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Daily associations between sleep and physical activity: A systematic review and meta-analysis

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Summary

The day-to-day variations of sleep and physical activity are associated with various health outcomes in adults, and previous studies suggested a bidirectional association between these behaviors. The daily associations between sleep and physical activity have been examined in observational or interventional contexts. The primary goal of the current systematic review and meta-analysis was to summarize existing evidence about daily associations between sleep and physical activity outcomes at inter- and intra-individual level in adults. A systematic search of records in eight databases from inception to July 2019 identified 33 peer-reviewed empirical publications that examined daily sleep – physical activity association in adults. The qualitative and quantitative analyses of included studies did not support a bidirectional daily association between sleep outcomes and physical activity. Multilevel meta-analyses showed that three sleep parameters were associated with physical activity the following day: sleep quality, sleep efficiency, and wake after sleep onset. However, the associations were small, and varied in terms of direction and level of variability (e.g. inter- or intra-individual). Daytime physical activity was associated with lower total sleep time the following night at an inter-person level with a small effect size. From a clinical perspective, care providers should monitor the effects of better sleep promotion on physical activity behaviours in their patients. Future studies should examine sleep and physical activity during a longer period and perform additional sophisticated statistical analyses.

Systematic review registration: https://osf.io/w6uy5/

Keywords: Ecological momentary assessment; sleep; insomnia; physical activity; exercise

Introduction

Sleep and physical activity are both important health behaviors in the general population. It has been well-established that low physical activity levels and poor sleep are related to a wide range of medical problems and chronic health conditions, including cardiovascular disease, overweight and obesity, type 2 diabetes, depression, and anxiety disorders (1, 2). Furthermore, these behaviors are likely to interact with each other. Chennaoui et al. (3) presented potential biological pathways explaining possible reciprocal interactions between sleep and physical activity in the short- and long-term. They suggested that acute or repeated physical activity increased Total Sleep Time (TST) through a decrease of insulin resistance and inflammation markers concentration, better regulation of circadian rhythm, and release of brain-derived neurotrophic factor. In return, sleep deprivation could alter the physical performance or facilitate fatigue during physical activity (4) by increasing cortisol concentration, decreasing growth hormone, and prolactin concentration and stimulating inflammation markers (5, 6).

Long-term bidirectional associations between sleep and physical activity have been hypothesized in narrative reviews (3, 7, 8) and examined in prospective studies. Reciprocal relationships between better sleep quality and high physical activity were found over 3 years in samples of students (9) and adults aged 42 to 72 years (10) in longitudinal studies. Another 2-year longitudinal study found a unidirectional, positive, and significant association between sleep quality and physical activity among community-dwelling older adults (11).

Short-term associations between sleep and physical activity have also been experimentally tested. Previous investigations examined the temporal consequences of a sleep-deprived night on physical activity. An induced sleep restriction was associated with a significantly lower time spent in objectively measured physical activity the following day, as well as the lower intensity of activity (4, 12). However, a contradictory finding was found in another investigation showing that increased energy expenditure was observed the day following a short night (13). The other side of this association whether physical activity is associated with sleep the following night; have been tested in a recent meta-analysis of experimental studies. This meta-analysis concluded that a session of physical exercise was associated with higher Sleep Efficiency (SE), TST, lower Sleep of Latency (SOL), and Wake After Sleep Onset (WASO) the following night (14). These short-term associations were characterized by a small-to-moderate effect size. These experimental studies thus suggested a possible bidirectional association between sleep and physical activity outcomes. However, these findings were limited in terms of ecological validity (i.e., the behaviors were not measured in participants' daily life and over multiple days).

In this perspective, previous studies investigated sleep – physical activity associations using ambulatory and daily measures and indicated that these two behaviours exhibited day-to-day variations (15-17). Furthermore, repeated measures provide data to differentiate inter- and intra-individual variations (i.e., daily deviations from an individual's usual behavior). Consequently, a better understanding of inter- and intra-individual associations between sleep and physical activity could be developed.

The daily associations between sleep and physical activity have been examined in observational or interventional contexts with self-report or objective measures (e.g., sleep device, pedometer) including a large spectrum of participants (e.g., older people with insomnia symptoms, athletes). An observational study used 7-day accelerometer data to examine the bidirectional association between sleep and physical activity in women with breast cancer (18) and found a unidirectional association. The lower WASO, Total Wake Time (TWT), and TST (at intra-individual level) on the previous night was significantly related to a higher daily physical activity the next day within-participants. However, no significant relationships were found at the inter-individual level (e.g., participants with a higher level of physical activity did not report significantly different sleep parameters than participants with lower physical activity level, (18)). Another observational study (19) asked depressed and pair-matched non-depressed participants to rate their sleep quality and duration and to wear an accelerometer for 30-day. Only one directional association was significant. The higher sleep quality was related to higher physical activity the following day within participants and between participants.

Other studies with repeated daily measures examined these associations with different sleep – physical activity measures or characterization and tested unidirectional or bidirectional associations. For instance, Bittner et al. (17) analyzed the unidirectional association between sleep parameters and physical activity the following day. Gabriel et al. (15) explored bi-directional associations between self-reported sleep parameters and several physical activity outcomes (e.g., moderate and vigorous physical activity, light physical activity). These methodological features do not facilitate a clear understanding of daily associations between sleep and physical activity. Moreover, a different pattern of associations was observed at the inter- and intra-individual level. Despite the evidence supporting the short-term associations between these two behaviors, it is currently unclear if these associations are empirically validated in an ecological context. A better understanding of short associations between sleep and physical activity could provide useful information for the development of future interventions and theoretical refinement (16).

The primary goal of the current systematic review and meta-analysis was to summarize existing evidence about daily associations between sleep and physical activity outcomes at inter- and intra-individual level in adults.

Methods

The systematic review and meta-analysis were conducted following the (Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines) (20). The study protocol was registered in PROSPERO (CRD42019132662) and all the study materials and data are on Open Science Framework (available at https://osf.io/w6uy5/).

Eligibility criteria

In order to be included, studies must have: adult humans aged 18 (without a maximum age limitation); assessed sleep and physical activity with daily repeated measures; reported original empirical findings based on quantitative analysis of repeated daily lagged associations between sleep and physical activity, and be published articles in French or English. Studies also needed to have measured (objectively or self-reported) at least one of the following parameters for sleep: sleep quality, sleep parameters (SOL, TST, WASO, SE, sleep fragmentation, time in bed) and rapid eye movement; and for physical activity: daily time spent in light, moderate, vigorous physical activity, physical activity in different domains (leisure, household, active travel, work), training load, rated perceived exertion during physical exercise. Observational and interventional studies were included. Exercise interventions were considered eligible if they included aerobic, resistance or a combination of both. Studies were excluded if: they included children or teenagers in their sample (21), were qualitative studies, reviews, comments, opinion papers, practice or protocol recommendations, letters, and conference abstracts; had a retrospective design or performed only correlational analysis (22, 23).

