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Citation for published version:
Gale, E, Williams, A & Cecil, J 2023, 'The relationship between multiple sleep dimensions and obesity in adolscents: A systematic review', *Sleep medicine reviews*. https://doi.org/10.1016/j.smrv.2023.101875

Digital Object Identifier (DOI):
10.1016/j.smrv.2023.101875

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Sleep medicine reviews

THE RELATIONSHIP BETWEEN MULTIPLE SLEEP DIMENSIONS AND OBESITY IN ADOLESCENTS: A SYSTEMATIC REVIEW

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Glossary of Terms

Term	Definition
Chronotype	Specific entrainment and activity-rest preference of that individual in each 24-hour day.
During sleep	Sleep outcomes that take place after sleep onset and before wake time.
Pre-sleep	Sleep outcomes that take place leading up to and including sleep onset.
Post-sleep	Sleep outcomes take place after and including wake time.
Sleep hygiene	Behavioural and environmental recommendations for individuals to follow pre-sleep that are intended to promote healthy sleep.

Abbreviations list

Abbreviation	Term
ACT	Actigraphy
AHI	Apnoea-hypopnea Index
BF%	Body fat percentage
BFM	Body fat mass
BMI	Body mass index
BMIp	Body mass index percentile
BMIz	Body mass index z-score
BT	Bedtime
BW	Body weight
CS	Cross-sectional
DR	Dual-reported sleep (parent/guardian and participant)
FFM	Fat free mass
FFM%	Fat free mass percentage
FFMI	Fat free mass index
FMI	Fat mass index
Frag	Sleep fragmentation
HC	Hip circumference
HW	Healthy weight
Int	Intervention
Long	Longitudinal
NREM	Non-rapid eye movement
OB	Obese
OW	Overweight
PSG	Polysomnography
RC	Retrospective cohort
REM	Rapid eye movement
SE	Sleep efficiency
SJ	Social jetlag
SN	School night
SO	Sleep onset
SOL	Sleep onset latency
SQ	Sleep quality
SR	Self-reported sleep
tBFI	Trunk body fat index
vBT	Variability of bedtime
vSleep	Variability of sleep duration and timings
vSO	Variability of sleep onset
vWT	Variability of wake time

W:He	Waist: height ratio
W:Hi	Waist: hip ratio
WASO	Wake after sleep onset
WC	Waist circumference
WD	Weekday
WE	Weekend
WT	Wake time

Summary

Sleep is an involuntary behaviour, biologically fundamental to survival and wellbeing. However, sleep is increasingly neglected, with significant health implications. Recent research has identified associations between sleep duration, quality, timing and risk of overweight/obesity in children and adults. The aim of this review was to systematically identify and examine research that investigates the relationships between multiple objective and subjective sleep outcomes and objective adiposity measures in adolescents.

A systematic review of literature, published to December 2022, was conducted using ten bibliographic databases. Search terms included objective and subjective sleep/circadian rhythm measurements, objective adiposity measurements, and adolescents aged 8-18 years. Eighty-nine studies were included in the final review. Sleep outcomes were synthesized into three sleep domains: pre-sleep, during sleep and post-sleep outcomes.

In summary, pre-sleep outcomes (including poor sleep hygiene, later chronotype and increased variability and later sleep timings) and increased sleep disturbance are consistently significantly associated with increased obesity and adiposity in adolescents. The relationship between during-sleep outcomes (sleep quality and efficiency) with adiposity and obesity measures was mixed. These findings suggest that adapting an individual's schedule to best suit chronotype preference and improving sleep hygiene, including a consistent bedtime routine, could reduce adiposity and obesity in adolescents.

1. Introduction

In children and adolescents, the prevalence of obesity across the world has risen from 4% (1975) to 18% (2016) [1]. In addition to poor diet and a sedentary lifestyle [2], sleep has been identified as important in maintaining a healthy energy balance and reducing the risk of obesity in adolescents [3].

Poor sleep leads to energy reduction [4], increased sedentary lifestyle [5], poorer dietary choices [6] and altered hormone regulation, such as decreased leptin and increased ghrelin [7]. Sleep duration and some adiposity measures have been significantly correlated in adolescents and reported in systematic review evidence [8]. More recently, sleep outcomes other than sleep duration have been associated with obesity and adiposity in adolescents. These include, but are not limited to, chronotype (specific entrainment and activity-rest preference of that individual in each 24-hour day) [9-11], sleep efficiency (ratio of time spent asleep to the time dedicated to sleep) [12-14], sleep quality (continuity of sleep) [15, 16], sleep timings [17, 18], and other sleep characteristics (for example, polysomnography (PSG) -specific rapid eye movement (REM)) [5, 16]. Studies in adolescents that have examined the relationship between these sleep outcomes and obesity and adiposity in adolescents are in their infancy. A later chronotype and social jetlag, independent of sleep duration, have been associated with higher body mass index z-score (BMIz), waist circumference (WC), body fat percentage (BF%), trunk body fat mass (TBFM) and skin folds in adolescents [9]. Adolescents with later sleep timings (later sleep onset, later bedtime, later wake times) have been found to have higher BMIz than those with earlier sleep timings, although no association was seen with short sleep duration and increased BMIz [19]. Furthermore, adolescents with poor sleep quality, later sleep timing or reduced sleep efficiency were shown to have a higher risk of obesity [18].

