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Special Issue: Timing of 24-hour movement behaviours: implications for research, policy and practice

Guest Editor: Sarah A. Moore

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Editorial

Reimagining healthy movement in the era of the COVID-19 pandemic

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Abstract

Does the timing of when children, youth and adults participate in physical activity, sedentary behaviour (e.g. screen time) and sleep matter when it comes to their overall health? This special issue of *Health Promotion and Chronic Disease Prevention in Canada* includes four papers that present evidence and recommendations on the timing of movement behaviours: three separate systematic reviews exploring the associations between health indicators and the timing of physical activity, sedentary behaviour and sleep; and a commentary that discusses the importance of this evidence in terms of practice, policy and research.

This editorial sets the stage for this special issue, reflecting on the challenges posed by COVID-19-related public health restrictions on healthy movement. Perhaps now is the optimal time to reimagine how and when we engage in physical activity, sedentary behaviour and sleep to support our health.

Keywords: *movement behaviours, timing, health outcomes, adaptations, public health restrictions*

Does when we move, when we are sedentary, and when we sleep affect our health?

The Canadian 24-Hour Movement Guidelines were introduced to help optimize health by encouraging people of all ages to move more, reduce sedentary time and sleep well.[1] Yet, ParticipACTION's report cards on physical activity, the most comprehensive assessments of physical activity, sedentary behaviour and sleep in Canada, show that large proportions of Canadians still do not meet the 24-Hour Movement Guidelines.[2,3]

The health benefits associated with integrative movement behaviours may vary depending on the time of day when we participate in these activities. Associations between physical activity and risk of cardiovascular disease, have been reported to differ depending on when the activity was performed (i.e. morning, afternoon, evening). For example, in one study, patients with cardiovascular disease who exercised in the evening were at lower risk of acute myocardial infarction than those who did sports-related physical activity in the morning.[4]

The timing of sedentary behaviour may also matter; there is some evidence that screen-based sedentary behaviour in the evening is deleterious compared with screen-based sedentary behaviour earlier in the day.[5] The benefits of a good night's sleep may also differ depending on timing. For example, later sleep timing was reported to be associated with increased odds of self-reported depressive symptoms among children and youth.[6]

To date, the timing of movement behaviours—and particularly that of physical activity, sedentary behaviour and sleep in relation to various health outcomes—has not been comprehensively reviewed. Recommendations are limited due to lack of evidence in this area. Hence, the rationale for this special issue of *Health Promotion and Chronic Disease Prevention in Canada*, on the timing of 24-hour movement behaviours.

Timing of movement behaviours and health outcomes: a short summary of the findings

This special issue sheds light on the relationship between physical activity, sedentary behaviour and sleep timing as it relates to health. The shift to using an integrated approach to movement behaviours[1] allows us to understand that daily physical activity, sedentary behaviour and sleep are interdependent, and the timing of one movement behaviour is likely to influence another. The three systematic reviews in this special issue collectively describe 125 studies with 465 518 unique participants (all searches current to January 2021). Janssen et al.[7] included studies of adults and described the timing of physical activity in relation to adiposity, cardiometabolic markers, cardiovascular disease, cancer, fat-free mass, mental health, mortality, physical functioning and mobility, and sleep.[7] Study results varied and the quality of evidence was mostly

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low. The authors suggest that people should be physically active when it suits them best.[7]

Saunders et al.[8] focussed on the effect of timing of screen- and non-screen sedentary behaviour on children's and youth's sleep health. The results indicated that evening/bedtime screen use was associated with reduced sleep duration and quality.[8] While the quality of evidence in the included studies was generally low, the authors concluded that children and youth should limit screen use before bedtime to improve sleep health.[8]

Dutil et al.[9] also limited their search to children and youth. The studies included in their systematic review described sleep timing as it related to accidents and injuries, adiposity, cardiometabolic risk factors, cognitive function and academic achievement, eating behaviours, emotional regulation, and quality of life and well-being.[9] Findings suggest that later sleep timing may be associated with poorer cognitive function and academic performance, eating behaviours and emotional regulation in children and youth.[9] Evidence for this review was also considered low.[9] The authors recommended earlier sleep timing for children and youth and adjusting bedtime to sleep the recommended amount.[9]

Finally, a commentary by Tomasone and colleagues[10] provides recommendations on practice, policy and research and a communications toolkit to support Canadians in optimizing movement behaviours throughout the day. The commentary gives suggestions by setting (e.g. education, workplace, health and community service settings).[10] Tomasone et al.[10] also offer "how to" tips for implementing the recommendations. This practical advice comes when many people living in Canada have been less active and more sedentary because of pandemic-related restrictions. This timely issue can help support Canadians in making their "whole day matter."[1]

When we moved, were sedentary, and slept may have changed during COVID-19

Pivot! Over the last 2 years, Canadians have undergone changes to how and when they were physically active, sedentary and slept.[11,12,13] As such, this special issue may be particularly relevant in the context of the COVID-19 pandemic. The Canadian 24-Hour Movement Guidelines[1] were first introduced because research consistently demonstrated that ample physical activity, reduced sedentary time and screen use and adequate sleep were associated with enhanced physical and mental health.[14] But since the start of the COVID-19 pandemic, many children and youth[11,12] and adults[13] in Canada have not been adequately active, have not been sleeping enough and have been too sedentary (with screens). Undoubtedly, COVID-19 has thrown us many challenges, including significant health and economic consequences.[15] Now, 2 years after the declaration of the pandemic, we have gained a better understanding of its collateral health consequences, including in relation to physical inactivity, excessive screen use and changed sleep schedules. Concerningly, pandemic-related changes in movement behaviours have been associated with poorer mental and physical health outcomes.[16]

Many individuals had to change their schedules and routines at some point during the COVID-19 pandemic. Many of us attended online school or worked from home and were restricted from attending recreational and sports programs (with gyms temporarily closed), and more of us were sedentary and using screens because of pandemic-related restrictions.[17] Evidence has shown that Canadian children and their caregivers largely adhered to public health measures, such as staying home and limiting social gatherings; however, adherence to public health measures was associated with reduced physical activity and increased screen time among children and youth,[18] and increased screen time has been associated with depression, anxiety, hyperactivity and irritability among young people.[19]

Overall, Canadians have been less active, and *when* they were active also changed. We relied less on structured activities and indoor programs at pre-scheduled times. Some people took this opportunity to change their work day and be active outdoors, in nature;[20] others embraced exercise apps or virtual programs when it suited them.[21] Bed and wake times may have shifted with more people attending classes and working from home.[22] With easing restrictions, we may be able to re-establish the routines and schedules we had before the pandemic or create new ones. And with this switch, now might be the ideal time to consider how and when Canadians can get moving to optimize our health.