Search and Study Selection

We conducted online research in the following databases: Pubmed/Medline, CINAHL, SPORTDiscus, PsycINFO, Academic Search Complete, ERIC, Psychology, and Behavioral Sciences Collection, for relevant publications up to June 2019. To reduce the risk of publication bias, two databases dedicated to grey literature were used (Open Grey and ProQuest Dissertations) (24). Furthermore, to find unpublished studies, we used two additional strategies. First, we contacted the sleep research societies (Canadian Sleep Society, Canadian Sleep and Canadian network, French Society of Sleep Medicine) ask them to share our documents request in their respective email lists and social network accounts. Second, we e-mailed the first authors of the included published papers to know whether they possessed any unpublished data or were aware of unpublished studies by other researchers. Studies were also sourced from three relevant systematic reviews (see PROSPERO for references).

The search strategy was adapted for each database using its specific vocabulary map, employing Mesh terms that referred to "daily measures", "sleep" and "exercise". More details about search strategy are available in supplementary files (S1). Titles and abstracts of the initially identified articles were scanned by five reviewers for exclusion criteria (CK, JP, AR, SA, PB). Then, full-text articles were screened by SA and PB. Any discrepancies were identified and resolved by the first author (SA).

Data Collection Process

Data were extracted on a pre-piloted spreadsheet by one author (SA) and cross-checked by two authors (SA, PB). All relevant studies were scrutinized to extract the following data:

(a) Participants' characteristics and study design: year, country, number of participants randomly assigned, demographics, study duration, chronic disease, mental illness, control condition, sampling interval (interval-contingent, signal-contingent, and event-contingent recordings) and special design features;

(b) Outcomes: primary outcome, daily assessment measures, outcome characterization for physical activity and sleep;

(c) Statistical analysis: the direction of the association (physical activity --> sleep; sleep --> physical activity), type of statistical analysis, variability presence (between-person, within-person), control variables included in multivariate models.

(d) Findings from univariate or multivariate tested associations between physical activity and sleep outcomes.

(e) Risk of bias: 11 items adapted from Konjarski et al. (25) examined study aims, population, exclusion and inclusion criteria, statistic analyses, sleep, and physical activity measures.

Data synthesis and analysis

Sleep and physical activity daily associations

Following the recommendation of Guidance on the Conduct of Narrative Synthesis in Systematic Reviews (26), a narrative description of the included studies presented.

Statistical Analyses

The effect sizes were computed with Meta-Essentials (27). Given that regression coefficients are sensitive to the inclusion of control variables between studies, we conducted a meta-analysis on (semi) partial correlation coefficients because the coefficient is adjusted on the number of included variables in the model. Consequently, the r-to-z transformation was automatically applied. When means and standard deviations were not reported in the publication, authors were contacted to request missing information. When the information was not provided, the effect size could not be calculated, and these studies were therefore excluded from the meta-analysis.

To quantify the associations between sleep and physical activity, a set of multilevel meta-analyses was performed because multiple measures of these behaviors are expected within the same study (e.g., physical activity characterized in terms of light physical activity and moderate and vigorous physical activity) (28). Indeed, several effects within studies violate assumptions of independence and might introduce error into effect size calculations (29). An association was tested when minimally three effects size for a sleep outcome were available. The physical activity outcomes were pooled together to decrease the beta risk. For instance, if the relationships between the time spent in light physical activity and the daily number of steps with SOL were examined in two different studies, they were pooled in one meta-analysis examining physical activity association (all different outcomes) with SOL. The associations at the inter- and intra-individual level were tested separately.

Sensitivity Analyses

A set of sensitivity analyses based on Robust Variance Estimation (30) was carried out following the recommendations provided by Quintana (29). All analyses were carried out in R 3.6 using the *metafor* and *robumeta* packages (31, 32).

Results

Study selection

The initial electronic searches identified 1666 references, of which 232 were duplicates. After a review of titles and abstracts, 1384 were excluded because they did not meet all inclusion criteria. Hence, 50 full-text articles were assessed for eligibility, and 12 were further included in the review. Twenty-one additional studies were identified through hand search of relevant articles, for a total of 33 articles (see Figure 1).

Studies' Characteristics

Participants

Table 1 summarizes the studies' characteristics (i.e., description of the sample, methods measuring physical activity and sleep). Across the 33 unique studies, 14,387 participants were included. Eleven studies (33%) included exclusively women (15, 18, 33-41). Sample sizes ranged from 7 (42) to 10,086 (15) participants. Eight studies (24%) included adults with sleep disturbances (e.g., insomnia) (18, 19, 41-46). Three (9%) investigations included adults with mental disorders such as major depressive disorder and bipolar disorder (19, 46, 47). Eight investigations included adults with medical conditions such as chronic pain, chronic obstructive pulmonary disease or breast cancer.

Location and setting

Most studies were conducted in the United States of America, six in Europe, and three in Canada. The daily measures ranged from 5 to 196 days. Four studies examined the effect of supervised exercise intervention (40, 41, 48, 49). More details about the exercise interventions are available in the supplementary file (S4).

Sleep and physical activity measures

Four studies exclusively used self-reported sleep and physical activity measures (36, 48, 50, 51). The two behaviors were exclusively objectively assessed in 10 studies (18, 34, 35, 40, 43, 44, 47, 49, 52, 53). Among the included studies, eight combined self-reported, and objective measures of sleep parameters (17, 33, 41, 45, 46, 54-56). All measures are detailed in Table 1.

Statistical analyses carried out

Over half of the studies (19 studies) examined a unidirectional temporal sequence between sleep and physical activity (17, 22, 23, 33, 39, 40, 42, 44, 45, 49-51, 53, 54, 56-60). Conversely, the 14 other studies investigated the bidirectional associations. Mixed linear models were carried out in 23 studies. Details about statistical analyses are in the supplementary file (Table S3).

Risk of bias assessments

Two independent reviewers assessed the risk of bias for each included study. None of the 33 studies have a sample size justification or reported the commitments of the protocol. Besides, eleven of the included studies disregards to statistically lagged value of sleep and/or for the physical activity that is, sleeps parameters in the previous night or the levels of physical activity in the previous day to estimate the effect of autoregression. Three out of the 33 did not report the confounding variables statistically adjusted. Details about statistical analyses are in the supplementary file (see details in Figure S2).

Sleep measures temporally associated with physical activity the following day

Twenty-four studies examined this association (Table 2). Among them, seven did not find a significant association between sleep parameters and physical activity (35-37, 43, 44, 49, 55).

Sleep onset latency. Among the eleven studies, only one study found a significant association between SOL and physical activity at the intra-individual level (41). High SOL was associated with low physical activity the following day. Otherwise, no other significant associations were found either for total physical activity (18, 38, 43, 45, 53, 56), moderate to vigorous physical activity (18, 35, 38, 48, 55), or light physical activity (37).

Wake time after sleep onset. Thirteen studies scrutinized the WASO – physical activity associations and 3 studies found a significant association. High WASO on a given night was significantly associated with physical activity counts the next day in breast cancer patients with sleep disorders at the intra-individual level (18). This association was also found in adults with retinitis pigmentosa patients (17) or cystic fibrosis (53). No other significant associations were observed with other physical activity characteristics (i.e., moderate to vigorous physical activity (34, 35, 41, 44, 48), physical activity counts (43, 45, 46, 52), and light, moderate, vigorous physical activity (37).