This systematic review is the first to examine and synthesize the relationship between sleep outcomes (objective and subjective, excluding sleep duration) and obesity and adiposity measures (objective) in adolescents. The aim of this systematic review was to determine the relationship between sleep outcomes of chronotype, sleep efficiency, sleep quality, sleep timings, other sleep characteristics and adiposity or obesity measures in adolescents aged 8-18 years.

2. Methodology

2.1. Literature search

A search of the following database took place in September 2021, followed by an updated search in December 2022: MEDLINE (Ovid), EMBASE, Web of Science, Scopus, PsychInfo, CINAHL, The Cochrane Library (including Cochrane Database of Systematic Reviews, the Cochrane Central Register of Controlled Trials (CENTRAL), and the Cochrane Protocols), and Education Research Information Centre (ERIC). Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines were used to conduct the search [20]. The search was limited to peer-reviewed studies, English language only and human studies only. No restriction was placed on the time of publication or the country where a study was conducted/published. The search terms are shown in Table 1. This systematic review was registered on PROSPERO (CRD42021246427). Due to the anticipated heterogeneity of the sleep outcomes and the age range of the population, a meta-analysis was not considered.

2.2. Selection of Studies

Studies were selected using inclusion and exclusion criteria (section 2.3). Firstly, duplicates were removed, and the remaining papers were screened based on title, then abstract and finally at a full-text level according to inclusion/ exclusion criteria (Table 2). One author conducted all database searches and screened all citations at the title and abstract level (EG). Two authors then independently screened all citations at the full-text level (EG, AJW), and one author reviewed a sample of potentially relevant papers (10%) at the full-text level (JC). Final decisions on study inclusion/exclusion were made by consensus.

2.3. Inclusion and exclusion criteria

Participants aged 8-18 years were included in this systematic review to ensure that the pubescent period was accounted for, with girls potentially starting puberty from 8 years [21]. Patients with declared underlying health conditions (excluding obesity/overweight) were excluded to allow for a generalisable sample. Studies with only self-reported obesity and adiposity measures were excluded due to issues concerning under-reporting [22] and inaccurately reporting [23] in adolescents. Research published only in abstract form (including conference abstracts) were excluded (Table2).

2.4. Quality assessment of the studies

Study quality was assessed using Joanna Briggs Institute (JBI) tools for cross-sectional studies (max. score 8) and cohort studies (including intervention, cohort and longitudinal studies) (max. score 11) [24]. Scores allocated for each criterion were awarded one point for “yes”, no points for “unsure”, “not-applicable”, and “no”. Scores were converted to percentages to make them comparable across study designs. A calibration exercise was conducted with 10% of included papers by three authors (EG, AJW, JC) before the remaining 90% of papers were quality assessed by the first author (EG).

3. Results

3.1. Data extraction recording and findings

A total of 52319 records were identified from the systematic search. Of the 604 records identified for screening at the full-text level, 339 records were conference abstracts or abstracts only (full body of text was not present) and 5 records were behind inaccessible paywalls. Subsequently, 260 records were accessed and screened at the full-text level. Overall, 89 records met the inclusion criteria for this systematic review (Figure 1)[23].

3.2. Study characteristics

The studies were conducted in 27 countries and consisted of 73 cross-sectional studies, 12 longitudinal studies, two cohort studies and two non-randomised controlled trials (non-RCT) intervention studies (S1).

Fifty-seven sleep outcomes and 16 different adiposity or obesity measures were examined across the 89 studies (S1). Forty-five studies measured subjective sleep outcomes using self-reported methods, ten measured sleep using a dual-report method (participant and parent), 26 measured sleep using actigraphy, three measured sleep using PSG, and five measured sleep via self-report and actigraphy.

3.3. Data synthesis

Sleep outcomes were grouped thematically into three sleep domains:

A) Pre-sleep - Circadian rhythm and chronotype, problematic sleep onset, increased variability and problematic sleep timings and sleep health, habits and regularity of routine.
B) During-sleep – Sleep efficiency, maintenance and fragmentation, sleep quality (including sleep architecture) and sleep mid-point.
C) Post-sleep – Wake times, sleep-wake routine, oversleeping, social jetlag and daytime sleepiness and napping.

