Abstract

Although physical activity and sleep may influence each other, little is known about the bidirectional association of the two behaviors. Analyses included 38,601 UK Biobank participants (51% female, 55.7±7.6 years old, 6.9±2.2 years of follow-up). Physical activity was categorized by the weekly metabolic equivalent of task minutes (highly active: ≥ 1200; active: 600 to < 1200; inactive: < 600), and sleep patterns were determined using a composite score of healthy sleep characteristics: morning chronotype, adequate sleep duration (7-8 hr/d), never or rare insomnia, never or rare snoring, and infrequent daytime sleepiness. We categorized the sleep score into three patterns (healthy: ≥ 4; intermediate: 2-3; poor: ≤ 1). Multiple logistic regressions examined the association of baseline (or the temporal changes in) sleep/physical activity with physical inactivity/poor sleep at follow-up. Participants with an intermediate or poor sleep pattern at baseline had higher odds (adjusted odds ratio: 1.24 [1.17, 1.32] and 1.65 [1.45, 1.88], respectively) for physical inactivity at follow-up, compared to those with healthy sleep, while shifting to a healthy sleep pattern over time attenuated these adverse associations. Compared to individuals highly active at both time points, being physically inactive at baseline and reducing physical activity over time were both associated with higher odds for poor sleep at follow-up. In conclusion, sleep improvements over time benefitted physical activity at follow-up, while reduced physical activity had a detrimental effect on sleep patterns at follow-up. Our results provide scope for interventions to concurrently target physical activity and sleep.

Introduction

Both poor sleep and physical inactivity are modifiable lifestyle risk factors for non-communicable chronic diseases and mortality [1–3]. Although increased physical activity may improve sleep while poor sleep may compromise physical activity through physiological and behavioral pathways, the evidence of the bidirectional associations between physical activity and sleep is sparse and equivocal [4–9].

Systematic reviews of randomized controlled trials lasting one day to six months in diverse populations suggested that exercise interventions may not improve all sleep characteristics (*e.g.*, sleep duration) in the short term [5,10], while sleep improvement interventions lasting up to nine months may not increase physical activity [4]. The very few available longitudinal studies were also inconclusive regarding this bidirectional relationship [7,8], and observed different relationships depending on the sleep outcome examined [9]. The heterogeneity of sleep characteristics used in different studies might hinder the interpretation of available literature [2,11].

This study aimed to examine the longitudinal bidirectional association between sleep and physical activity using a repeated examination sub-sample of the UK Biobank.

Methods

Sample

The UK Biobank is a prospective cohort recruiting adults across the UK between 2006 and 2010, with ethical approval by the National Research Ethics Service (Ref 11/NW/0382). 502,616 participants provided consent and completed interviews, physical measurements, and questionnaires at the baseline visit, with details described elsewhere [12]. Two repeated measurements occurred between 2012 and 2018. In this study, we considered participants completing at least one repeat measurement of both sleep and physical activity (n = 39,582). In total, 38,601 participants were eligible for further analyses after exclusion due to missing data on covariates or having inpatient sleep disorder records.

Measures

Physical activity (weekly Metabolic Equivalent of Task, MET mins/wk) was quantified using the short-form International Physical Activity Questionnaire (IPAQ), which measured the duration and frequency of walking, moderate-intensity, and vigorous-intensity physical activity [13]. Participants were categorized according to the World Health Organization physical activity guidelines based on MET min/wk into three groups (highly active, ≥ 1200; active, 600 to < 1200; inactive, < 600) [14]. Sleep patterns were determined based on an established method [11]. In brief, we categorized participants by how many healthy sleep characteristics (morning chronotype, adequate sleep duration (7-8 hr/d), never or rare insomnia, never or rare snoring, and infrequent daytime sleepiness) they displayed into three groups (healthy: ≥ 4; intermediate: 2-3; poor: ≤ 1). This method has shown its clinical utility for identifying high-risk sleep patterns for cardiovascular diseases over 8.5 years of follow-up [11]. Potential confounders included age, sex, follow-up time, body mass index (BMI), socioeconomic status (Townsend area deprivation index), vegetable and fruit intake, shift work, cigarette smoking, alcohol consumption, mental health issues, and history of major cardiovascular disease and cancer. Models were mutually adjusted for baseline sleep or physical activity, as appropriate.