Reimagining movement in the context of COVID-19: Recommendations

The COVID-19 pandemic may have long-lasting implications on our schedules and routines. Daily routines are either primary (i.e. those necessary for maintaining biological needs, such as eating, hygiene and sleep) or secondary (i.e. those to do with motivations and preferences, such as leisure, physical activity, practices with work and study).[23] During the COVID-19 pandemic, schedules and routines were notably disrupted.[24] Fewer children and youth were engaging in organized physical activity and sport, and more adults working fully or partly from home over the course of the COVID-19 pandemic. Is there an opportunity for children, youth and adults to consider new ways to integrate movement into their day? For example, caregivers of children and youth may build in time for unstructured physical activity and play throughout their day.[25] Adults may take more activity breaks throughout their day or may select active ways to commute.[26] To integrate healthy movement, reduce sedentary behaviour and improve sleep in our daily lives, we have a few simple recommendations:

- Add movement at the start of your day—try walking, wheeling or cycling to school or work;
- Spend time outdoors—try natural playscapes or loose parts play, find new trails and outdoor spaces;
- Use activity as a way to engage with family or friends, connect and re-connect;
- Add movement breaks and set screen time reminders with the use of apps;
- Designate screen-free zones at home, such as bedrooms, and screen-free times, for example, during meals;
- Create consistent nighttime routines, with no screen use;
- Set-up for the morning the night before, prepare items to reduce the morning rush;
- Apply harm reduction principles to address screen time, yet remain pragmatic and empathetic;[27]

- Use a family- or friend-based approach to create goals together and support each other—play together and model healthy movement behaviours;[28]
- Seek support, particularly if you are experiencing more barriers and/or need more targeted or individualized strategies (e.g., children and youth living with a disability).[29]

Recognizing the limitations of this special issue and next steps

This special issue of *Health Promotion and Chronic Disease Prevention in Canada* provides a comprehensive overview on how the timing of movement may be related to various health outcomes. However, it is important to recognize the limitations of the included papers.

While the reviews were conducted using evidence-based and rigorous systematic review methodologies, the authors were not able to conduct meta-analyses due to the heterogeneity of the included studies, their methods and reported outcomes. As Janssen et al.[7] primarily included studies of adults, it would be advantageous for future studies and reviews to explore benefits of different timing of physical activity among children and youth. Conversely, Saunders et al.[8] and Dutil et al.[9] included studies exclusively with children and youth (a previous review is available on sleep timing and health in adults[30]); future reviews may wish to expand their searches on the timing of sedentary behaviours and various health outcomes to adults.

In addition, future studies and reviews may try to not limit the search by outcome but include studies that investigate the timing of sedentary behaviours with additional health indicators. It may also be worthwhile to investigate the moderating effects of age, sex/gender, race/ethnicity, socioeconomic status, family structure, disability and other factors to provide more specific recommendations and design appropriate interventions for those who may be experiencing barriers to healthy movement. Given the literature emerging in this area, it may also be worthwhile to investigate the role and timing of physical activity, sedentary behaviour and sleep to counter symptoms of long COVID.[31,32]

Conclusion

The three systematic reviews in this special issue synthesize evidence about the timing of movement behaviours in relation to health. The commentary offers practical advice and resources on optimizing movement behaviours across the day and in various settings. This special issue is thus timely and important, particularly in the era of COVID-19. Now may be the time for people living in Canada to consider (or reconsider) what healthy movement looks like in our daily lives—to improve how and when we are active, sedentary and sleep.

Conflict of interest

The authors have no conflict of interest to declare.

Authors' contributions and statement

SAM, LMV, CSB and LAR contributed to the conceptualization of the work; SAM drafted the manuscript; SAM, LMV, CSB and LAR contributed to editing and revising the manuscript critically for important intellectual content; all co-authors reviewed and approved the final manuscript.

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Evidence synthesis

Timing of physical activity within the 24-hour day and its influence on health: a systematic review

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This article has been peer reviewed.

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Abstract

Background: Recent studies report that the health benefits of physical activity differ depending on whether the activity is performed in the morning, afternoon or evening. The purpose of this systematic review was to examine whether the timing of physical activity within the 24-hour day is associated with health.

Methods: Five databases were searched for English or French language peer-reviewed studies that examined whether the timing of physical activity within the day is associated with health. No limits were placed on publication year, study population, study design or health outcomes. Studies that examined acute effects of physical activity or timing of physical activity around food intake were excluded.

Results: This systematic review examined 35 studies, with 17 259 participants, and the following health outcomes: measures of sleep health, adiposity, fat-free mass and muscle size, cardiometabolic biomarkers, physical function and mobility, mental health, and risk of cardiovascular disease, cancer, and mortality. Heterogeneity across studies precluded meta-analyses, and we present our findings using narrative syntheses. Of the 35 studies, 11 reported that morning physical activity provides greater health benefits than afternoon/evening physical activity, while 12 found that morning physical activity provides fewer health benefits than afternoon/evening physical. In the remaining 12 studies, there was no clear difference in health benefits based on the timing of physical activity. The quality of evidence for the different health outcomes across study designs was very low.

Conclusion: There is no consistent evidence that physical activity at one time of day provides more favourable health benefits than physical activity at a different time of day. (PROSPERO registration no.: CRD42021231088)

Keywords: *physical activity, exercise, timing, health, systematic review*

Highlights

- This systematic review examined whether the timing of physical activity within the day is associated with health.
- Thirty-five studies, with 17 259 participants, were included.
- The results of 11 studies suggest that morning physical activity provides greater health benefits than afternoon or evening activity, the results of 12 studies suggest that morning physical activity provides smaller health benefits than afternoon or evening activity, and the results of 12 studies found no differences in health outcomes based on the timing of physical activity.
- There is no consistent evidence that physical activity performed at one time of day provides more favourable health benefits than physical activity performed at a different time of day.

Introduction

The US Surgeon General's 1996 report on physical activity and health provided the first national physical activity recommendations for public health[1]. The report recommended that adults get "a minimum of 30 minutes of physical activity of moderate intensity (such as brisk walking) on most, if not all, days of the week."[1p.6] That recommendation was informed by evidence that adults need to expend about 1000 kcal/week through moderate-to-vigorous physical activity (MVPA) to reduce morbidity and mortality risk[1]. This can be achieved with about 150 minutes of MVPA spread out in 30-minute bouts performed 5 days/week[1]. *Canada's Physical Activity Guide to Healthy Active Living*[2] made similar recommendations in 1998.

About a dozen years after the Surgeon General's report was published, the United States[3], Canada[4] and the World Health Organization[5] released updated physical activity recommendations. These recommendations removed the stipulation that MVPA takes place on most or all days of the week, and simply stated that adults need to accumulate 150 minutes/week of MVPA in bouts lasting at least 10 minutes.