Obesity and adiposity outcomes:

Obesity variables included BMIz, BMIp, BMI, weight status (WS) and body weight. Adiposity measures included BF%, body fat mass, TBFM, fat mass index (FMI), fat-free mass (FFM) percentage, WC, hip circumference, a sum of skin folds, waist: height ratio and waist: hip ratio.

3.4. Pre-sleep outcomes, obesity and adiposity in adolescents

3.4.1. Circadian rhythm and chronotype

Four of the seven studies used self-reporting methods for assessing chronotype [10, 19, 25, 26]. Three studies used actigraphy [9, 27, 28] (S1).

Five of the seven studies that measured chronotype or circadian rhythm amplitude showed significant positive correlations between a later chronotype and increased obesity (S1-2) [9, 10, 19, 25, 28]. In addition, significant correlations were found between a subjective measure of chronotype (including the Morningness Eveningness Questionnaire (MEQ) and the Munich Chronotype Questionnaire (MCQ)) and adiposity and obesity measures, including BMIz [9, 19, 25], BMI [10], WC [9, 10], body fat mass [9], TBFM [9], the sum of skinfolds [9], and BF% [10] (S1-2). No significant associations were identified between chronotype and WS (overweight and obesity defined using BMIz cut-offs) [26, 27] or FFM percentage [10] (S1-2). Circadian rhythm amplitude was significantly associated with BMIz [28] (S1-2).

3.4.2. Problematic sleep onset

3.4.2.1. Sleep onset latency

Two studies reported significant positive associations between sleep onset latency (SOL) and BMIz [29, 30], and two studies reported a significant positive association between SOL and WS [31, 32]. No significant associations were found between SOL and BMIz in four studies [14, 16, 33, 34], two studies found no significant association between SOL and WS [16, 35], one study found no significant association between SOL and BF% [33] and between SOL and WC [33] (S1 and S3).

3.4.2.2. Insomnia symptoms

Insomnia symptoms were significantly positively correlated with BMIz [36] and WS [37] longitudinally and bi-directionally. Two cross-sectional studies reported no significant associations between insomnia symptoms and BMIz [38] and WS [39] (S1 and S3).

3.4.2.3. Sleep onset anxiety

No significant associations were found between sleep onset anxiety, BMIz and WC [40]. A significant positive association was reported between sleep onset anxiety and WS [40] (S1 and S3).

3.4.3. Increased variability and problematic sleep timings

Forty-two studies assessed the relationship between different sleep timing measurements and adiposity and obesity measures [4, 9, 10, 13-15, 18, 31, 32, 34, 38-69] (S1 and S3).

Twenty-one studies used self-reporting methods to measure sleep timing [10, 15, 18, 31, 32, 34, 38-40, 42-44, 47, 50, 52-54, 63, 64, 67, 69], seventeen studies used actigraphy [4, 9, 13, 14, 45, 46, 48, 49, 51, 56-58, 60, 62, 65, 66, 68] and four used dual -reporting methods (self-report and parent-report) [47, 50, 54, 61] (S1 and S3).

3.4.3.1. Sleep onset

Most studies found that sleep onset was not significantly associated with obesity and adiposity measures, including BMIz [45, 49, 60], BMIp [49], BMI [45] and WS [45] (S1 and S3). One study found a significant positive association between sleep onset and WS [65]. One longitudinal study reported a significant positive association between the variability of sleep onset across the week and BMIz [46].

3.4.3.2. Bedtime

Seventeen studies reported on the relationship between bedtime and obesity and adiposity measures (S1 and S3) [4, 10, 14, 15, 18, 32, 38, 41, 42, 47, 52, 54, 56, 57, 59, 61, 64]. Bedtime had a significant positive association with BMIz [15, 18, 38, 42, 52, 54, 56, 61], WS [32, 41, 47, 56], BF% [18, 54], WC [18, 52, 54, 56], hip circumference [18] and waist: height ratio [54]. A few studies found that bedtime was not significantly associated with BMIz [4, 14, 57, 64], WS [10, 57, 59] and BF% [15].

The variability of bedtime was reported to have a significant positive correlation with BMIz [18, 56], BMI [13], WS [56], body fat mass [13], TBFM [13], and WC [13, 56] (S1 and S3). Some studies found there was no significant association between variability of bedtime and BMIz [43, 50], WS [43], BF% [18, 43], WC [18] and hip circumference [18].

3.4.4. Sleep health, habits and regularity of routine

Significant negative associations were found between sleep health composite, BMIz and WS [17] and between sleep habits and BMIz [18], WS [70, 71], BF% [18], WC [72] and hip circumference [18] (S1 and S3). Four studies found no significant association between sleep habits and BMIz [30, 73, 74] and FMI [75].