Statistical Analysis

Using multiple logistic regression, we examined the multivariate-adjusted association of baseline sleep patterns (or physical activity) with physical inactivity (or poor sleep) at follow-up, as a healthy sleep pattern (or high physical activity) serving as a reference. Another set of logistic regression examined the association of temporal changes in sleep patterns (or physical activity) with physical inactivity (or poor sleep) at follow-up, as maintaining a healthy sleep pattern (or highly active) at both time points serving as a reference. All the models were two-sided and performed using SAS 9.4 or R 3.6.3 software, as Dunnett's correction was applied for multiple comparisons.

Results

Table 1 shows the baseline sample characteristics stratified by sleep patterns (51% female, 55.7±7.6 years old, 6.9±2.2 years of follow-up). At baseline, 22% of participants were physically inactive, and 4% of participants had a poor sleep pattern. Most participants remained highly active (48%) or maintained an intermediate sleep pattern (44%) over time. 23% of participants improved physical activity while 16% of participants reduced it; 15% of participants improved their sleep pattern, while sleep patterns deteriorated in 18% of the participants.

At baseline, compared to participants with a healthy sleep pattern, those with either an intermediate or a poor sleep pattern showed higher odds for physical inactivity at follow-up (adjusted Odds Ratio (AOR): 1.24 [1.17, 1.32] and 1.65 [1.45, 1.88], respectively). There was an incremental decrease toward temporally improving sleep patterns in odds of physical inactivity at follow-up (**Figure 1a**). For example, compared to participants maintaining a healthy sleep pattern, those shifting from poor to healthy sleep showed no significant differences in odds of physically inactive at follow-up (1.20 [0.66, 2.18]). Compared to the highly active participants at baseline, their physically inactive counterparts had higher odds for poor sleep at follow-up (1.23 [1.10, 1.39]). Shifting to higher physical activity categories overtime reduced such an adverse association compared to maintaining highly active, despite not full attenuation (Maintaining inactive: 1.59 [1.35, 1.87]; Inactive to active: 1.30 [1.05, 1.62]; Inactive to highly active: 1.24 [1.04, 1.49]) (**Figure 1b**). Decreasing physical activity from any level was also associated with higher odds of poor sleep at follow-up.

In the sensitivity analyses, by applying baseline continuous weekly physical activity (MET min/wk) as an independent variable, each standard deviation more of physical activity (2656 MET min/wk) was associated with 5% lower odds for poor sleep at follow-up (0.95 [0.90, 1.00], $p = 0.049$). Besides, by extending the guidelines-based physical activity categorization ($\geq$ 2400; 1800 to < 2400; 1200 to < 1800; 600 to < 1200; <600 MET min/wk), compared to the most active group, there is an incremental increase in AOR of poor sleep toward physical inactive group (0.93[0.78, 1.12], 1.19 [1.03, 1.39], 1.14 [0.99, 1.13], 1.28 [1.12, 1.46], respectively).

Discussion

To our knowledge, this is the largest prospective study investigating the prospective bidirectional association between sleep and physical activity. Even when analyses were adjusted for potential confounders, poor sleep at baseline was associated with physical inactivity at follow-up and *vice versa*. Individuals shifting to a healthy sleep pattern over time were associated with higher physical activity at follow-up. Physical activity reductions over time were associated with poor sleep at follow-up regardless of the baseline physical activity level. Improving physical activity from baseline inactivity reduced the unfavorable association with poor sleep at follow-up.

This study broadens the evidence base on this bidirectional relationship between sleep and physical activity by assessing a thorough sleep score comprising both duration and quality. We also highlighted the importance of measuring temporal changes in both lifestyle behaviors. There is a paucity of studies on the potential mechanisms through which the two behaviors influence each other. Physical activity might improve sleep by increasing cardiovascular fitness, regulating circadian rhythm, and ameliorating depressed mood [8,10,15], while adequate sleep might reduce physical inactivity by reducing daytime fatigue and sleepiness [4]. In agreement with our results, Kim et al. (2019) reported that individuals maintaining an adequate sleep duration (7 hr/d) had higher physical activity levels at a 5.7-year follow-up, based on a small sub-sample of the UK Biobank study (n = 7,709) [7]. Our results also highlight the potential value of both consistency and improvement in health behaviors by showing that decreasing physical activity from any level was associated with poor follow-up sleep, while increases in physical activity over time partially attenuated the unfavorable effect of baseline physical activity.