In the past few years, the United States[6], Canada[7] and the World Health Organization[8]

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released updated physical activity recommendations. These new recommendations no longer stipulate that MVPA needs to be accumulated in bouts of 10 minutes or longer. This stipulation was removed based on evidence that intermittent MVPA (< 10 minutes) provides equivalent health benefits to regular bouts of MVPA[6-8]. Thus, although the amount and intensity of MVPA in public health recommendations have not changed since 1996, the significant changes to the components of the recommendations reflect the patterns in which the MVPA should be accumulated.

What has not been considered in the context of the recommendations is the time when physical activity is accumulated during the day (e.g. morning, afternoon or evening). Recent studies report that equivalent doses of physical activity in the morning, afternoon and evening may be differentially associated with adiposity[9], cardiometabolic biomarkers[10], cardiovascular disease[11] and cancer[12]. These new studies, coupled with media interest[13,14], have fuelled some individuals to prescribe exercise at specific times of the day because they believe it will optimize health benefits. However, the effects of the timing of physical activity has not been comprehensively examined.

The purpose of this systematic review was to examine whether the timing of physical activity during the 24-hour day is associated with health. The results could shed light as to whether the timing of physical activity should be considered in future public health recommendations and health promotion efforts.

Methods

Protocol and registration

This review is registered with the International Prospective Register of Systematic Reviews (PROSPERO; Registration no. CRD42021231088) and was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement[15].

Eligibility criteria

We used the PICOS (Participants, Intervention/Exposure, Comparisons, Outcomes, Study design) framework to facilitate the search process and identify study concepts[16].

Population

The population of interest were people, irrespective of age, sex, race/ethnicity or health status.

Intervention/exposure

The intervention or exposure was the timing of physical activity within the 24-hour day, irrespective of the intensity. We studied the effects of habitual physical activity or physical activity interventions. Studies looking at acute responses to a single bout of physical activity were excluded. We did not study the timing of physical activity relative to food or beverage intake, medication use or other therapeutics.

Comparison/control

The comparator was varying levels of the timing of physical activity. A non-exercise control group was not required for intervention studies.

Outcomes

All health outcomes were included (i.e. the search strategy was not limited to a specific health outcome or small number of health outcomes). We also included sleep and sedentary behaviour—the other movement behaviours that, in addition to physical activity, sum up to 24 hours in a day from a time-use perspective[17]—as potential outcomes. Physical fitness and athletic performance outcomes (e.g. maximal oxygen consumption [$VO2_{max}$], muscle strength, sprinting speed) were not considered.

Study designs

All original primary research study designs were eligible except case studies, studies that only used qualitative data analysis and studies that only examined the acute effects of physical activity.

Information sources and search strategy

Five databases were searched: Ovid MEDLINE/PubMed, Ovid Embase, Ovid PsycINFO, EBSCO Cumulative Index to Nursing & Allied Health Literature (CINAHL) and EBSCO SPORTDiscus. Searches were conducted on 6 January 2021, with no limits placed on publication dates. Studies were eligible if they were published or in-press, in English or French, and were peer reviewed. Grey literature (e.g. book chapters, dissertations) and abstracts were excluded because this literature is difficult to search and is often not peer reviewed.

The following search terms were used: (1) "physical activity" OR "physical activities" OR "physically active" OR "physical exercise" OR "exercise" or "walk"; AND (2) "time of day" OR "timing." More details on the search strategy are included in the supplementary materials (https://osf.io/qcw6j/?view_only=4130e81638684feaa2dfa74f5e589d58).

To remove duplicates, records were imported into Covidence (Veritas Health Innovation, Melbourne, AU). During level 1 screening, two reviewers (IJ or JC or SZ) working independently, screened article titles and abstracts. Articles meeting initial screening criteria by either reviewer proceeded to level 2 screening. During level 2 screening, two reviewers (IJ or JC or SZ) examined full texts of the retrieved articles. Discrepancies were resolved via discussion until the reviewers reached consensus.

Data extraction

A reviewer (JC and SZ) extracted data from eligible studies into Microsoft Excel 365 (Microsoft Corp., Redmond, WA, US) worksheets, and the other (JC or SZ) verified their colleague's results. Reviewers were not blinded to the article authors' or journals' names when extracting data. For each study, we extracted data on the results and important features such as the design, population examined, sample size, participants' age, how the physical activity timing variables were measured and classified, and intervention characteristics. When the results of more than one regression model were reported, the results from the most fully adjusted model were extracted.

Risk of bias and study quality assessment

Risk of bias assessment was completed using methods described in the Cochrane Handbook[18]. These assessments were completed by one reviewer (JC or SZ) and verified by another (IJ). The quality of evidence for each health outcome was determined systematically using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework[19]. GRADE categorizes the quality of evidence into "high," "moderate," "low" and "very low." The rating starts at "high" for randomized studies and at "low" for all other studies (e.g. observational studies, nonrandomized trials). The quality of evidence can be downgraded one or two levels if there are serious limitations across studies, for example, serious risk of bias, inconsistency of effects, indirectness or imprecision. The quality of evidence can be upgraded one level if there is no cause for downgrading, that is, there are no serious limitations, and there is a large magnitude of effect or evidence of a dose–response relationship[19].