3.5. During-sleep outcomes, obesity and adiposity in adolescents

3.5.1. Sleep efficiency, maintenance and fragmentation

Thirty-three studies measured sleep efficiency associations with obesity or adiposity measures (S1 and S4) [5, 12-14, 16, 18, 25, 29-40, 45, 46, 48, 54, 57, 60, 69, 76-83]. Across all sleep efficiency-related measurements, there were mixed findings when assessing associations with obesity measures.

Thirteen studies used self-report methods to measure sleep efficiency [12, 18, 25, 29, 31, 32, 34, 36, 38-40, 69, 80, 83]. Three studies used dual-reported sleep measures (parent and participant combined reporting) [37, 54, 79]. Fourteen studies used actigraphy to measure sleep efficiency [13, 14, 30, 33, 34, 45, 46, 48, 57, 60, 76-78, 81]. Finally, three studies used PSG to measure sleep efficiency [5, 16, 35].

3.5.1.1. Sleep efficiency

Sleep efficiency was measured by two different definitions:

1. (Sleep Epochs÷Total Time in Bed (Bedtime to Waketime))×100

   [14, 16, 30, 33-35, 48, 81]
2. (Sleep Epochs÷Total Sleep Duration (Sleep Onset to Waketime))×100

   [5, 45, 46, 57, 60, 76-78]

Using the first definition, significant negative associations were reported between sleep efficiency and BMIz [16, 48], body weight [48], WC [48] and waist: height ratio [48] (S1 and S4). However, no significant associations were reported between sleep efficiency and BMIz [14, 30, 33, 34], BMI [81], WS [35], BF% [33, 48] and WC [33] (S1 and S4).

Using the second definition, significant negative associations were reported between sleep efficiency and BMIz [77], BMIp [78] and WS [5]. No significant associations were reported between BMIz [45, 46, 57, 60, 76], BMI [45] and WS [45, 57] (S1 and S4).

3.5.1.2. Wake after sleep onset and fragmentation

The majority of studies measuring wake-after-sleep onset (WASO) found no significant association between WASO and BMIz [30, 33], BMI [13], WS [16, 32, 35], BF% [33], body fat mass [13], TBFM [13] or WC [13, 33]. However, two studies found significant positive associations between WASO and BMIp [78] and WS [31] (S1 and S4). No significant associations were found between sleep fragmentation and BMIz [77] and WS [80] (S1 and S4).

Two studies found a significant positive association between the number of awakenings and BMIz [25, 77]. One study found no significant association between the number of awakenings and BMIz [29] (S1 and S4).

3.5.1.3. Sleep disturbance

Sleep disturbance was significantly positively associated with BMIz [18, 54, 83], BMI [69], BF% [18, 69], body fat mass [69], FMI [69], WC [18, 54] and hip circumference [18]. No significant association was reported between sleep disturbance and BMIp [79], BF% [79], waist: height ratio [79] and waist: hip ratio [69] (S1 and S4).

3.5.2. Sleep quality, obesity and adiposity in adolescents

Twenty studies assessed the association between sleep quality and obesity or adiposity measures [5, 12, 15, 16, 31, 32, 35, 82, 84-95] (S1 and S4).

Seventeen studies used self-report methods to assess sleep quality [12, 15, 31, 32, 82, 84-95]. Three studies used PSG to measure sleep quality (NREM and REM characteristics) [5, 16, 35].

3.5.2.1. One question measurement of sleep quality

Six studies measured sleep quality using a single question [31, 32, 82, 84, 86, 87, 92], such as ‘how well do you sleep?’. Three of these studies reported a significant negative association between sleep quality and WS [31, 32, 84] (S1 and S4). Four studies found no significant association between WS [31, 82, 87] and WC [86].

3.5.2.2. Validated questionnaires as a measurement of sleep quality

Eight studies assessed sleep quality using the Pittsburgh Sleep Quality Index (PSQI) [12, 85, 89, 91, 93-96]. Significant negative associations were reported between PSQI score and BMIz [85, 89], WS [85, 88, 95], WC [85] and waist: hip ratio [94] (S1 and S4). Some studies reported no significant association between PSQI score and BMIz [94], BMI [91], body weight [94], WS [12, 94], the sum of skin folds [93], WC [94], hip circumference [94] and waist: height ratio [94]. One study did not report on significance [96].

No significant associations were reported between the insomnia severity index (as a measure of sleep quality), BMIz and BF% [15] or between the mini-sleep questionnaire and BF% [90] (S1 and S4). One study reported a significant negative association between the sleep self-report scale and WS but not BMIz and WC [40].

