subsequent night’s self-report of sleep quality. (iii) The observed acute exercise-SQR relationship was reciprocal in nature among our older adult sample. (iv) The location in which the exercise was conducted (indoor versus outdoor) did not impact the relationship between exercise and sleep. Specifically, we found that neither average level of physical activity nor daily fluctuations in physical activity significantly predicted the amount of time to fall asleep. However, participants who reported engaging in more physical activity on average also reported experiencing lesser amounts of wake time during the night on average. Finally, while the average level of physical activity did not predict sleep quality, fluctuations in sleep quality did predict subsequent sleep quality. Previous research has revealed that exercise is associated with sleep in various ways (Morgan, 2003; Sherrill et al., 1998) and that this relationship might change with age (Oudegeest-Sander et al., 2013); however, Buman and King (2010) suggest the cross-sectional nature of these studies ‘precludes an understanding of the temporal nature of the relationship (i.e. individuals experiencing better sleep may be more inclined or disposed to be more physically active during the day)’.

Furthermore, experimental trials primarily test the chronic effects of exercise on sleep, but are unable to explore the relative contributions of both chronic and acute effects that exercise may have on sleep.

Previous research has been able to demonstrate the chronic effect of exercise on sleep behaviour in older adults through exercise intervention studies (King et al., 1997, 2008) and cross-sectional designs (Morgan, 2003; Sherrill et al., 1998). Acute effects of exercise behaviour on sleep

### Table 2 Two-level MLMs predicting sleep from minutes of moderate to vigorous physical activity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SOL</th>
<th>WASO</th>
<th>SQR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate SE</td>
<td>Estimate SE</td>
<td>Estimate SE</td>
</tr>
<tr>
<td>Fixed effects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>$\beta_{00}$</td>
<td>0.032 0.070</td>
<td>$-0.038$ 0.053</td>
</tr>
<tr>
<td>Group†</td>
<td>$\beta_{01}$</td>
<td>$-0.125$ 0.071</td>
<td>$-0.084$ 0.054</td>
</tr>
<tr>
<td>Age‡</td>
<td>$\beta_{02}$</td>
<td>0.046 0.078</td>
<td>0.132 0.059*</td>
</tr>
<tr>
<td>Gender§</td>
<td>$\beta_{03}$</td>
<td>$-0.027$ 0.070</td>
<td>0.024 0.053</td>
</tr>
<tr>
<td>Education¶</td>
<td>$\beta_{04}$</td>
<td>$-0.172$ 0.072*</td>
<td>$-0.075$ 0.055</td>
</tr>
<tr>
<td>BMI</td>
<td>$\beta_{05}$</td>
<td>0.037 0.073</td>
<td>0.017 0.055</td>
</tr>
<tr>
<td>TICS</td>
<td>$\beta_{06}$</td>
<td>$-0.101$ 0.080</td>
<td>$-0.033$ 0.061</td>
</tr>
<tr>
<td>Physical activity (BP)</td>
<td>$\beta_{07}$</td>
<td>$-0.108$ 0.174</td>
<td>$-0.340$ 0.132*</td>
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<tr>
<td>Physical activity (WP)</td>
<td>$\beta_{08}$</td>
<td>$-0.007$ 0.020</td>
<td>0.021 0.024</td>
</tr>
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<td>Random effects</td>
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<tr>
<td>Intercept</td>
<td>$\gamma_{00}$</td>
<td>0.292 0.053***</td>
<td>0.163 0.031***</td>
</tr>
<tr>
<td>Residual</td>
<td>$\gamma_{01}$</td>
<td>0.813 0.015***</td>
<td>0.877 0.016***</td>
</tr>
<tr>
<td>Physical activity (WP)</td>
<td>$\gamma_{02}$</td>
<td>0.002 0.004</td>
<td>0.006 0.005</td>
</tr>
<tr>
<td>Model fit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviance (df)</td>
<td>3113.301(9)***</td>
<td>3548.137(9)***</td>
<td>3753.605(9)***</td>
</tr>
</tbody>
</table>

BMI, body mass index; BP, between-persons; Physical Activity, minutes of moderate to vigorous physical activity; SOL, sleep-onset latency; SQR, sleep quality rating; TICS, Telephone Interview for Cognitive Status (higher scores are indicative of better overall cognitive functioning); WASO, wake time after sleep onset; WP, within-persons.