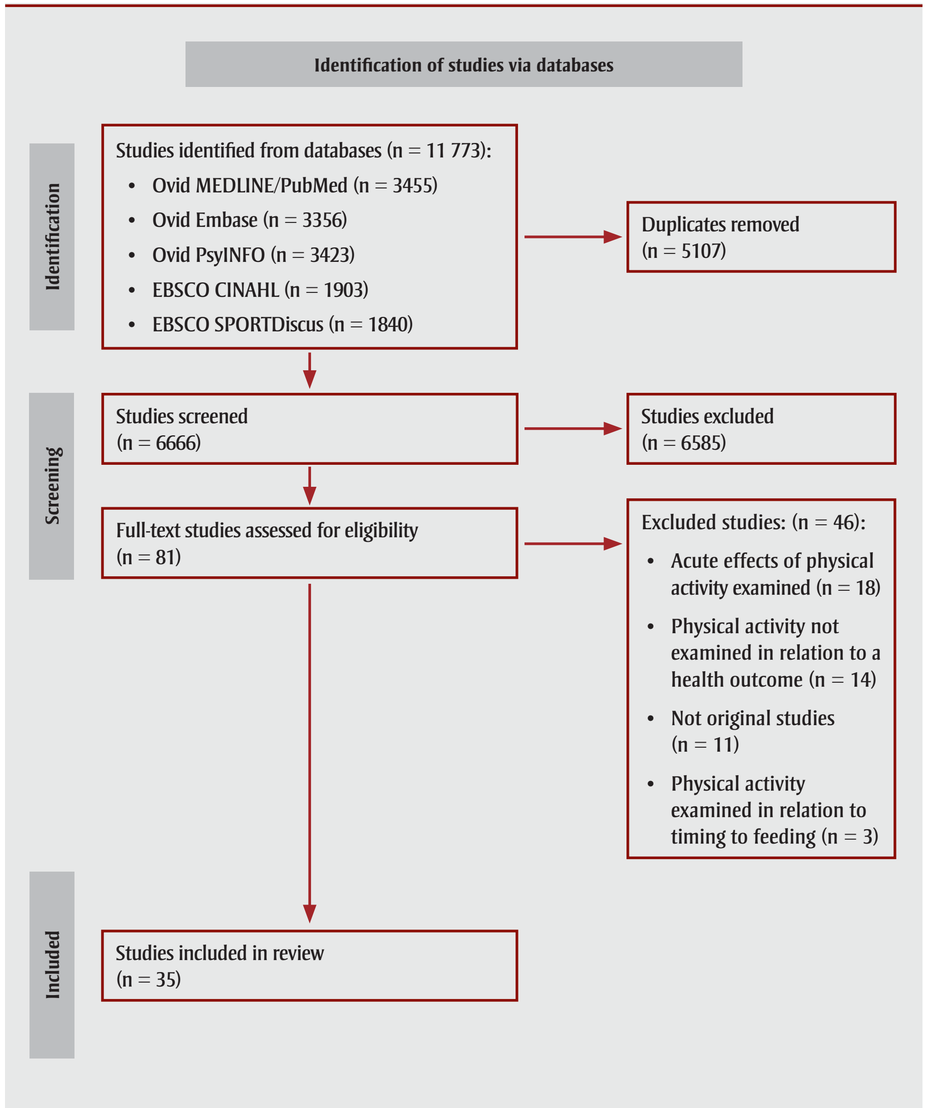
Results

Description of studies

A total of 11 773 studies were identified (PubMed, n = 3455; EMBASE, n = 3356; PsycINFO, n = 3423; CINAHL, n = 1903; SPORTDiscus, n = 1840). After removal of duplicates, 6666 unique studies remained. Eighty-one studies passed level 1 screening and 35 passed level 2 screening for inclusion in the systematic review. Studies were excluded because they examined the acute effects of exercise (n = 18); they did not examine the timing of physical activity in relation to a health outcome (n = 14); they were not primary research studies (n = 11); and they examined the timing of physical activity in relation to feeding (e.g. meal, dietary supplement) (n = 3).

The PRISMA diagram[15] is in Figure 1.

FIGURE 1
PRISMA statement 2020 flow diagram[15] of the identification, screening, eligibility and inclusion of studies in this systematic review



Abbreviation: PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

Characteristics and results of the 35 studies included in this review are in Supplementary Tables S1–S9, and risk of bias assessments of individual studies are in Tables S10–S18 (https://osf.io/qcw6j/?view_only=4130e81638684feaa2dfa74f5e589d58). Tables S1–S9 and S10–S18 are organized according to health outcome: sleep health (Tables S1 and S10), adiposity (Tables S2 and S11), fat-free mass and muscle size (Tables S3 and S12), cardiometabolic biomarkers (Tables S4 and S13), risk of cardiovascular disease (Tables S5 and S14), risk of cancer (Tables S6 and S15), physical function and mobility (Table S7 and S16), mental health (Tables S8 and S17) and risk of mortality (Tables S9 and S18). Several studies presented data for outcomes that covered two or more of these categories.

The samples in the 35 studies ranged from a small convenience sample of 11 to a large and diverse sample of 9952. Two studies examined children and youth while the remainder examined adults. Data across studies involved a total of 17259 participants. Eight studies were randomized controlled trials (RCTs), 2 were randomized crossover studies, 5 were randomized studies without a control group, 4 were nonrandomized trials, 1 used a prospective cohort design, 5 were case–control studies and 10 were cross-sectional studies.

In the 17 observational studies, physical activity timing was assessed using self-reported methods in 6 studies and device-based measures in 11 studies. Three approaches were used to assess or categorize physical activity timing: 8 studies measured the amount of physical activity accumulated during different time intervals (e.g. minutes of MVPA accumulated in the morning, afternoon and evening); 6 studies categorized participants according to the time of day they typically exercised (e.g. non-exercisers or morning, afternoon or evening exercisers); and 3 studies looked at changes in MVPA patterns across the day (e.g. low activity in day but active in the evening, active in the day but inactive in the evening, etc.).

The exercise interventions lasted between 2 weeks and 10 months; 11/19 studies had a 12-week intervention. One study prescribed light-intensity physical activity and 1 study prescribed high-intensity interval training; the others prescribed MVPA. Seven interventions prescribed aerobic exercise, 3 prescribed resistance exercise, 3 prescribed both aerobic and resistance exercise and the remainder prescribed multimodal exercise programs. Six interventions compared morning versus afternoon exercise, 7 compared morning versus evening exercise, 2 compared morning versus afternoon versus evening exercise and 1 compared exercise completed either prior to or within 4 hours of bedtime.

Data synthesis

Meta-analyses could not be performed because of the heterogeneity in study design, measurement and classification of physical activity for observational studies, type and duration of exercise prescribed for interventions and type of statistical analyses used. We therefore present our results as narrative syntheses.

The process of conducting the narrative synthesis included: (1) constructing a method to abstract relevant study details and findings; (2) grouping studies based on health outcomes, study design and physical activity measures and timing classification; (3) tabulating positive, negative and null associations for these groupings; and (4) exploring whether study design, age or sex were moderator variables. Within the narrative syntheses, the term “mixed results” describes situations where there was a combination of null findings, findings that favoured morning physical activity and findings that favoured afternoon or evening physical activity. Results are consistent across age and sex unless otherwise stated.

Physical activity timing and sleep health

Five studies examined relationships between physical activity timing and measures of sleep health: a randomized crossover study[20], a randomized trial without a control group[21], a nonrandomized trial[22] and 2 cross-sectional studies[23,24] (Table S1; https://osf.io/qcw6j/?view_only=4130e81638684feaa2dfa74f5e589d58). Sleep health measures examined included sleep duration, sleep quality, sleep onset latency, wake after sleep onset, sleep efficiency, sleep fragmentation, sleep satisfaction and feeling refreshed or fatigued after awakening.

Mixed results were observed across these studies. One experimental study reported that evening exercise led to greater improvement in sleep onset latency and sleep satisfaction than morning exercise[21]. Conversely, 2 studies reported an association between physical activity in the morning[23] or at least 4 hours before bedtime[22] with better sleep health outcomes compared to when physical activity is performed later in the day. In 2 studies, physical activity timing was not associated with sleep health[20,24].

The quality of evidence was very low for all study designs (Table 1) because of concerns related to bias, inconsistency and imprecision, with no evidence of large effects or dose–response relationships.

Physical activity timing and adiposity

Three RCTs[25-27], 2 nonrandomized trials[9,28] and 4 cross-sectional studies[29-32] examined the relationship between physical activity timing and adiposity (Table S2; https://osf.io/qcw6j/?view_only=4130e81638684feaa2dfa74f5e589d58). A variety of adiposity measures were examined including body mass index (BMI), waist circumference, body fat and trunk fat.