Total sleep time. TST – physical activity daily associations were investigated in 19 studies. A significant and negative association was found in six studies. High TST was related to low physical activity total physical activity (18, 52), and moderate to vigorous physical activity (34, 58) at intra-individual level, in four studies. The same pattern of association was found at the inter-individual level in four studies (18, 34, 57, 58). Twelve studies did not identify a significant association between TST and moderate to vigorous physical activity (18, 35, 38, 39, 44, 49, 53, 55), light, moderate or vigorous physical activity (37, 44) and total physical activity (34, 38, 43, 45, 53) at intra- and/or inter-individual level. One study with elderly women suggests that short sleep duration, between 7 to 9 hours was associated with additional light physical activity the next day, while a long time in bed (>9 hours) decreased the likelihood of engaging in moderate to vigorous physical activity the following day (15).

Total wake time. Four studies examined the TWT – physical activity association. High TWT was associated with reduced total physical activity in two studies at the intra-individual level (18, 46). Otherwise, no significant association was observed in the studies (34, 45).

Sleep quality. Sleep quality and physical activity associations were studied in ten studies. Four studies concluded that high sleep quality was associated with greater physical activity counts (19), moderate to vigorous physical activity (48), and total physical activity at intra-person (45) and inter-individual level (17). No significant association was observed in the six other investigations (36, 41, 42, 49, 56, 57).

Sleep and physical activity daily associations

Fragmentation index. Five studies examined the Fragmentation index – physical activity associations. Lower fragmentation index was significantly associated with increased of physical activity counts and moderate to vigorous physical activity the following day were found in two studies (17, 38) at the inter-individual level. Otherwise, no significant associations were found in the three other studies (37, 41, 55).

Sleep efficiency. Twelve studies considered the SE – physical activity association. One study, conducted in elderly women (38), identified that higher SE was significantly associated with increased physical activity outcomes (moderate to vigorous physical activity and total physical activity) at the between-person level. The eleven other studies did not find a significant association between SE and moderate to vigorous physical activity and total physical activity the following day (18, 34, 35, 37, 41, 44, 45, 53, 55) at the inter- and intra-individual levels.

Physical activity measures temporally associated with sleep the following night

Detailed findings of the 27 studies examining the daily association between physical activity outcomes and sleep parameters are in Table 3. Thirteen out of the 27 studies did not find a significant temporal relationship between physical activity and sleep (19, 33, 35-37, 40, 41, 49, 50, 57, 59, 61).

Total physical activity. Six studies investigated the association between total physical activity and the SOL parameter. A greater physical activity counts on a given day were significantly associated at the inter-individual level with an increase of the SOL in pregnant women (39), as well as, a decrease of the SOL in two other studies (43, 54) in individuals with chronic obstructive pulmonary disease and spinal cord injury, respectively. Otherwise, in three other studies, no significant associations were observed with SOL (18, 38, 50). Nevertheless, conflicting results were found between total physical activity – WASO association among the 8 included studies. Two indicated that greater physical activity counts were associated with greater WASO the following night at the intra-individual level (52) and at the intra- and inter-individual level (18). The six other studies did not indicate any significant association with WASO (34, 43, 50, 54, 59, 61). A complex pattern of findings was observed about the total physical activity – TST association. Three studies suggest that the increase of the total physical activity was significantly associated with higher TST (at intra-individual level) (18, 34, 60), three other studies identified the opposite of the previous association (at inter-individual level) (38, 43, 54), and six included studies did not identify a significant association (19, 39, 50, 52, 59, 61).

Light physical activity. Two studies scrutinized the light physical activity – sleep outcomes associations and no significant association with SOL, WASO, TST, SE parameters, and FI was observed in one study (37). However, more daily time spent in light-intensity physical activities was significantly related to an increasingly higher probability to have a night ranged from 7 to 9 hours of TST (15).

Moderate to vigorous physical activity. Eleven studies did not observe a significant association between moderate to vigorous physical activity and SOL (18, 33-35, 37, 38, 40, 41, 46, 48, 55)(32,34,35,37,45,47,13,54,30,38). Ten studies examined the moderate to vigorous physical activity - TST associations. No significant association was found in seven studies at the different individual levels (18, 33-35, 40, 41, 49). However, one study showed that the increase of moderate to vigorous physical activity was significantly associated with a higher TST only at the intra-individual levels in older adults (55). Conversely, results with older women (38), suggest that more minutes of moderate to vigorous physical activity were temporally associated with less TST across the week at the inter-individual levels. Further, participants classified in the ≥20 min·d−1 of accumulated moderate to vigorous physical activity category was associated with a reduced likelihood of reporting short or long sleep that night at the inter-individual levels' older women (15).

The results obtained from our narrative synthesis are summarized in Figure 2. The green and red arrows represent positive and negative associations, respectively and dash arrows figure a no significant association. The inter- and at intra-individual level associations were combined.

Sleep and physical activity daily associations

Meta-Analysis of included studies

Findings from the set of the multi-level meta-analysis are presented in Table 5. Overall, 11 of the 33 studies were excluded in the meta-analysis due to the missing information. For each computed association, two meta-analysis techniques were performed to ensure robust results across meta-analytical technics. The number of computed effect sizes and different studies are also presented. Three significant temporal associations between sleep outcomes and physical activity were found on 22 test-ed. Higher WASO was significantly associated with decreased physical activity (r = -.15, 95% CI= -.31 – .00, p = .05) at the intra-individual level. The analyses also revealed that higher SE and sleep quality were significantly associated with an increase in physical activity the following day. SE was associated at the inter-individual level (r = .09, 95% CI = .01 – .18, p = .03) and sleep quality at intra-individual level (r = .35, 95% CI = .00 – .07, p = .05). Among the tested associations between physical activity and sleep outcomes, high physical activity was associated with low TST the following night at inter-individual level (r = -.05, 95% CI = -.09 – .00, p = .05). In our sensitivity analyses, effect sizes were generally similar, but the significance threshold varied (see details in Table 4) and the SOL – physical activity association varied in terms of effect size and significance.

Discussion

Summary of Evidence

This systematic review summarized the available empirical evidence on the daily, bidirectional relationship between physical activity and sleep outcomes in adults. To the best of our knowledge, this is the first systematic review to address this specific question. A total of 33 studies were included in the systematic review. Given that the effect of physical activity on sleep parameters in the general population has received attention relatively recently, both RCTs and non-RCTs, as well as observational and interventional studies, were included.

Sleep and physical activity daily associations

Overall, the qualitative and quantitative analyses of included studies did not support a bidirectional daily association between sleep outcomes and physical activity. Furthermore, our study suggested the absence of a consistent unidirectional pattern of association between sleep and physical activity characteristics (Figure 2). More granular results were found by distinguishing the inter- and intra-individual level in meta-analyses. More specifically, WASO and sleep quality were significantly positively and negatively associated with physical activity at the intra-individual level. SE was positively associated with physical activity at the inter-individual level.

These findings should be interpreted with caution because diverse methodological approaches have been used in included investigations. The behavioral measures and characterizations, study designs, and performed statistical analyses in each study had probably affected our results.