Although the comprehensive sleep score allowed us to investigate the associations with physical activity from a broader perspective, our study has some limitations, such as the possibility of residual confounding, the lack of repeated-measured confounders and population representativeness, as well as the self-reported exposures which might introduce measurement errors and social desirability bias. In particular, over-reporting of physical activity and the subsequent ceiling effect may compromise our ability to detect self-reported changes in physical activity.

Conclusion

Our results support interventions that concurrently target physical activity and sleep to enhance improvements in both health behaviors. Future studies with more sophisticated modeling and repeated device-based measurements of physical activity and sleep could shed further light on these bidirectional associations as well as the underlying explanatory mechanisms.

Acknowledgment

The authors gratefully thank all the participants and professionals contributing to the UK Biobank. MJD is supported by a Career Development Fellowship (APP1141606) from the National Health and Medical Research Council, Australia. ES is supported by a Senior Research Fellowship (APP1110526) from the National Health and Medical Research Council, Australia. BH, MH, and PAC have no financial disclosures.

Author Contributions

BH: Conceptualization, Methodology, Software, Formal analysis, Writing - Original Draft, Visualization; **MH:** Validation, Writing - Review & Editing; **MJD:** Validation, Writing - Review & Editing, Funding acquisition; **PAC:** Validation, Writing - Review & Editing; **ES:** Validation, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition

References

1. Piercy KL, Troiano RP, Ballard RM, et al. The Physical Activity Guidelines for Americans. *JAMA*. 2018;320(19):2020. doi:10/gfpfhs

2. Kwok CS, Kontopantelis E, Kuligowski G, et al. Self-Reported Sleep Duration and Quality and Cardiovascular Disease and Mortality: A Dose-Response Meta-Analysis. *J Am Heart Assoc*. 2018;7(15):e008552. doi:10/ggcp69

3. Huang B-H, Inan-Eroglu E, Hamer M, Stamatakis E. Joint associations of device-measured physical activity and sleep duration with cardiometabolic health in the 1970 British Cohort Study. *Journal of Science and Medicine in Sport*. Published online August 2, 2020. doi:10.1016/j.jsams.2020.07.012

4. Kline CE. The bidirectional relationship between exercise and sleep: Implications for exercise adherence and sleep improvement. *Am J Lifestyle Med*. 2014;8(6):375-379. doi:10/ggtbng

5. Banno M, Harada Y, Taniguchi M, et al. Exercise can improve sleep quality: a systematic review and meta-analysis. *PeerJ*. 2018;6:e5172. doi:10.7717/peerj.5172

6. Gerber M, Börjesson M, Jonsdottir IH, Lindwall M. Association of change in physical activity associated with change in sleep complaints: results from a six-year longitudinal study with Swedish health care workers. *Sleep Medicine*. 2020;69:189-197. doi:10.1016/j.sleep.2019.01.026

7. Kim Y, Wijndaele K, Sharp SJ, et al. Specific physical activities, sedentary behaviours and sleep as long-term predictors of accelerometer-measured physical activity in 91,648 adults: a prospective cohort study. *International Journal of Behavioral Nutrition and Physical Activity*. 2019;16(1):41. doi:10/ggjqrv

8. Mesas AE, Hagen EW, Peppard PE. The bidirectional association between physical activity and sleep in middle-aged and older adults: a prospective study based on polysomnography. *Sleep*. 2018;41(9). doi:10.1093/sleep/zsy114

9. Rayward AT, Burton NW, Brown WJ, Holliday EG, Plotnikoff RC, Duncan MJ. Associations between Changes in Activity and Sleep Quality and Duration over Two Years: *Medicine & Science in Sports & Exercise*. 2018;50(12):2425-2432. doi:10/gfngrk

10. Dolezal BA, Neufeld EV, Boland DM, Martin JL, Cooper CB. Interrelationship between Sleep and Exercise: A Systematic Review. *Advances in Preventive Medicine*. 2017;2017:1-14. doi:10.1155/2017/1364387

11. Fan M, Sun D, Zhou T, et al. Sleep patterns, genetic susceptibility, and incident cardiovascular disease: a prospective study of 385 292 UK biobank participants. *European Heart Journal*. Published online December 18, 2019:ehz849. doi:10/ggjqrt

12. Sudlow C, Gallacher J, Allen N, et al. UK Biobank: An Open Access Resource for Identifying the Causes of a Wide Range of Complex Diseases of Middle and Old Age. *PLoS Med*. 2015;12(3):e1001779. doi:10/bfn8