Results were mixed. One RCT reported that participants who performed more exercise in the morning had greater reductions in body fat than participants who performed more exercise in the late afternoon[26]. The other 2 RCTs reported no differences in adiposity in the morning and evening exercise groups[25,27]. The 2 nonrandomized trials reported that morning exercise resulted in smaller improvements to body fat than afternoon or evening exercise[9,28]. Two of the cross-sectional studies observed that morning physical activity was more strongly associated with obesity than physical activity at other times[29,30]. The other 2 cross-sectional studies mostly observed that the timing of physical activity was not associated with adiposity[31,32].

The quality of evidence was very low across study designs (Table 1). There were concerns related to bias, inconsistency (randomized trials and observational studies only) and imprecision (randomized and nonrandomized trials only), with no evidence of large magnitude of effect or dose–response relationships.

Physical activity and fat-free mass and muscle size

Eight studies examined the relationship between physical activity timing and measures of fat-free mass and muscle size: 5 RCTs[25-27,33,34], 2 nonrandomized trials[10,35] and 1 cross-sectional study[31] (Table S3; https://osf.io/qcw6j/?view_only=4130e81638684feaa2dfa74f5e589d58). The interventions consisted of resistance training[27,33,34], aerobic training[25,26] or a combination of resistance and aerobic training[10,35]. The results of the cross-sectional study[31] and 5/7 experimental studies[10,25,26,33,34] suggest that the timing of physical activity is not associated with measures of fat-free mass and muscle size. In the remaining 2/7 experimental studies, one reported that morning exercise results in greater changes in muscle size than evening exercise[27], while the other reported the opposite[35].

The quality of evidence was very low across study designs (Table 1). There were concerns related to bias, inconsistency (randomized and nonrandomized trials only) and imprecision, with no evidence of large effects or dose–response relationships.

Physical activity timing and cardiometabolic biomarkers

Eight studies examined the relationship between physical activity timing and cardiometabolic biomarkers[10,25,27,36-40], including measures of glucose and insulin homeostasis, plasma lipids and lipoproteins, blood pressure, inflammatory markers and other hormones (e.g. testosterone, cortisol) (Table S4; https://osf.io/qcw6j/?view_onl_y=4130e81638684feaa2dfa74f5e589d58). All 8 studies used an experimental design; 4 used either an RCT[25,27,37] or randomized crossover[36] design. Of these 8 studies, 7 prescribed a 12-week intervention[10,25,27,37-40].

The studies examined a variety of exercise modalities: aerobic exercise[25,37,38], resistance exercise[27], combined aerobic and resistance exercise[10,39,40] and high-intensity interval training[36]. Mixed results were observed across these 8 studies. Four reported that the timing of exercise training did not influence changes in cardiometabolic biomarkers[25,27,39,40]. Three reported that training in the morning resulted in less favourable changes in cardiometabolic biomarkers than training the evening[36-38], while one study reported the opposite[10].

The quality of evidence was very low for both the randomized trials and the nonrandomized trial (Table 1). For the randomized trials, there was a moderate concern of inconsistency and a high concern of imprecision. For the nonrandomized trial, there was a moderate concern of imprecision. There was no evidence of

TABLE 1
Quality assessment and quality of evidence rating based on studies examining the relationship between physical activity timing and health

Health outcome	Study design	No. of studies	No. of participants[a]	Quality assessment indicator						Quality
				Risk of bias	Inconsistency	Indirectness	Imprecision	Large magnitude of effect	Dose response	
Sleep	Randomized trials	3	174	Moderate risk	High inconsistency	No indirectness	Moderate imprecision	No evidence	No evidence	Very low
	Observational studies	2	1223	High risk	Moderate inconsistency	No indirectness	Moderate imprecision	No evidence	No evidence	Very low
Adiposity	Randomized trials	3	135	Moderate risk	Moderate inconsistency	No indirectness	Moderate imprecision	No evidence	No evidence	Very low
	Nonrandomized trials	2	51	High risk	No inconsistency	No indirectness	Moderate imprecision	No evidence	No evidence	Very low
	Observational studies	4	8427	High risk	Moderate inconsistency	No indirectness	No imprecision	No evidence	No evidence	Very low
Fat-free mass and muscle size	Randomized trials	5	183	Moderate risk	Moderate inconsistency	No indirectness	High imprecision	No evidence	No evidence	Very low
	Nonrandomized trials	2	84	High risk	Moderate inconsistency	No indirectness	Moderate imprecision	No evidence	No evidence	Very low
	Observational studies	1	263	High risk	No inconsistency	No indirectness	Moderate imprecision	No evidence	No evidence	Very low
Cardiometabolic biomarkers	Randomized trials	8	437	Moderate risk	Moderate inconsistency	No indirectness	High imprecision	No evidence	No evidence	Very low
	Nonrandomized trials	1	32	High risk	No inconsistency	No indirectness	Moderate imprecision	No evidence	No evidence	Very low
Risk of cardiovascular disease	Observational studies	4	1922	High risk	High inconsistency	No indirectness	Moderate imprecision	No evidence	No evidence	Very low
Risk of cancer	Cross-sectional	1	2795	High risk	No inconsistency	No indirectness	High imprecision	No evidence	No evidence	Very low
Physical function	Randomized trials	1	31	Moderate risk	No inconsistency	No indirectness	High imprecision	No evidence	No evidence	Very low
	Nonrandomized trials	1	29	High risk	No inconsistency	No indirectness	High imprecision	No evidence	No evidence	Very low
	Observational studies	3	1605	High risk	Moderate inconsistency	No indirectness	No imprecision	No evidence	No evidence	Very low
Mental health	Randomized trials	2	118	High risk	Moderate inconsistency	No indirectness	Moderate imprecision	No evidence	No evidence	Very low
	Observational studies	1	92	Moderate risk	No inconsistency	No indirectness	Unclear	No evidence	No evidence	Very low
Risk of mortality	Observational studies	1	2978	Moderate risk	No inconsistency	No indirectness	No imprecision	No evidence	No evidence	Very low

[a] The total exceeds the actual total number of participants due to overlap across some of the studies.

a large magnitude of effect or dose–response relationships.

Physical activity timing and risk of cardiovascular disease

Three case–control studies[11,41,42] and 1 cross-sectional study[43] examined the association between physical activity timing and cardiovascular disease (Table S5; https://osf.io/qcw6j/?view_only=4130e81638684feaa2dfa74f5e589d58). One examined children and adolescents[42], while the others examined adults[11,41,43]. One study examined high cardiovascular disease risk (i.e. 10-year cardiovascular disease risk prediction)[43], while the others examined cardiovascular disease end points[11,41,42].