The type of measure of sleep and physical activity (i.e., objective or self-reported) could explain conflicting findings. The correlations between objective and self-reported measures are low for sleep and physical activity, respectively (62). For instance, the lack of concordance between subjective and objective sleep measures is a consistent result in adults with sleep disorders (63, 64). The self-reported physical activity measures are negatively affected by social desirability and recall bias (63-65). Moreover, the validated sleep – physical activity thresholds of accelerometers vary across different populations (e.g., athletes, inactive adults) limiting the comparison between objective time spent in physical activity or TST (66). Consequently, the associations between sleep - physical activity behaviors could widely vary. For instance, five studies exclusively used self-reported measures of TST, sleep quality, and accelerometer data of total physical activity/moderate to vigorous physical activity (15, 19, 39, 42, 57) and vice versa (37, 58, 59, 61).

The sleep or physical activity characterizations could also modify the tested associations. If sleep monitors or diaries allow computing sleep parameters, it is more complex with physical activity. Indeed, commercial or scientific wearable devices used in included studies provided one or several physical activity outcomes: moderate to vigorous physical activity, daily steps, total physical activity, or daily counts. Based on their hypotheses, or to decrease the number of statistical analyses, the authors generally selected one physical activity characteristic. However, a significant association between total daily physical activity with a sleep parameter could be explained by the proportion of time spent in moderate to vigorous physical activity during the day. Sleep – physical activity associations may exist only for a threshold of activity level (e.g., > 40 minutes of daily physical activity with moderate intensity), a type (e.g., outdoor physical activity) or physical activities performed less than 3 hours before the bedtime (14).

Participants' characteristics (age, sex, chronic illness), level of physical activity intensity performed but also the habitual level of physical activity of participants have been previously identified as moderators of acute or regular exercise interventions. Consequently, uni- or bi-directional associations between sleep and physical activity outcomes may exist in a specific context.

As recommended for longitudinal data analysis (67), mixed linear models were carried out in two-thirds of included studies. However, most of the investigators did not consider the dependent variable autocorrelation in their models. For instance, Bernard et al. (18) included previous night SE as a covariate in his model examining physical activity – SE association. Furthermore, the models' specifications were very different. The following covariables were generally missing in tested models, although their respective associations with sleep and physical activity are established: weekday (68, 69), season (70, 71), and psychotropic use (72).

The contradicted findings of this review could also suggest that sleep-physical activity associations should not be examined with a lag-1 (i.e., association with previous night or day) but with a higher lag between sleep and physical activity. Irish et al. found that lag-7 bivariate models had best-fit indices that lag-1 models to describe temporal associations between physical activity and sleep parameters (37). Indeed, possible accumulation effect, social or hormonal rhythms have been proposed in studies examining behavioral circadian rhythm (73). Furthermore, a lag-1 association could be found only in a short sleeper. Indeed, lower TST has associated with social activities only adults with TST < 6h30 min. Higher duration of social activities was associated with lower TST (74).

The different relationships between sleep and physical activity found at intra- and inter-individual level also suggests that these associations and their directions could be an idiosyncratic phenomenon, i.e., that differs in magnitude and direction from one person to another (75). Previous studies examining the daily associations between sleep or physical activity with another bio- or psychological variable revealed a different pattern of association at the group and individual level but also a causal heterogeneity (76-78). A study investigating the daily relationships between stress and physical activity shows that, on average, stress on one day was significantly associated with reduced physical activity the following day (76). This association was found in only 17/61 participants at the individual level. The examination of temporal daily relationships between TST and depressive symptoms showed that unidirectional associations could be positive, negative, or not significant at the idiographic level (78).

Finally, the sleep – physical activity daily associations could be mediated by exogeneous variables associated with a context or clinical features such as light exposition (79), physical fitness (80), hot flashes frequency (81, 82) who are respectively related to both, sleep and physical activity.

Future Directions

To develop a full picture of sleep and physical activity daily associations, additional studies will be needed. Future studies should assess these behaviors during minimally 12 consecutive days to examine different lagged associations. The first night of sleep monitoring is generally not represented in the ecological context, then missing data is the rule even if the adherence rate is generally good (i.e., >80%), and sleep parameters are modified during the weekend nights.

Sleep and physical activity daily associations

A combination of self-reported and device measures is recommended to examine sleep and physical activity behaviors (83). Except for perceived sleep quality, the statistical analyses between self-reported and objective measures should be avoided.

Nomothetic and idiographic statistical analyses should be carried out to verify that the results obtained at the group level match the ones obtained at the idiographic level (84). For instance, individual vector auto-regressive modelling allows the comparison of different lagged associations and facilitates Granger causality tests to explore bidirectional associations at the individual level, for each participant separately (see an example here (78), and tutorial (85)). It is important to note that these models require long time series (>50-time points or days of observation), hence might be difficult to realize.

Future interventional studies should combine ambulatory daily assessment of sleep and physical activity pre- and post-intervention to compare the effects of treatment for sleep disorders or exercise interventions on the possible associations between these behaviors (86). The single case experimental studies combined with ecological momentary assessment could also provide more granular findings of the effects of an intervention on sleep-physical associations (87).

In a more clinical perspective, the care providers in sleep medicine or physical activity, but also coaches should help their patients and athletes to carefully monitor both behaviours during their intervention. For instance, cognitive behavior therapy for insomnia disorders may have a temporary negative impact on physical activity during the implementation of sleep restriction strategies in the short term (88). However, the decrease of insomnia symptoms at mild term may enhance the daily time spent in physical activities.

Finally, a future individual data participant meta-analysis could provide a fine analysis of sleep – physical activity associations and identify potential participant or physical activity-related moderators (89). Thus, investigators in sleep medicine and physical activity sciences should strengthen their data sharing practices.

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Strengths and Study Limitations

This study is the first to systematically and specifically review the literature on daily associations between sleep and physical activity in adults and to quantify these relationships in a meta-analysis. Conclusions from the present meta-analysis should be tempered by several limitations. First, our decision to pool all physical activity variables in meta-analyses could conceal existing associations between sleep parameters and different types (e.g., aerobic) or intensity of physical activity (90). Second, a selection bias could affect our quantitative findings because the number of studies in our meta-analyses was relatively small in comparison to the 33 included studies. Third, the variation of sleep-wake accelerometer thresholds in the participants' function status (inactive adults vs athlete) was not anticipated in the included studies. Fourth, we included trials involving good sleepers, adults with insomnia symptoms or with medical comorbidity. In future studies, our findings could be modified according to the presence of sleep disorders because poor sleepers generally have a lower level of physical activity (91).

Conclusion

Our systematic reviews of literature, combined with the meta-analyses, revealed that sleep parameters and physical activity were, overall, not significantly associated at the individual level. The different methodological approaches to measure these behaviors and examine their relationships were an important barrier to draw a general perspective about sleep and physical activity daily associations. Future studies should systematically explore these patterns of the association at inter- and intra-individual levels and investigate these behaviors at the idiographic level.