3.5.2.3. Sleep architecture

Significant negative associations were reported between REM characteristics (for example, REM latency, REM activity and time spent in the REM) and BMIz [16] and WS [5, 16, 35] (S1 and S4). Two studies found NREM characteristics (time spent in NREM) negatively associated with WS [5, 35]. Liu et al. (2008) [16] found no significant association between NREM characteristics and BMIz and WS.

3.5.3. Sleep mid-point

Three studies found significant positive associations between sleep mid-point and BMIz [62], WS [65] and waist: height ratio [51]. Additional studies found no significant association between sleep mid-point and BMIz [14, 48, 51], BMI [68], body weight [48], WS [51], BF% [48], WC [48] and waist: height ratio [48] (S1 and S4). One longitudinal study [67] found that the change in sleep mid-point, FFMI and FMI across a year were significantly correlated, but not BMIz.

3.5.4. Breathing and arousal events during sleep

Two studies reported significant positive associations between WS and the arousal index [97] and between WS and the AHI [5] (S1 and S4). Two studies reported no significant associations between AHI and WS [35, 97]. One study reported that snoring was significantly associated with increased WS [47], however another study reported no significant association [80]. No significant associations were reported between night eating and BMIz, WS and BF% [43].

3.6. Post-sleep outcomes, obesity and adiposity in adolescents

3.6.1. Wake time

Some studies reported that wake time had a significant positive association with BMIz [14, 18, 41], WS [65], BF% [18], WC [18, 56] and hip circumference [18] (S1 and S5). Other studies reported no significant association between wake time and BMIz [10, 34, 45, 49, 60], BMIp [49], BMI [45] and WS [10, 32]. Variability of wake times had a significant positive association with BMIz [18, 56], WS [43, 56], BF% [43] and hip circumference [18]. Alternatively, some studies found no significant association between variability of wake times and BMIz [50], WS [39], BF% [18] or WC [56].

3.6.2. Sleep-wake routine

Sleep timing routine was defined as early to sleep and early to wake (E-E), late to sleep and early to wake (L-E), early to sleep and late to wake (E-L), and late to sleep and late to wake (L-L) [31, 32, 40, 44, 52, 53, 57]. A later sleep and later wake (L-L) routine was significantly associated with an increase in WS [31, 32, 44] (S1 and S5). No significant associations were found between sleep timing routine and BMIz [40, 52], WS [40, 53] and WC [40, 52]. Two studies reported no significant association between sleep timing routine variability and BMIz [57] and between sleep variability and WS [66].

3.6.3. Oversleeping

No significant association was found between oversleeping and BMIz, BF% or WC, but oversleeping was significantly positively associated with hip circumference [18] (S1 and S5).

3.6.4. Social jetlag

Social jetlag was defined as the difference between average weekday/school night waketime and weekend/holiday waketime [9, 15, 38, 50, 51, 55, 58, 63, 65, 67]. Social jetlag was found to have a significant positive association with BMIz [15, 38, 51], BMI [69], WS [63], body fat mass [9, 69], BF% [69], FMI [69], TBFM [9], skin folds [9] waist: hip ratio [69] and waist: height ratio [51] (S1 and S5). One longitudinal study [67] found that a change in social jetlag across one year was significantly associated with a change in FFMI, FMI and BMIz across one year.

Other studies found no significant association between social jetlag and BMIz [14, 50, 55, 63], WS [51, 58, 65], BF% [15, 55] and WC [55, 63].

3.6.5. Daytime sleepiness and napping

There were mixed findings between napping and obesity measures and between daytime sleepiness and obesity measures (S1 and S5). One study found a significant positive association between napping (specifically on a weekend) and BMIz [98]. Some studies found no significant correlation between napping and BMIz [51] (weekday only [38, 98]), WS [10, 51, 80] or waist: height ratio [51]. A significant positive association was reported between daytime sleepiness and BMIz [98], BMI [10], WS [10] and BF% [10]. Other studies found no significant associations between daytime sleepiness and BMIz [38], WS [38, 39, 99], FFM percentage [39] and WC [39].

3.7. Quality assessment of the studies

3.7.1. Cross-sectional studies

Seventy-three studies were assessed using the JBI cross-sectional study tool [24] (S6). The mean quality assessment score for cross-sectional studies was 5.81±0.95. Many studies received a nonapplicable score for domain four related to whether control groups were used. The most common threats to quality in cross-sectional studies were identified confounding variables, strategies to deal with confounding variables, and the outcome measure measured validly and reliably.

3.7.2. Cohort, longitudinal and non-randomised controlled intervention studies

Sixteen studies were assessed using the JBI cohort study tool [24] (S7). The cohort studies' mean score was 8.81±1.84. A common threat to quality in the studies assessed using the cohort study tool was that multiple studies failed to achieve complete follow-up with participants or report strategies to address incomplete follow-up.