Mixed results were observed across these 4 studies. The first case–control study reported that sports performed in the morning and evening but not afternoon were associated with a reduced odds of acute myocardial infarction[11]. The second case–control study reported that physical activity in the late afternoon (15:00–18:00), but not during the school day or evening, was associated with heart disease[42]. The third case–control study found that the reduced odds of coronary artery disease was similar irrespective of the typical time of day of exercise[41]. Finally, the cross-sectional study reported that higher cardiovascular risk was associated with a lack of physical activity in the afternoon and evening but in not the morning[43].

The quality of evidence was rated as very low as there were high concerns related to bias and inconsistency and moderate concerns related to imprecision (Table 1).

Physical activity timing and risk of cancer

A single prospective cohort study examined the association between physical activity timing and cancer[12] (Table S6; https://osf.io/qcw6j/?view_only=4130e81638684feaa2dfa74f5e589d58). This study looked at prostate cancer in men and breast cancer in women. No significant protective effects were observed for early morning, late morning or afternoon physical activity.

The quality of evidence was rated as very low (Table 1) as there was a high risk of bias and imprecision with no evidence of a large magnitude of effect or dose–response relationship.

Physical activity timing and physical function and mobility

Five studies examined the relationship between physical activity timing and measures of physical function and mobility[9,27,44-46] (Table S7; https://osf.io/qcw6j/?view_only=4130e81638684feaa2dfa74f5e589d58). Three studies examined direct measures of function (e.g. walking speed, functional mobility)[9,27,45], one examined falls[44] and one examined frailty[46]. Four of these studies were cross-sectional[27,44-46], and the fifth was a nonrandomized trial[9].

The results of 3/5 studies suggest that while physical activity is associated with better physical function outcomes, the timing of physical activity is not relevant[27,44,45]. One cross-sectional study indicated that less physical activity in morning through afternoon, but not evening, was associated with frailty[46]. Conversely, walking test scores in the nonrandomized trial improved more in evening exercisers than morning exercisers[9].

The quality of evidence was rated as very low across study designs (Table 1). There were concerns related to bias for all study designs, to inconsistency for observational studies and to imprecision for the randomized and nonrandomized trials. There was no evidence of a large magnitude of effect or dose–response relationships.

Physical activity timing and mental health

Three studies examined the association between physical activity timing and mental health[47-49] (Table S9; https://osf.io/qcw6j/?view_only=4130e81638684feaa2dfa74f5e589d58). In a 12-week RCT of older adults, afternoon exercise was more effective than morning exercise at improving cognitive function and mood[47]. In a 12-week nonrandomized trial of retired elite athletes with depression, morning and evening exercise led to comparable improvement in mood state[48]. In a case–control study of patients with Alzheimer disease and older adult controls, the altered physical activity levels in the patient group were most pronounced in the morning[49].

The quality of evidence was rated as very low for both the randomized trials and case–control study (Table 1). For the randomized trials, there was a high concern of bias and a moderate concern of inconsistency and imprecision. For the case–control study there was a moderate concern of bias. There was no evidence of a large magnitude of effect or dose–responses relationships.

Physical activity timing and risk of mortality

A single study that used a prospective cohort design in 50- to 85-year-olds examined the association between physical activity timing and risk of mortality[50] (Table S10; https://osf.io/qcw6j/?view_only=4130e81638684feaa2dfa74f5e589d58). The authors used accelerometers to measure physical activity over 7 days and examined whether average daily physical activity performed in each of 12 two-hour time intervals contributed to an all-cause mortality prediction model[50]. The prediction model also contained total physical activity and several sociodemographic, behavioural and health variables. None of the activity counts for the 12 two-hour time intervals reached statistical significance in the model.

The quality of evidence was rated as very low (Table 1). There was a moderate risk of bias without evidence of a large magnitude of effect or a dose–response relationship.

Discussion

This review was prompted by evolving public health recommendations for physical activity and the desire to understand if the timing of physical activity within the day may be a consideration in future recommendations. We synthesized evidence from 35 peer-review studies of over 15 000 unique participants that examined the relationship between the timing of physical activity within the day and indicators of health. Across the 35 studies, participant characteristics, study design and physical activity characteristics varied tremendously. A summary of findings is presented in Table 2.

There is no consistent evidence that physical activity performed at one time of day provides more favourable health benefits than that performed at a different time of day. Although the results of 11 of the reviewed studies (31%) suggest that physical activity in the morning provides greater health benefits than physical activity in the afternoon or evening, the results of 12 of the reviewed studies (37%) suggest that physical activity in the morning provides fewer health benefits than physical activity later in the day. The remaining studies found no clear difference in health outcomes based on the timing of physical activity. This pattern of mixed findings was observed for all 9 health outcome categories.

To the best of our knowledge, this is the first review to examine the relationship between physical activity timing within the 24-hour day and health outcomes. Previous systematic reviews have considered the timing of exercise around food intake (e.g. meals, nutritional supplements) as well as whether exercise performance varies according to the time of day when the exercise is performed. One recent systematic review concluded that exercise performed post-meal has a greater impact on postprandial glycemia than exercise performed pre-meal[51]. Another review and meta-analysis of protein timing around resistance exercise concluded that consuming adequate protein in combination with resistance exercise is key to maximizing gains in muscle size, but the timing of protein intake around the training session does not significantly influence these gains[52]. Other reviews concluded that performance in aerobic and anaerobic exercises is highest in the late afternoon to early evening[53,54].

Strengths and limitations

Several gaps and limitations exist in the studies included in this review. Most

TABLE 2
High-level summary of findings by health outcome

Health outcome	No. of studies	No. of participants	Quality of evidence	Summary of findings
Sleep health	5	1397	Very low	Timing of physical activity not important in 2 studies Morning or afternoon physical activity favoured in 2 studies Evening physical activity favoured in 1 study
Adiposity	9	8613	Very low	Timing of physical activity not important in 4 studies Morning physical activity favoured in 3 studies Afternoon or evening physical activity favoured in 2 studies
Fat-free mass and muscle size	8	530	Very low	Timing of physical activity not important in 6 studies Morning physical activity favoured in 1 study Evening physical activity favoured in 1 study
Cardiometabolic biomarkers	8	469	Very low	Timing of physical activity not important in 4 studies Morning physical activity favoured in 1 study Evening physical activity favoured in 3 studies
Risk of cardiovascular disease	4	1922	Very low	Timing of physical activity not important in 2 studies Morning physical activity favoured in 1 study Afternoon physical activity favoured in 1 study
Risk of cancer	1	2795	Very low	Timing of physical activity not important in 1 study
Physical function and mobility	5	1665	Very low	Timing of physical activity not important in 3 studies Morning physical activity favoured in 1 study Afternoon physical activity favoured in 1 study
Mental health	3	210	Very low	Timing of physical activity not important in 1 study Morning physical activity favoured in 1 study Afternoon physical activity favoured in 1 study
Risk of mortality	1	2978	Very low	12:00–2:00 physical activity most favourable

studies focussed on MVPA and only one examined light physical activity[21]. The number of studies was small (1 to 9) for the 9 health outcomes where there was at least some evidence, and nonexistent for all other health outcomes. Almost half (47%) of the interventions lacked a control group and/or were nonrandomized. Furthermore, most interventions had small sample sizes (typically <20 per treatment arm) and were underpowered to detect small effects. Many of the observational studies also lacked precision.