Practice Points

1 The qualitative and quantitative analyses of included studies did not support a bidirectional daily association between sleep outcomes and physical activity

2 Older women were the subgroup of patients the most represented among included studies

3 Methodological weaknesses in included studies (statistical analyses, covariates) are limiting our conclusions

Research Agenda

1 To address the possible dynamic process between sleep parameters and daily physical activity, participants should be assessed repeatedly over time (> 12 days/nights) during everyday life

2 The analyses between self-reported and objective measures of sleep and physical activity should have been used

3 Nomothetic and idiographic statistical analyses should be carried out to examine sleep and physical activity associations

4 A set of single-case experimental studies combined with ecological momentary assessment could provide granular findings of the effects of an intervention on sleep-physical associations

Table 1: Details of the included studies

Author (years)	Description of sample					L/ d	PA measures					Sleep measures				
	☼	♀%	*M*a	Group	№		OB	Type	SR	Type	Outc	OB	Type	SR	Type	Outcomes
Observational studies																
Mead et al., 2019 (52)	US	66.5	18.86	College students	155	7	○	-	●	1 item	EP & EI	●	ActiGraph	○	-	WASO, TST, SE
Mead et al., 2019 (59)	US	70.4	19.35	College students	54	6	●	Fitbit Flex	○	-	TPA	●	Fitbit Flex	○	-	WASO, TST
Cox et al., 2019 (53)	Australia	40.42	29	Cystic Fibrosis	47	7	●	SWA	○	-	TPA MVPA EC	●	SWA	○	-	SOL, WASO, TST, SE
Albu et al., 2019 (54)	EU	14.28	43.10	Spinal cord injury	14	7	●	ActiGraph	○	-	TPA	●	ActiGraph	●	PSQI, ESS, MEQ	OB: SOL, WASO, TST*, SE SR: SQ, chronotype, daytime sleepiness,
Bouwmans et al.*, 2018 (19)	EU	50	34	Depressed G: 27 Control G: 27	54	30	●	Actical	○	-	TPA	○	-	●	2 items PSQI	TST*, SQ
Mead et al., 2018 (61)	US	55.6	18.86	College students	384	14	○	-	●	1 item	EP	●	ActiGraph	○	-	WASO, TST, SE

Kim et al., 2018 (43)	US	46.42	65	COPD	56	7	●	Actiwatch	○	-	LPA MPA VPA	●	Actiwatch	○	-	SOL, WASO, TST, SE
Merikangas et al., 2018 (47)	US	61.9	48	Mental disorder G: 145 Control G: 97	242	14	●	ActiGraph	○	-	Motor activity	●	ActiGraph	○	-	TST*
Bittner et al., 2018 (17)	US	48.5	54	Retinitis pigmentosa	33	7	●	Actiwatch	○	-	TPA	●	Actiwatch	●	Sleep diary	**OB**: FI, WASO **SR**: SQ
John R. Best et al., 2018 (55)	Canada	67	71	Elderly adults	152	14	●	ActiGraph	○	-	MVPA	●	ActiGraph	●	CSD	**OB:** SOL, SE, FI, TST **SR:** Bedtime, TST, TWT, SQ
Spina et al., 2018 (44)	UK	34	66.4	COPD	932	6	●	SWA	○	-	LPA MVPA	●	SWA	○	-	WASO, TST, SE
McDonald et al., 2017 (42)	UK	71.42	65.5	Approaching retirement	7	87-196	●	Tri-axial	○	-	TPA	○	-	●	Sleep diary	TST, SQ
Murray et al., 2017 (33)	US	100	55	Multiple chronic diseases	377	5.5	●	ActiGraph	○	-	MVPA , out doors time	●	ActiGraph	●	Sleep diary	**OB**: SOL, WASO, TST, SE
Knufinke et al.*, 2017 (58)	EU	57	23	Elite athletes	98	7	○	-	●	Diary ratings	training load*	●	ActiGraph	○	-	SOL, WASO, TST*, SE, FI & Sleep stages
Pettee et al.*, 2017 (15)	US	100	71	Elderly women	10086	7	●	ActiGraph	●	Diary of leisure time	MVPA LPA	○	-	●	Sleep diary	TST*
Bernard et al., 2016	Canada	100	52	Breast cancer	66	7	●	Actiwatch	○	-	MVPA TPA	●	Actiwatch	○	-	SOL, WASO, TST, TWT, SE

(18)																
Kishida et al, 2016 (34)	US	100	53	Elderly women	103	21	●	ActiGraph	○	-	MVPA	●	ActiGraph	○	-	WASO, TST, TWT*, SE
Fanning et al., 2016 (57)	US	75	20	College-adult	33	7	●	ActiGraph	○	-	MVPA	○	-	●	2 items PSQI	TST*, SQ
Mitchell et al., 2016 (35)	US	100	53	Sedentary & overweight	353	7	●	ActiGraph	○	-	MVPA	●	ActiGraph	○	-	SOL, WASO, TST, SE
Whitehead et al., 2016 (51)	US	74	79	Elderly adults	127	14	○	-	●	Diary ratings*	AP AT EP ET	○	-	●	Sleep diary	SQ
Fortier et al.*, 2014 (36)	Canada	100	42	Working women	63	14	○	-	●	RPE	MVPA	○	-	●	Likert-type scale	SQ*
Tang et al., 2014 (45)	UK	74	46	Chronic pain	119	7	●	ActiGraph	○	-	TPA	●	ActiGraph	●	Sleep diary	**OB:** SE **SR:** SOL, WASO, TST, TWT, SE
McGlinchey et al.*, 2014 (46)	US	70	33	Mental disorder: 32 Control G: 36	68	60	●	ActiGraph	●	Diary ratings MET	**SR** & **OB**: TPA	●	ActiGraph	●	Sleep diary	**OB** &**SR**: TWT
Irish et al.*, 2013 (37)	US	100	52	72.9% pre- or early perimenopausal	303	29	○	-	●	Diary ratings	LPA MPA VPA	●	ActiGraph	○	-	SOL, WASO, SE, FI, TST
Lambiase et al.*, 2013 (38)	US	100	73	Postmenopausal	143	7	●	ActiGraph	○	-	MVPA TPA	●	ActiGraph	○	-	SOL, SE, FI, TST
Andrews et al., 2013 (60)	Australia	60	49	Chronic pain	50	5	●	Tri-axial	○	-	TPA	●	Tri-axial	○	-	TST

Booth et al., 2012 (56)	US	56.25	26	Diabetes type 2 history	48	14	●	Actical	○	-	TPA	●	Actiwatch	●	2 items	OB: SOL, TST SR: TST, SQ
Youngstedt et al., 2003 (50)	US	72	22.9	Students	31	102	○	-	●	Diary	TPA	○	-	●	Diary	SOL, WASO, SE, TST
Nodine et al., 2011 (39)	US	100	30	Pregnant women	29	7	●	Pedometer	○	-	TPA	○	-	●	Diary	SOL, WASO, TST, SQ
Exercise program interventions																
Breneman et al., 2019 (40)	US	100	64	lower-dose exercise group: 24 higher-dose exercise group: 27	51	14	●	SWA	○	-	MVPA	●	ActiGraph	○	-	SOL, WASO, TST*
Nelson et al., 2017 (49)	US	0	32.5	Sedentary men	19	14	●	AP	○	-	MVPA	●	SWA	○	-	TST, SQ
Dzierzewski et al.*, 2014 (48)	US	83	63	Sedentary adults	79	126	○	-	●	LTEQ	MVPA	○	-	●	Sleep diary	SOL, WASO, SQ
Baron et al.*, 2013 (41)	US	100	61	Sedentary women	11	112	●	ActiGraph	○	-	**OB:** MVPA **SR:** ET*	●	ActiGraph	●	Sleep diary	**SR**: bedtime, get up time, WASO, SQ **OB:** SOL, WASO, TST, SE, FI