13. Hagströmer M, Oja P, Sjöström M. The International Physical Activity Questionnaire (IPAQ): a study of concurrent and construct validity. *Public Health Nutr*. 2006;9(6):755-762. doi:10/bt7kpw

14. World Health Organization. Global Physical Activity Surveillance. Accessed April 24, 2020. https://www.who.int/ncds/surveillance/steps/GPAQ/en/

15. Lewis P, Korf HW, Kuffer L, Groß JV, Erren TC. Exercise time cues (zeitgebers) for human circadian systems can foster health and improve performance: a systematic review. *BMJ Open Sport & Exercise Medicine*. 2018;4(1):e000443. doi:10.1136/bmjsem-2018-000443

Figure Tiles and Footnotes

Figure 1. The association of changes in (a) sleep/ (b) physical activity with follow-up (a) physical inactivity/ (b) poor sleep.

Physical activity (MET-mins/wk) was categorized based on public health guidelines (highly active, ≥ 1200; active, 600 to < 1200; inactive, < 600). Sleep patterns were categorized based on the number of healthy sleep characteristics (healthy, 4~5; intermediate, 2~3; poor, 0~1). The model was adjusted for baseline outcome, age, sex, follow-up time, socioeconomic status, body mass index, vegetable and fruit intake, mental health issues, general health, shift work, cigarette smoking, alcohol consumption, and mutually adjusted for physical activity or sleep, as appropriate. Dunnett's correction was applied for multiple comparisons.

Tables and Footnotes

Table 1. **The baseline characteristics of the present subsample (n = 38,601)**

Variables	Value
Age (mean (SD))	55.7 (7.6)
Female (n (%))	19,713 (51)
Follow-up (yr) (mean (SD))	6.9 (2.2)
Physical Activity (MET mins/wk) (mean (SD)) [a]	2428.8 (2655.6)
Socioeconomic Status (mean (SD)) [b]	-2.1 (2.6)
BMI (kg/m^2) (mean (SD))	26.7 (4.3)
Vegetable and Fruit Intake (serves/d) (mean (SD)) [c]	4.4 (2.8)
Mental Health Issues (n (%)) [d]	12,756 (33)
Cardiovascular Diseases/ Cancer History (n (%)) [e]	5,825 (15)
Shift Work (n (%))	
Retired/not in the workforce	13344 (35)
Employed not in shift work	21857 (57)
Employed in night shift work	1742 (5)
Employed in day shift work	1658 (4)
Cigarette Smoking (n (%))	
Never	23314 (60)
Previous Smoker	12893 (33)
Current Smoker	2394 (6)
Alcohol Consumption (n (%)) [f]	
Never	982 (3)
Previous Drinker	884 (2)
Occasional Drinker	7299 (19)
Within Guideline	13878 (36)
Above Guideline	9579 (25)
Above Double Guideline	5979 (16)
Physical Activity Level (n (%)) [g]	
Inactive	8321 (22)
Active	7113 (18)
Highly Active	23167 (60)
Sleep Pattern (n (%)) [h]	
Poor	1,706 (4)
Intermediate	22,771 (59)
Healthy	14,124 (37)

a. Weekly Metabolic Equivalent of Task (MET mins/wk) was quantified using the short-form International Physical Activity Questionnaire.

b. Townsend area deprivation index assigns each participant a score based on postcodes, as higher the score representing greater the socioeconomic deprivation.

c. Self-reported daily intake of fruit and vegetable consumption served as a proxy for dietary quality by asking, for example, “about how many pieces of fresh fruit would you eat per day?”.

d. Mental health issues were defined as the self-reported history by asking, “have you ever seen a general practitioner (GP) for nerves, anxiety, tension, or depression?”.

e. ICD 10-based inpatient cardiovascular diseases and cancer history.

f. Self-reported alcohol consumption was converted into UK unit (1 unit = 10 mL alcohol) and further categorized based on the UK guideline (14 UK units/wk).

g. The 600/1200 MET mins/wk guideline was used to categorize the physical activity level.

h. Sleep patterns were categorized based on based the presence of five healthy characteristics (morning chronotype, adequate sleep duration (7-8 hr/d), never or rarely insomnia, no snoring, and infrequent daytime sleepiness): healthy, 4~5; intermediate, 2~3; poor, 0~1.