4. Discussion

4.1. Overall findings

The aim of this systematic review was to determine the relationship between sleep outcomes of chronotype, sleep efficiency, sleep quality, sleep timings, other sleep characteristics (excluding sleep duration) and adiposity or obesity measures in adolescents aged 8-18 years. Systematic searches of ten databases identified 89 studies that met the inclusion criteria. Sleep outcomes were synthesized into three sleep domains: pre-sleep, during sleep and post-sleep outcomes.

The main findings of this systematic review suggest that pre-sleep outcomes (including bedtime, sleep onset and bedtime and sleep onset variability), chronotype, sleep habits and sleep hygiene outcomes were consistently correlated with adiposity and obesity measures in adolescents (Figure 2). Most of the sleep outcomes found to be correlated with adiposity and obesity are modifiable, which suggests they could be useful targets for health-promoting interventions. Mixed findings were revealed for associations with adiposity and obesity with during-sleep outcomes of sleep quality, sleep efficiency and post-sleep timing measures.

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4.2. Pre-sleep measurements and sleep hygiene

4.2.1. Chronotype

The evidence from this review suggests that individuals with later chronotypes and later regular bedtimes are more likely to have higher levels of adiposity than individuals with earlier chronotypes [9, 10] and higher BMI [10] or BMIz [9, 19, 25].

The mechanism linking chronotype and obesity in adolescents has been explored, particularly as an indirect association using diet and exercise as mediators. One study reported an association between later chronotype and unhealthy dietary choices in 7–11-year-olds [100]. Evening-chronotype preference girls consumed more fast food, whereas evening-chronotype preference boys skipped breakfast, suggesting the existence of clear gender differences. The association between later chronotype and unhealthy dietary choices has been observed as both a direct and indirect effect, mediated by screen-time and sleep duration [100]. Furthermore, studies have directly linked unhealthy food choices [101] and sugar-sweetened beverage intake [102, 103] with obesity in adolescents and indirectly mediated with physical activity [102, 104] and psychological stress [101].

The lack of longitudinal studies investigating the relationship between chronotype and obesity negates any conclusions on directionality being made. However, we could suggest that later chronotype could predispose adolescents to mediators such as unhealthy dietary choices, reduced exercise, low mental wellbeing and increased screen-time, predisposing adolescents to obesity and increased adiposity. Furthermore, the mediators listed could act as shared determinants between a later chronotype and obesity and could potentially be used in health-promoting interventions to improve sleep and adiposity in adolescents.

4.2.2. Sleep hygiene, health and habits

Other sleep characteristics occurring pre-sleep onset, identified in this review, included sleep health and sleep habits. Poor sleep health [17] and irregular and poorer sleep habits [18, 70-72] were associated with obesity and increased adiposity. The sleep health composite score is split into six domains: sleep regularity, sleep quality, daytime alertness, timing, efficiency and duration. A poorer sleep health composite score [17] was associated with poorer mental wellbeing, poorer social interaction and social anxiety, cognitive attention, physical health and BMIz. Poor mental wellbeing [105], social anxiety [106] and cognitive attention difficulties [107] have been linked with obesity in adolescents. These potential mediators or shared determinants could play a role in the link between sleep health and obesity and could be prevented, modified, or treated to help improve the overall health of adolescents at risk of obesity.

Irregular sleep routine has been associated with poorer dietary choices [108], particularly with high fat and carbohydrate-based foods [109], a decrease in mental wellbeing and emotional eating [110], increased ghrelin and cortisol levels [7], increased screen-time [111] as well as decreased physical activity [109], leading to weight gain in adolescents.

Consequently, improving sleep hygiene and the regularity of healthy sleep habits leading up to sleep onset may be critical in reducing the risk of obesity and increased adiposity in adolescents.

4.2.3. Problematic sleep onset

Our findings show that insomnia symptoms were associated with BMIz [36] and WS [37] longitudinally and bi-directionally. As two of the few longitudinal studies that met the review inclusion criteria, this evidence suggests that improving sleep hygiene and thus reducing insomnia symptoms could reduce an adolescent's risk of obesity and increased adiposity. However, reducing adiposity and weight loss could also improve insomnia symptoms [37]. Future research should incorporate a longitudinal design to understand the directionality of relationships highlighted in this review by cross-sectional studies.