Abbreviation: Bold characters: represent studies reported data from participants with sleep complaints (diagnosis of insomnia or insomnia symptoms), *: specific details for studies present in Annex –II-, ○: Absence, ●: Presence, ☼: Study setting & location, ♀%: Percentage of women, Ma: Mean age, №: Total number of sample, L/ d: length of study per day, OB: Objective, SR: Self-Reported, Outc: Outcomes, US: United States , EU: Europe, UK: United

Kingdom, CSD: Consensus Sleep Diary, PSQI: The Pittsburgh Sleep Quality Index, PSG: Polysomnographic, OG: Older Group, YG: Younger Group, BD: Bipolar Disorder, DG: Depressed Group, CG: Control Group, SWA: SenseWear Armband, EG: Exercise Group, MET: Metabolic Equivalent of Task, expressing the energy cost of physical activity, AP: Activity Presence, AT: Activity Time, EP: Exercise Presence; EI: Exercise Intensity, EC: Exercise Capacity, LPA: Light Physical Activity, MPA: Moderate Physical Activity, VPA: Vigorous Physical Activity, MVPA: Moderate to Vigorous Physical Activity, LTEQ: Leisure-Time Exercise Questionnaire, RPE: Rating of Perceived Exertion, ET*: Exercise Time or exercise duration, SOL: Sleep Onset Latency, WASO: Wake After Sleep Onset, TST*: Total Sleep Time or sleep duration or time in bed, TWT*: Total Wake Time or awakening length, SE: Sleep Efficiency, FI: Fragmentation Index, SQ*: Sleep Quality or sleep satisfaction.

Table 2: Sleep parameters predicting physical activity

Author	Sleep parameters							PA
	SOL β	**WASO β**	**TST β**	**TWT β**	**SQ β**	**FI β**	**SE β**	
Observational studies								
Mead et al., 2019 (52)								EP&EI
Mead et al., 2019 (59)		WP & BP: NS	WP: -2.75 BP: NS					TPA
Cox et al., 2019 (53)	BP: NS	BP: - 1.0	BP: NS				BP: NS	TPA
	BP: NS	BP: NS	BP: NS				BP: NS	EC
	BP: NS	BP: - .3	BP: NS				BP: NS	MVPA
Albu et al., 2019 (54)								TPA
Bouwmans et al.*, 2018 (19)			WP: .31 BP: - .21		WP: .23 BP: NS			TPA
Mead et al., 2018 (61)		OR: .991	OR: .99				WP: NS	EP
Kim et al., 2018 (43)	BP: NS	BP: NS	BP: NS				BP: NS	TPA
Merikangas et al., 2018 (47)			BP: - .027					Motor activity
Bittner et al., 2018 (17)		BP: .12			BP: .06	BP: .21		TPA
John R. Best et al., 2018 (55)	WP&BP: NS		WP&BP: NS			WP & BP: NS	WP & BP: NS	MVPA
Spina et al., 2018 (44)		BP: NS	BP: NS				BP: NS	LPA MVPA
McDonald et al., 2017 (42)			BP: 7.0		BP: NS			TPA
Murray et al.,								MVPA

2017 (33)								
Knufinke et al.*, 2017 (58)								Training load
Pettee et al.*, 2017 (15)			OR: .73 > 9 h.d^{-1} (95% CI: .67, .78)					MVPA
			1.2< 7 – 9 h.d^{-1} > -1.6					LPA
Bernard et al., 2016 (18)	WP &BP: NS	NS	NS	NS			WP & BP: NS	MVPA
		WP: - .12	WP: - .14	WP: - .14				TPA
Kishida et al, 2016 (34)		WP&BP: NS	WP: - .03	WP&BP: NS*			WP& BP: NS	MVPA
			WP&BP: NS					TPA
Fanning et al., 2016 (57)			BP: - .17		BP: NS			MVPA
Mitchell et al., 2016 (35)	BP: NS	BP: NS	BP: NS				BP: NS	MVPA
Whitehead et al., 2016 (51)		NS						AP, AT EP, ET
Fortier et al.*, 2014 (36)					BP: NS*			MVPA
Tang et al., 2014 (45)	WP: NS	WP: NS	WP: NS	WP: NS	WP: 4.06		WP: NS	TPA
McGlinchey et al.*, 2014 (46)				WP: - .03 BP: NS				TPA
Irish et al.*, 2013 (37)	BP: NS	BP: NS	BP: NS			BP: NS	BP: NS	LPA MPA VPA
Lambiase et al.*, 2013 (38)	BP: NS		BP: NS			BP: - .11	BP: .64	MVPA
						BP: - .06	BP: .37	TPA
Andrews et al., 2013 (60)								TPA

Booth et al., 2012 (56)	NS	■	BP: .308	■	NS	■	■	TPA
Youngstedt et al., 2003 (50)	■	■	■	■	■	■	■	TPA
Nodine et al., 2011 (39)	■	■	■	■	■	■	■	TPA
Exercise program interventions								
Breneman et al., 2019 (40)	■	■	■	■	■	■	■	MVPA
Nelson et al., 2017 (49)	■	■	WP: NS	■	WP: NS	■	■	MVPA
Dzierzewski et al. *, 2014 (48)	WP &BP: NS	WP & BP: NS	■	■	WP: .04 BP: NS	■	■	MVPA
Baron et al.*, 2013 (41)	WP: -2.30 BP: NS	WP & BP: NS	WP: -2.66 BP: NS	■	WP & BP: NS	WP & BP: NS	WP & BP: NS	MVPA

Abbreviation: NS: Not Significant, ■ NE: Not Evaluated, AP: Activity Presence, AT : Activity Time, EP: Exercise Presence; EI: Exercise Intensity, LPA: Light Physical Activity, MPA: Moderate Physical Activity, VPA: Vigorous Physical Activity, MVPA: Moderate to Vigorous Physical Activity, ET: Exercise Time, SOL: Sleep Onset Latency, WASO: Wake After Sleep Onset, AL : Awakening Length, SS: Sleep Satisfaction, TWT: Total Wake Time, SE: Sleep Efficiency, TST: Total Sleep Time, SQ: Sleep Quality, FI: Fragmentation Index, AIC: Akiake Information Criterion, P: Relative Probability, OR: Odds Ratio, CI: Confidence Interval, $h.d^{-1}$: hours per day, BP: Between Person, WP: Within Person