It was difficult to examine dose–response relationships because the timing was often examined over broad time spans (e.g. all morning hours versus all evening hours). Studies in this topic area have also not considered whether the findings are modified by physical activity characteristics (e.g. type, intensity, dose) and sociodemographic characteristics (e.g. age, sex, race/ethnicity). Future studies should examine the timing of physical activity using a compositional data analysis approach that considers physical activity across the full 24-hour day[17].

A notable strength of this systematic review is its comprehensive search strategy, with all study designs, all health outcomes and all populations included. A primary limitation is that the evidence was of very low quality because of concerns to do with bias, a lack of consistent findings and imprecise findings. Because this systematic review was limited to peer-reviewed studies, it is susceptible to publication bias because null findings are less likely to be published[55]. This review was also limited to English and French language papers; however, a recent analysis indicates that excluding non-English publications from evidence syntheses did not change the conclusions[56].

Conclusion

The results of 35 studies examining the association between physical activity and health outcomes are mixed. The findings, which are based on very low quality evidence, do not consistently support that it would healthier to be physically active at one time of day over another. People should be encouraged to be active when it is most convenient for them.

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Registration of the protocol

PROSPERO registration no. CRD42021231088, available from www.crd.york.ac.uk/PROSPERO/.

Conflicts of interest

The authors have no conflicts to declare.

Authors' contributions and statement

JC came up with the idea for the systematic review with input from IJ, TJS and JT.

IJ designed the systematic review with input from all other authors.

IJ, JC and SZ performed literature searches, article screening, data abstraction, risk of bias assessments and quality of evidence assessments.

IJ wrote the first draft of the manuscript; this was edited for important intellectual content by all other authors.

The content and views expressed in this article are those of the authors and do not necessarily reflect those of the Government of Canada.

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Evidence synthesis

Timing of sedentary behaviour and access to sedentary activities in the bedroom and their association with sleep quality and duration in children and youth: a systematic review

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Abstract

Background: The purpose of this study was to systematically review the relationship between the timing of sedentary behaviours and access to sedentary activities in the bedroom with sleep duration and quality in children and youth. A secondary purpose was to examine whether these relationships differ when comparing screen-based and non-screen-based sedentary activities.

Methods: We searched four databases for peer-reviewed studies published between 1 January 2010 and 19 January 2021. Risk of bias assessment for each study and certainty of evidence were assessed using the GRADE framework.

Results: We identified 44 eligible papers reporting data from 42 separate datasets and including 239 267 participants. Evening participation in screen-based sedentary behaviours and access to screen-based devices in the bedroom were associated with reduced sleep duration and quality. Daytime screen use was also associated with reduced sleep duration, although this was examined in relatively few studies. Whether performed during the day or night, non-screen-based sedentary behaviours were not consistently associated with sleep duration or quality. The quality of evidence was rated as low to very low for all outcomes.

Conclusion: In order to maximize sleep duration and quality, children and youth should be encouraged to minimize screen time in the evening and remove screens from bedrooms. (PROSPERO registration no.: CRD42020189082)

Keywords: *sedentary behaviour, screen time, sleep duration, sleep quality, timing, systematic review, youth, public health*

Highlights

- Using screen-based devices in the evening and access to screen-based devices in the bedroom were associated with reduced sleep duration and quality.
- Findings were based primarily on observational studies, using self-report methodologies.
- Children and youth should be encouraged to minimize the use of screen-based devices before bed and remove screens from bedrooms.

Introduction

Sedentary behaviours (waking behaviours characterized by an energy expenditure of 1.5 or less metabolic equivalents while in a sitting, reclining or lying posture)[1] are linked with numerous important health outcomes among school-aged children and youth.[2] While screen-based sedentary behaviours are often associated with detrimental health outcomes, non-screen-based sedentary behaviours such as reading typically show null or even beneficial associations with health.[3,4]

In a 2016 systematic review of 235 studies, Carson et al.[4] reported that higher durations and frequencies of screen time were associated with unfavourable body composition, behavioural conduct, fitness, self-esteem and clustered cardiometabolic risk. In contrast, reading and homework were positively associated with academic achievement.[4] Other recent systematic reviews and meta-analyses report that higher levels of screen-based sedentary behaviours are also associated with increased risk of depression,[5,6] although questions remain regarding the magnitude of this relationship.[7]

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Inadequate sleep duration and quality likely mediate the relationship between screen-based sedentary behaviour and health outcomes.[8] Longer sleep duration is associated with favourable body composition, emotional regulation, academic achievement and quality of life.[9] A systematic review reported that 90% of studies examined found that screen time is associated with poor sleep outcomes (primarily shorter and delayed sleep) among children and youth.[10] Reductions in total daily screen time are also associated with small increases in sleep duration among children and youth.[11]

A number of mechanisms have been suggested to explain these associations, the most obvious being time displacement; more time using screens means less time for other behaviours, including sleep.[10,12] Other mechanisms include increased arousal and negative effects on circadian rhythms.[10,13] Limited evidence has also suggested that interactive screen time (e.g. using a computer, smartphone or video game console) is more consistently associated with poor sleep than more passive forms of screen time (e.g. television viewing).[10]

Based on these suggested mechanisms, it is plausible that the timing of screen-based sedentary behaviours may have a greater impact on sleep than total daily volume. A meta-analysis by Carter et al.[14] reported a strong and consistent association between bedtime use of smartphones and tablets with deleterious sleep quantity (odds ratio [OR] = 2.17; 95% confidence interval [CI]: 1.42–3.32) and quality (OR = 1.46; 95% CI: 1.14–1.88). Not surprisingly, it is common to recommend that children and youth avoid screens in the hour(s) before bed and limit using screen-based devices in the bedroom.[10,13,15,16]

While this evidence suggests that the timing of sedentary behaviour may be associated with sleep quality and duration, several key questions remain. Although previous reviews have examined the impact of screen use in the bedroom, or immediately preceding sleep, to date none have compared this with the impact of screen use during other periods of the day or with the impact of non-screen-based sedentary behaviours during these same periods. It is therefore unclear whether the relationship between evening screen use and sleep differs markedly from that of daytime screen use. It is also unclear whether non-screen-based sedentary behaviour such as reading a book or doing paper-based homework show similar or different associations with sleep. These are important research gaps, as they preclude specific public health recommendations related to sedentary behaviour and sleep.