Synthesis of findings in the current review revealed that a later bedtime was correlated to a range of adiposity and obesity measures in adolescents. Adolescents with a later chronotype preference tended to have later bedtimes [112], which supports our findings that both a later bedtime and later chronotype are associated with adiposity and obesity measures in adolescents. A later bedtime creates a shorter window for sleep and is associated with shorter sleep duration [113]. Shorter sleep duration, a popular area of interest in current literature, is associated with increased nighttime screen use [114], problematic social media usage [115], poor dietary decisions [116], impaired decision-making [117], reduced exercise [5], and adiposity and obesity. A later bedtime shifts the melatonin peak during sleep to later in the sleep cycle [118], thereby increasing cortisol production time, reducing leptin and increasing ghrelin production [7]. This increase in cortisol can lead to worsening mental wellbeing [110] and an increase in ghrelin to poorer dietary choices [6], which have been associated with obesity and increased adiposity in adolescents [6].

Notably, the variability of bedtime (a later bedtime on the weekend than a weekday) was also correlated with both adiposity and obesity measures. This variability supports the finding that social jetlag is associated with adiposity and obesity measures [9, 15, 38, 51, 63]. It could be suggested that individuals may shift their bedtimes on the weekend, causing variability to align with their chronotype. In addition, it could be suggested that the variability results from increased nighttime social media usage on a weekend evening rather than on a weekday [119]. An irregular sleep routine and hormone levels between weekdays and weekends contribute to obesity development [120]. Whilst sleep onset was not found to be associated with adiposity or obesity by some studies in our review [45, 49, 60], the variability of sleep onset was associated with BMIz [46], which further supports the idea of a shift between weekday and weekend lifestyles causing irregularity in both sleep routine and hormone production could lead to obesity.

4.3. During sleep measurements

4.3.1. Sleep efficiency

Our review revealed inconsistencies in the findings within the sleep efficiency domains other than sleep disturbance. One reason could be the lack of consistency in definitions and the tools used to measure sleep efficiency. For example, one study highlighted the issue of consistency of sleep efficiency definitions in research and the difficulty in comparing studies [121]. For example, total sleep time (TST) divided by time in bed (TIB), multiplied by 100, does not consider activities that occur in bed before sleep onset, like screen-time usage. Thus, duration of sleep episode (SOL+TST+WASO+time attempting to sleep after final awakening) would be a more accurate denominator and would consider sleep disruption that is pre-sleep onset but after trying to sleep, during sleep and then after waking before getting up from bed.

4.3.2. Sleep quality

There was inconsistency in the findings within the subjective sleep quality measures and between subjective and objective sleep quality measures. For example, PSG studies in this review indicated that REM latency, REM activity, time spent in REM and the time spent in each NREM stage were correlated to obesity and adiposity measures [5, 16, 35]. In contrast, subjective measures, for example, the PSQI or a question on sleep quality, showed a mixture of significant and non-significant findings between sleep quality scores and a variety of obesity and adiposity measures (section 0). A lack of consistency within subjective sleep quality measures and between subjective and objective measures could be due to the range of tools used to measure sleep quality. It is important to recognise that sleep quality is a complex concept and that the use of a single question assessment limits the ability to compare findings with more defined subjective and objective tools, such as PSQI and PSG, respectively. Moreover, no studies conducted both measures nor adjusted for or considered other sleep measures that may impact sleep quality.

Sleep quality, measured both subjectively and objectively, is known to be poorer in adults forced into desynchrony from their habitual bedtimes (changing sleep timings from a 24-hour rest-activity cycle to a 20-hour rest-activity cycle) compared with those with habitual bedtimes [122]. Thus, chronotype and sleep timing should be accounted for when measuring sleep quality by adjusting for or excluding/including desynchrony.

Subjective sleep quality questions/questionnaires are often given at baseline or after collecting PSG or actigraphy. To obtain a more representative subjective sleep quality score, sleep quality should be collected daily along with an objective measure. In the adolescent population, this systematic review showed a significant association between social jetlag and obesity and variation in sleep timings (onset and wake) and obesity. One study reported that sleep timing variation was largest between a weekend and a Monday due to early school start times [123]. Thus, measuring sleep quality subjectively and daily on those days affected by social jetlag or variation in sleep timing would give the most reliable result for sleep quality.

Sleep quality in adolescents, assessed subjectively, can be improved or facilitated with sleep education-related intervention. For example, one study conducted a randomised controlled trial using an intervention composed of five educational sessions, one surrounding sleep education (information about the stages of sleep and the importance of sleep), one involving sleep hygiene practices and three sessions involving visualisation training and stress reduction [124]. The intervention saw an increase in subjective sleep quality scores between pre-and post-intervention. Thus, if sleep hygiene education is associated with subjective sleep quality improvement, a sleep hygiene-based intervention could improve subjective sleep quality in adolescents and potentially reduce obesity and adiposity.