Table 3: Physical activity predicting sleep parameters

Author	PA	Sleep parameters						
		SOL β	WASO β	TST β	TWT β	SE β	FI β	SQ β
Observational studies								
Mead et al., 2019 (52)	EP & EI		WP: NS	WP: NS		WP: NS		
Mead et al., 2019 (59)	TPA		WP: 2.23 BP: NS	WP&BP: NS				
Cox et al., 2019 (53)	NE							
Albu et al., 2019 (54)	TPA	BP: - p = 0.039	BP: NS	BP: - p = 0.002		BP: NS		
Bouwmans et al.*, 2018 (19)	TPA			WP&BP: NS				WP&BP: NS
Mead et al., 2018 (61)	EP		WP: NS	WP: NS		WP: NS		
Kim et al., 2018 (43)	TPA	BP: -.48	BP: NS	BP: -.50		BP: NS		
Merikangas et al., 2018 (47)	Motor activity			BP: - .154				
Bittner et al., 2018 (17)	TPA							
John R. Best et al., 2018 (55)	MVPA	WP&BP: NS		WP: .01 BP: NS		WP&BP: NS	WP&BP: NS	
Spina et al.,	NE							

2018 (44)		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
McDonald et al., 2017 (42)	NE	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Murray et al., 2017 (33)	MVPA	NS	NS	NS	[redacted]	NS	[redacted]	[redacted]
Knufinke et al.*, 2017 (58)	Training load	WP & BP: NS	WP & BP: NS	WP & BP: NS	[redacted]	WP &BP: NS	[redacted]	[redacted]
Pettee et al.*, 2017 (15)	MVPA	[redacted]	[redacted]	-1.61 < 7– 9 h.d^{-1} >. 09	[redacted]	[redacted]	[redacted]	[redacted]
	LPA	[redacted]	[redacted]	7 h.d^{-1}– 9 h.d^{-1}= -.006	[redacted]	[redacted]	[redacted]	[redacted]
Bernard et al., 2016 (18)	MVPA	WP&BP: NS	WP&BP: NS	WP&BP: NS	WP: .08	WP&BP: NS	[redacted]	[redacted]
	TPA		WP: .18	WP: .22	WP: .12		[redacted]	[redacted]
Kishida et al, 2016 (34)	MVPA	[redacted]	WP&BP: NS	WP&BP: NS	WP&BP: NS	WP&BP: NS	[redacted]	[redacted]
	TPA	[redacted]		WP: 18.8			[redacted]	[redacted]
Fanning et al., 2016 (57)	NE	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Mitchell et al., 2016 (35)	MVPA	BP: NA	BP: NA	BP: NA	[redacted]	BP: NA	[redacted]	[redacted]
Whitehead et al., 2016 (51)	AT	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	WP& BP: NS
	ET	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	WP& BP: NS
Fortier et	MVPA	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	WP &BP: NS

al.*, 2014 (36)								
Tang et al., 2014 (45)	NE							
McGlinchey et al.*, 2014 (46)	TPA				WP: -. 01 BP: NS			
Irish et al.*, 2013 (37)	LPA MPA VPA	BP: NS	BP: NS	BP: NS		BP: NS	BP: NS	
Lambiase et al.*, 2013 (38)	MVPA	NS		BP: -. 03		NS	NS	
	TPA			BP: -. 05				
Andrews et al., 2013 (60)	TPA			WP: .0002				
Booth et al., 2012 (56)	NE							
Youngstedt et al., 2003 (50)	TPA	WP&BP: NS	WP&BP: NS	WP&BP: NS		WP&BP: NS		
Nodine et al., 2011 (39)	TPA	BP: 2.102	BP: NS	BP: NS				BP: -2.625
Exercise program interventions								
Breneman et al., 2019 (40)	MVPA	BP: NS	BP: NS	BP: NS				
Nelson et al., 2017	MVPA			WP: NS				WP: NS

(49)								
Dzierzewski et al. *, 2014 (48)	MVPA	NS	WP: NS					WP: .06
		NS	BP: -.34					BP: NA
Baron et al.*, 2013 (41)	MVPA	WP & BP: NS	WP & BP: NS	WP & BP: NS		WP &BP: NS	WP& BP: NS	WP &BP: NS

Abbreviation: NS: Not Significant, ■ : Not Evaluated, AP: Activity Presence, AT : Activity Time, EP: Exercise Presence; Ei: Exercise Intensity LPA: Light Physical Activity, MPA: Moderate Physical Activity, VPA: Vigorous Physical Activity, MVPA: Moderate to Vigorous Physical Activity, ET: Exercise Time, SOL: Sleep Onset Latency, WASO: Wake After Sleep Onset, AL : Awakening Length, SS: Sleep Satisfaction, TWT: Total Wake Time, SE: Sleep Efficiency, TST: Total Sleep Time, SQ: Sleep Quality, FI: Fragmentation Index, $h.d^{-1}$: hours per day, BP: Between Person, WP: Within Person

Table 4: Results of meta-analyses

Associations	Effect size	Effect size	k	Studies
	WP	**BP**	**WP/BP**	**WB/BP**
SOL				
SOL → PA	-.03 (95% CI = -.21 – .14)	-.22 (95% CI = -.59 – .15, *p* = .20)	5/8	4/7
	-.03 (95% CI = -.27 – .20)	-.09 (95% CI =-.18 - -.00, *p* = .05)		
PA → SOL	.02 (95% CI = -.06 – .11)	-.04 (95% CI = -.11 – .03)	7/9	7/7
	.02 (95% CI = -.19 – .13)	-.04 (95% CI = -.11 – .04)		
WASO				
WASO → PA	-.15 (95% CI = -.31 – .00, *p* = .05)	-.08 (95% CI = -.25 – .08)	5/8	4/6
	-13 (95% CI = -.28 – .02, *p* = .06)	-0.07 (95% CI =-.02 - .08)		
PA → WASO	---	-.06 (95% CI = -.17 – .06)	/9	/6
	---	-.05 (95% CI = -.19 – .08)		
TST				
TST → PA	-.48 (95% CI = -1.73 – .77)	-.09 (95% CI = -.43 – .24)	7/20	6/11
	-.02 (95% CI = -0.09 – .13)	-.08 (95% CI = -.36 – .20)		
PA → TST	.08 (95% CI = -.11 – .28)	-.05 (95% CI = -.09 – .00, *p* = .05)	8/22	7/12
	.07 (95% CI = -0.11 – .28)	-.04 (95% CI = -.09 – .01, *p* = .13)		
TWT				
TWT → PA	-.28 (95% CI = -.67 – .10, *p* = .08)	---	3/	2/
	-.26 (95% CI = -.38 – -.15, *p* = .02)			
PA→ TWT	-.23 (95% CI = -.35 – .82)	---	3/	2/
	-.21 (95% CI = -1.42 – 1.83)			
FI				
FI → PA	---	-.15 (95% CI = -.32 – .03)	/3	/2

	---	-.13 (95% CI = -.58 – .31)		
PA→FI	---	-.008 (95% CI = -.10 – .09)	/5	/4
	---	-.008 (95% CI = -.19 – .21)		
SE				
SE → PA	.06 (95% CI = -.05 – .17)	.09 (95% CI = .01 – .18, *p* = .03)	6/10	4/6
	.05 (95% CI = -.05 – .15)	.08 (95% CI = -.05 – .21, *p* = .12)		
PA → SE	.03 (95% CI = -.09 – .15)	-.01 (95% CI = -.06 – .03)	5/13	5/8
	.02 (95% CI = -.14 – .18)	-.02 (95% CI = -.07 – .04)		
SQ				
SQ → PA	.35 (95% CI = -.00 – .70, *p* = .05)	.04 (95% CI = -.27 – .36)	3/3	3/3
	.32 (95% CI = -.03 - .70, *p* = .06)	.04 (95% CI = -.22 – .31)		
PA → SQ	---	-.09 (95% CI = -.53 – .35)	/4	/4
	---	-.07 (95% CI = -0.04 - .31)		

Notes. The second line of each tested association represents findings from sensitivity analyses.
SOL: Sleep Onset Latency, WASO: Wake After Sleep Onset, AL : Awakening Length, SS: Sleep Satisfaction, TWT: Total Wake Time, SE: Sleep Efficiency, TST: Total Sleep Time, SQ: Sleep Quality, FI: Fragmentation Index, $h.d^{-1}$: hours per day, BP: Between Person, WP: Within Person, k = number of available effect sizes.