Original model parameterization included linear, quadratic and cubic time effects. However, as these terms were not significant predictors and their removal did not substantively change parameter estimates, they were subsequently removed from models to facilitate interpretation. All variables were transformed into a Z-score metric prior to model parameterization.

†0 = Health Education; 1 = Active Lifestyle.
‡Measured in years since birth.
§0 = female; 1 = male.
¶Measured in years of schooling.

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. 

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have been demonstrated through experimental manipulation of exercise (Youngstedt et al., 1997). As Buman and King (2010) have suggested, implementation of MLM techniques allowed modelling of both chronic (mean-level) and acute (person-centred) effects simultaneously. In doing so we found that chronic and acute exercise appears to influence various aspects of sleep distinctly. While chronic exercise showed a relationship to wake time during the night, acute exercise was beneficial for subjective ratings of overall sleep quality. Such results may be useful in determining optimal intervention strategies based on the specific sleep complaints of older adult patients (such that an older individual complaining of poor sleep quality may respond quickly to exercise, while an individual complaining of lengthy WASO will likely require longer-term exercise to see an improvement).

The differing effects of chronic and acute exercise behaviour on sleep may shed light on the hypothesized mechanisms of action responsible for such relationships. Mood regulation mechanism acts acutely in older adults. Similarly, as sleep has been found to be acutely related to mood in older adults (McCrae et al., 2008), mood may also be the mechanism through which sleep affects subsequent exercise behaviour.

It has been suggested that some of the effects of exercise on sleep may be the result of increased exposure to daylight (O’Connor and Youngstedt, 1997), and the lack of examination into exposure to natural light occurring within exercise trials has been noted as a significant shortcoming. In our specific sample the location of the exercise behaviour (which likely correlates with exposure to natural bright light) was not significantly related to the sleep variables. The addition of the exercise location variables also did not significantly attenuate any of the previously observed relationships. As such, it does not appear that increased exposure to natural bright light is driving the observed relationships between exercise behaviour and sleep. As our sample was comprised primarily of young-old adults living in North-Central Florida, they may...

### Table 3 Two-level MLMs predicting minutes of moderate to vigorous physical activity from sleep

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Estimated SE</th>
<th>Estimated SE</th>
<th>Estimated SE</th>
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<td>Fixed effects</td>
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<tr>
<td>Intercept</td>
<td>β  0</td>
<td>—0.066  0.050</td>
<td>—0.075  0.047</td>
<td>—0.065  0.050</td>
</tr>
<tr>
<td>Group</td>
<td>β  1</td>
<td>—0.008  0.053</td>
<td>—0.021  0.050</td>
<td>—0.29E-4  0.051</td>
</tr>
<tr>
<td>Age</td>
<td>β  2</td>
<td>0.080  0.055</td>
<td>0.108  0.054*</td>
<td>0.069  0.056</td>
</tr>
<tr>
<td>Gender</td>
<td>β  3</td>
<td>—0.022  0.050</td>
<td>—0.016  0.048</td>
<td>—0.013  0.051</td>
</tr>
<tr>
<td>Education</td>
<td>β  4</td>
<td>—0.072  0.054</td>
<td>—0.077  0.049</td>
<td>—0.066  0.051</td>
</tr>
<tr>
<td>BMI</td>
<td>β  5</td>
<td>0.026  0.052</td>
<td>0.028  0.050</td>
<td>0.026  0.052</td>
</tr>
<tr>
<td>TICS</td>
<td>β  6</td>
<td>—0.001  0.058</td>
<td>—0.006  0.055</td>
<td>0.0004  0.057</td>
</tr>
<tr>
<td>Sleep (BP)</td>
<td>β  7</td>
<td>—0.042  0.085</td>
<td>—0.278  0.106*</td>
<td>0.079  0.082</td>
</tr>
<tr>
<td>Sleep (WP)</td>
<td>β  8</td>
<td>—0.009  0.010</td>
<td>—0.016  0.019</td>
<td>0.045  0.013**</td>
</tr>
<tr>
<td>Random effects</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>r00</td>
<td>0.151  0.008***</td>
<td>0.136  0.025***</td>
<td>0.150  0.027***</td>
</tr>
<tr>
<td>Residual</td>
<td>r01</td>
<td>0.403  0.008***</td>
<td>0.399  0.008***</td>
<td>0.400  0.008***</td>
</tr>
<tr>
<td>Sleep (BP)</td>
<td>r10</td>
<td>0.27E-5  0.0004</td>
<td>0.011  0.005*</td>
<td>0.003  0.002</td>
</tr>
</tbody>
</table>