4.3.3. Sleep stages and arousal markers

Polysomnography measures such as the arousal index were correlated with WS [97]. This, along with PSG-based sleep quality findings (REM and NREM), could indicate that obesity is correlated with pre-sleep measures and sleep architecture changes. Alongside reduced REM latency and reduced time spent in REM, the arousals will increase daytime sleepiness [125], limit memory consolidation [126], increase ghrelin and cortisol levels [16] and increase the risk of obesity [5, 16, 35] and poor mental wellbeing [127]. Therefore, if funding and specialist training permit, polysomnography measures would be a useful tool to be used when conducting sleep and obesity interventions. Furthermore, AHI [5] and arousal index [35, 97] scores were associated with obesity measures. Whilst no interventions exist for improving adolescents' AHI or arousal index scores, increased REM and reduced sleep fragmentation (thus fewer arousals) were observed with a sleep education promotion intervention [124].

4.4. Post-sleep measurements

4.4.1. Sleep timing

This review identified inconsistencies in the findings for wake time, oversleeping and social jetlag. This could be due to different reporting tools, as some studies used actigraphy, and others used self-reporting methods. For example, social jetlag had positive correlations identified in cross-sectional studies and used self-reporting. However, only one longitudinal study assessed the relationship between social jetlag and adiposity and the findings were non-significant [67]. Furthermore, waketimes and oversleeping have not been assessed longitudinally. Therefore, more longitudinal research must occur before a conclusion can be made on the relationship between post-sleep timings and adiposity.

4.4.2. Daytime sleepiness

Findings of associations of both daytime napping and sleepiness with obesity and adiposity measures were mixed. However, more studies identified significant associations with excessive daytime sleepiness and adiposity or obesity than non-significant associations. In addition, daytime sleepiness was correlated with social jetlag [128] and sleep quality [129], which have been reported to be correlated with obesity and adiposity also. Thus, some measures could directly affect other sleep measures, which could affect obesity rates and adiposity levels.

4.5. Strengths and limitations of the systematic review

This review makes a significant contribution to the literature by systematically synthesising the evidence of a full range of sleep outcomes, as opposed to solely sleep duration, with multiple obesity and adiposity measures in adolescents. The reliability of the outcomes was assessed through quality appraisal. Sleep duration measurements have previously been comprehensively reported [8, 130] and were not assessed in this review. An additional strength of this systematic review is the age range studied. Whilst sleep does vary significantly across childhood, adolescence and transition into adult life, focusing solely on adolescents provides an insight into the changes that occur over puberty and how those may correlate with obesity. A final strength is the breadth of study designs included in this review.

The comparability of sleep across studies is difficult due to the variation in definitions and measurement tools and is a limitation of this review. However, categorising sleep measures into the three sleep domains (pre-, during or post-sleep) in this review has highlighted differences between groups of characteristics. Furthermore, the comparability of studies is limited due to a variation in cofounders considered in statistical analysis. The substantial variation restricted the aggregation of data for a meta-analysis. Future research should consider confounders such as pubertal status, circadian preference, and sleep duration when measuring sleep. Finally, during the full-text screening process, many abstracts or abstract only records were excluded as part of inclusion/exclusion set criteria, highlighting that studying the relationship between sleep and obesity **is** a growing field of research.

5. Conclusion

To conclude, pre-sleep measures such as sleep hygiene, sleep habits, insomnia symptoms, and sleep timings (bedtime, sleep onset and variability of bedtime and sleep onset) are significantly correlated with increased adiposity and obesity in adolescents aged 8-18 years. Future research should include standardisation of measurements and definitions of during- and post-sleep measurements to enable reliable and valid comparisons across studies. Furthermore, longitudinal studies should be conducted to assess the directionality of the association between the pre-sleep measures highlighted in this review and adiposity and obesity in adolescents.

Practice points

1). Sleep hygiene and pre-sleep measures such as sleep habits, insomnia symptoms, and sleep timings (bedtime, sleep onset and variability of bedtime and sleep onset) are significantly correlated with increased adiposity and obesity in adolescents

2). Sleep health should be considered when planning a weight loss or healthy lifestyle intervention.

Research agenda

Sleep outcomes that occur during pre-sleep onset are associated with adiposity and obesity measures. There are mixed findings among sleep outcomes taking place during sleep or after wake with adiposity and obesity measures. Future research should consider the following:

1). Longitudinal research to assess causality and directionality, thereby increasing our understanding of the aetiology of the sleep-obesity relationship.

2). Studies designed to assess shared determinants of the three sleep domains (pre-, during- and post-sleep) and adiposity and obesity to aid in identifying key areas of focus for a health-promoting intervention that would improve adolescents' overall health.

3). Assessing sleep outcomes that occur during sleep and after waking, with adiposity and obesity.

4). Strategies to standardise methodologies for sleep outcomes during sleep and after waking to increase comparability of studies analysing these measures.

Acknowledgements

This review was supported by the University of St Andrews as part of a doctoral research program.

Conflicts of Interest

There are no conflicts of interest.

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