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Figure 1: Flowchart of the search results. Note. PA: Physical activity

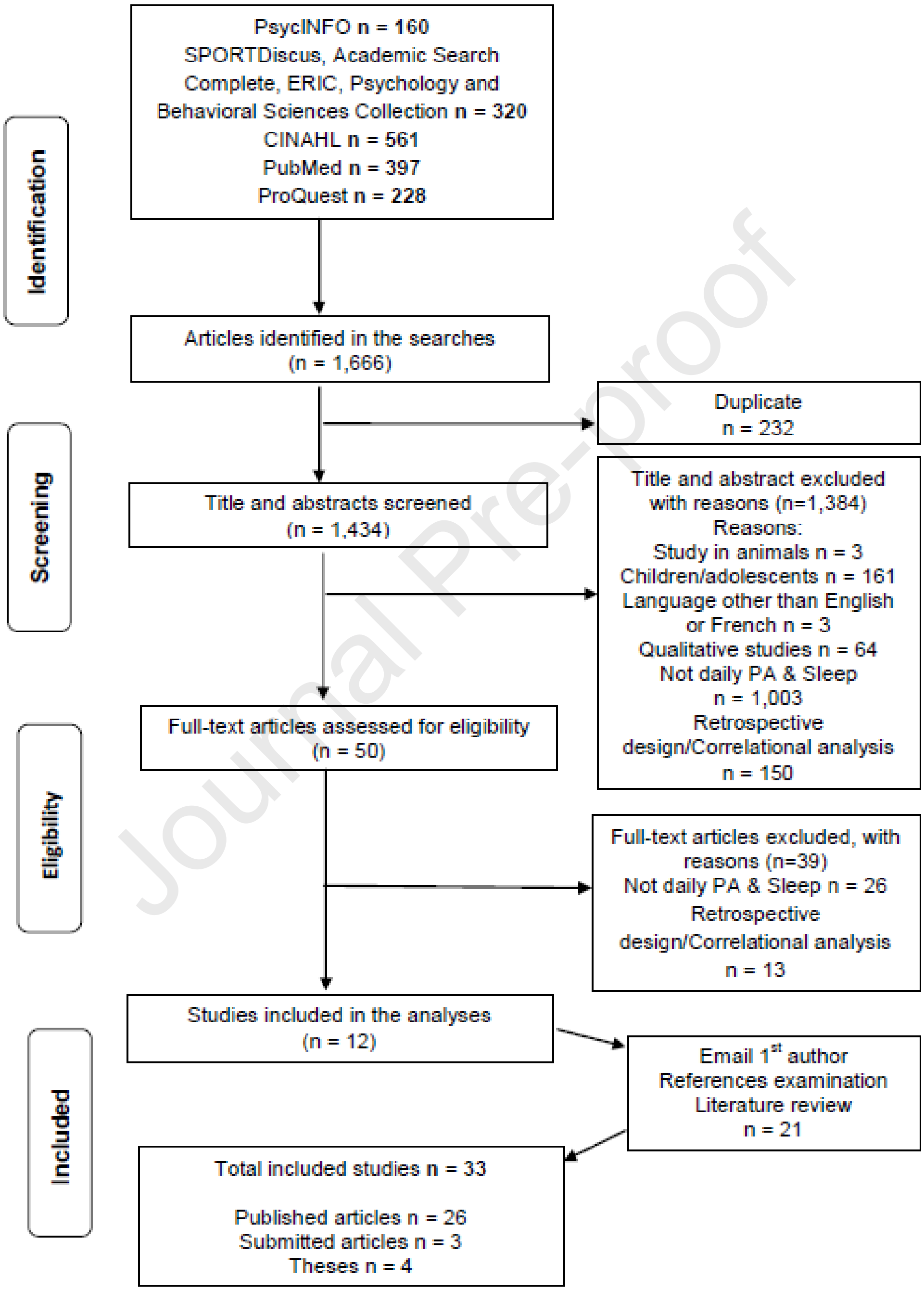
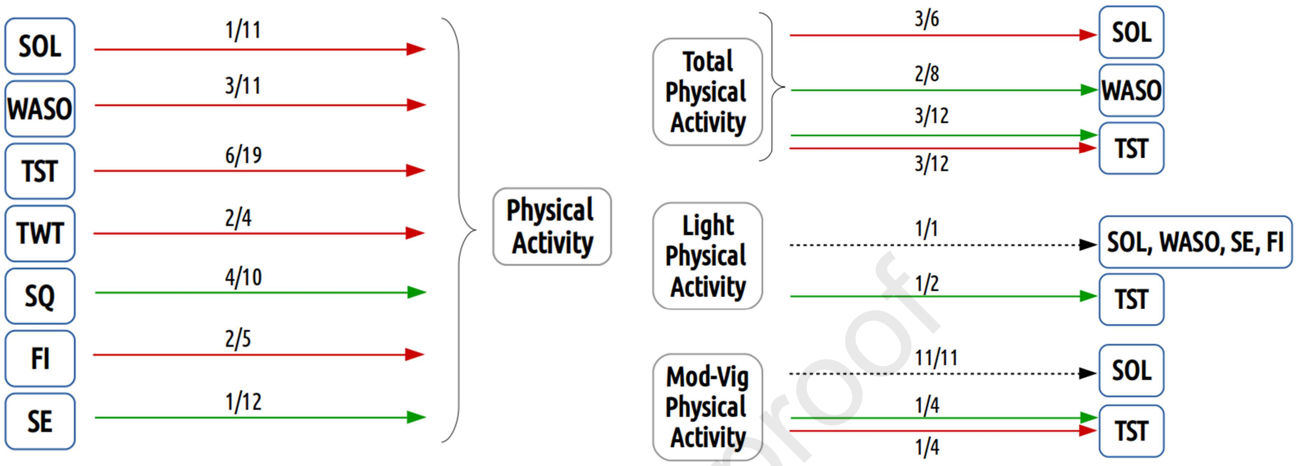


Figure 2. Summary of narrative review findings



Notes. The green and red arrows represent positive and negative associations, respectively and dash arrows figure a no significant association. The inter- and at intra-individual level associations were combined. SOL: Sleep Onset Latency, WASO: Wake After Sleep Onset, TST: Total Sleep Time or sleep duration or time in bed, TWT: Total Wake Time or awakening length, SQ: Sleep Quality or sleep satisfaction, FI: Fragmentation Index, SE: Sleep Efficiency.