BMI, body mass index; BP, between-persons; Physical Activity, minutes of moderate to vigorous physical activity; SOL, sleep-onset latency; SQR, sleep quality rating; TICS, Telephone Interview for Cognitive Status (higher scores are indicative of better overall cognitive functioning); WASO, wake time after sleep onset; WP, within-persons.

Original model parameterization included linear, quadratic and cubic time effects. However, as these terms were not significant predictors and their removal did not substantively change parameter estimates, they were subsequently removed from models to facilitate interpretation. All variables were transformed into a Z-score metric prior to model parameterization.

*0 = Health Education; 1 = Active Lifestyle.
†Measured in years since birth.
‡Measured in years of schooling.
§0 = female; 1 = male.

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have already been exposed to significant levels of bright light. Future research, conducted in other regions, would be well suited to measure either location of exercise or directly measure light exposure to determine if there is a regional effect of light exposure subsequent to exercise in older adults.

Temperature regulation following exercise behaviour is another hypothesized mechanism through which exercise may affect sleep. Core body temperature is elevated during and following exercise behaviour (Lim et al., 2008). This increased temperature is followed by temperature downregulation, which is associated with deepness of sleep (Youngstedt, 2005). As older adults are more likely to complain of wake time during the night than sleep-onset problems (Morgan, 2000), and because deepness of sleep is related to consistency of sleep, temperature regulation may be a particularly important mechanism in this population. We found that chronic exercise impacts wake time during the night in older adults. If temperature regulation is responsible for improvements in wake time during the night associated with exercise, it appears that this may be a cumulative effect such that chronic exercise behaviour is needed to engender wake time changes. Perhaps chronic engagement in exercise behaviour is needed for temperature downregulation to significantly impact sleep. Reciprocally, older adults with consistently less WASO may experience more consistent temperature regulation and thus awake more refreshed and be more likely to exercise. These questions should be addressed in future studies.

Limitations and future directions

Our exercise and sleep measures were both self-report in nature, and are therefore subject to the common issues of recall bias, potential non-compliance and potentially have shared method-related variance. Additionally, the nature of the diaries precludes any means to determine if they were completed on time. However, we feel that the increase in ecological validity due to the non-invasive nature of our repeated assessments and pure length of observation (126 days) outweighs the lack of control inherent in self-report measures. Additionally, self-reports and self-observation are intrinsic and required aspects of developing a complaint, seeking treatment for the complaint, and subsequently determining satisfaction with any treatments received. Thus, self-reports are the preeminent judge of behaviour and behaviour change. Yet, future investigations into the exercise-sleep relationship would be wise to include objective measures of both exercise and sleep in addition to self-report measures. Our sample was not screened for sleep complaints and/or sleep-disordered breathing, and therefore contains an unknown number of individuals with organic and non-organic sleep disturbances, and exercise has been found to improve indices of disordered breathing and sleep quality in adults with sleep apnoea (Kline et al., 2011). Lastly, the sample was recruited for low levels of physical activity. Such low levels of activity likely precluded reductions in activity from occurring, and could be limiting any dynamic associations between sleep and physical activity.

Summary

The results of the present investigation suggest that older adults suffering from poor sleep quality may benefit from acute exercise behaviours, while older individuals with extended wake time after sleep onset may require more prolonged, chronic exercise to achieve benefits to sleep. Interestingly, sleep quality was found to be an acute predictor of subsequent exercise behaviour in sedentary older adults. Such information should be considered when recommendations regarding increased exercise are relayed to older, sedentary individuals.

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CONFLICT OF INTEREST

No conflicts of interest declared.

REFERENCES


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