The purpose of this study was to systematically review the relationship between the timing of sedentary behaviours and access to sedentary activities in the bedroom with sleep duration and quality in children and youth. A secondary purpose was to examine whether these relationships differ based on the mode of sedentary behaviour (i.e. screen based and non-screen based).

Methods

Protocol and registration

This systematic review was registered with the International Prospective Register of Systematic Reviews (PROSPERO; Registration no. CRD42020189082) and conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.[17] Methods are presented below using the Population, Intervention/Exposure, Comparison/Control and Outcome (PICO) framework.

Eligibility criteria

Population

The population of interest was apparently healthy children and youth aged 5 to 17.99 years. Studies with participants outside of this age range were included if participants aged 5 to 17.99 were reported separately or if the mean age fell within this range. Studies exclusively targeting disease-specific populations (e.g. children with diabetes, children with congenital heart defects) or patients with sleep disorders were excluded.

Intervention/exposure

The intervention or exposure was the timing of sedentary behaviour as well as access to both screen-based and non-screen-based sedentary activities in the bedroom. Sedentary behaviours were defined as any waking behaviour characterized by low energy expenditure and a sitting, reclining or lying posture.[1] This included measures of time spent sitting as well as screen-based sedentary behaviours (e.g. watching TV, playing video games, accessing social media, reading an ebook) and non-screen-based sedentary behaviours (e.g. reading a print book, listening to music, playing board games).

Sedentary behaviour timing refers to the time of day that sedentary behaviours occur. The timing may be reported as time of day or time relative to bedtime. Studies were eligible if they included device-measured (e.g. using an inclinometer, actigraph unit/accelerometer) or self-reported (e.g. questionnaire) measures of sedentary behaviour timing or both. Studies were also included if they reported the presence of objects used to engage in screen-based or non-screen-based sedentary activities in the bedroom. For experimental studies, the interventions must have targeted sedentary behaviour timing or presence of sedentary activities exclusively and not multiple health behaviours (e.g. both sedentary behaviour and diet or sedentary behaviour and physical activity).

Comparison/control

Various levels of sedentary behaviour timing/access to sedentary activities in the bedroom were used for comparison. However, a comparator or control group was not required for inclusion.

Outcomes

This systematic review had two outcomes: sleep duration (e.g. hours per night, hours per 24-hour period), and sleep quality, which included the following measures: sleep onset latency, sleep efficiency (% of time in bed spent sleeping), waking after sleep onset, waking up too early, sleeping restlessly, difficulty falling asleep, insomnia symptoms and overall sleep quality.

Study designs

All study designs, except case studies, were eligible for inclusion, but only published or in-press English or French language peer-reviewed studies were eligible; all grey literature (e.g. book chapters, dissertations, conference abstracts) were excluded. For longitudinal studies, any length of follow-up was allowed, but there must have been at least one measure of sleep timing at 5 to 17 years of age. Because we initially identified a large number of small cross-sectional studies, we set the minimum sample size for cross-sectional studies to 1000 midway through the review. This threshold is consistent with previous systematic reviews in this field.[9] There were no sample size limitations for longitudinal or experimental studies.

Information sources and search strategy

A comprehensive search strategy was developed by a research librarian (AR-W). Four bibliographic databases were searched: Ovid MEDLINE, Ovid Embase, Ovid PsycINFO and EBSCO Cumulative Index to Nursing & Allied Health Literature (CINAHL). Searches were conducted on 19 January 2021. All studies had to have been published on or since 1 January 2010; these dates were chosen to manage scope and to focus on the most recent body of evidence.

The search strategy is shown in Supplementary Table 1 (https://osf.io/q7wes/?view_only=420496c898b740f988e9077c3a9010e1).

We also searched the reference lists of all review studies identified during level 2 screening for additional relevant studies.

Data extraction

To remove duplicates, bibliographic records were extracted and imported into EndNote software (Clarivate, Philadelphia, PA, US). During level 1 screening, two reviewers (any combination of JC, TM, SP or TJS), working independently, screened titles and abstracts of potentially relevant articles using Covidence (Veritas Health Innovation, Melbourne, AU). We obtained full-text copies of the articles that met initial screening criteria. During level 2 screening, two reviewers (any combination of JC, TM, SP, KD or TJS), working independently, examined all the full-text articles. Any discrepancies were resolved via discussion until consensus was reached.

A reviewer (TM) extracted the relevant data using a customized Google Form, and another (TJS) verified the data. Authors' and journal names were not blinded when the reviewers were extracting data. The extracted information included descriptive study characteristics (e.g. author, publication year, study design, country, sample size, age, sex), intervention/exposure, outcome(s), results and confounders. Where studies reported multiple models, the reviewers extracted results from the most fully adjusted model, including both the direction and statistical significance of any associations.

Risk of bias and study quality assessment

Using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework,[18] we systematically examined the quality of primary research contributing to each health indicator and assessed the overall quality and risk of bias of the evidence across health indicators. We completed the risk of bias assessment for individual intervention studies according to methods described in the Cochrane Handbook.[19] GRADE does not have a tool for assessing risk of bias in observational studies, but does recommend the types of characteristics to examine.[18] For individual observational studies, we assessed selection bias, performance bias, selective reporting bias, detection bias, attrition bias and other biases (e.g. inadequate control for key confounders). Risk of bias for individual studies was assessed by one reviewer (TM) and verified by another (TJS). According to the GRADE framework, randomized controlled trials start with a quality of evidence rating of "high"; all other designs start at a rating of "low."[18] The quality of evidence can be downgraded if there are limitations across studies as a result of risk of bias (operationalized as ≥50% of studies showing high risk of bias for a given outcome), inconsistency, indirectness, imprecision or other factors.[18] The quality can be upgraded if there are no serious limitations, as well as a large magnitude of effect or evidence of a dose–response relationship.[18]

Results

Description of studies

A total of 3548 studies were identified through database searches, leaving 2999 after duplicates were removed. After title and abstract screening, 803 papers underwent full-text review. Of these, 42 met all inclusion criteria. Searching the reference lists of all reviews identified at level 2 screening identified 132 potentially relevant papers, of which 2 met the inclusion criteria. This left a total of 44 papers, reporting on 42 individual datasets. (See Figure 1 for the PRISMA flow diagram[17].)

The most common reasons for excluding an article at level 1 full-text screening was that the study failed to measure or report sedentary behaviour timing (n = 290), it was a conference abstract (n = 154) or that it examined ineligible populations (n = 110). Forty-three cross-sectional studies that met other inclusion criteria were excluded because the sample size was less than 1000. A list of reasons for excluding individual papers is in Supplementary Table 2 (https://osf.io/q7wes/?view_only=420496c898b740f988e9077c3a9010e1). Quality of evidence for each outcome are presented in Table 1, and a high-level summary of findings is presented in Table 2.

Characteristics of the individual studies included in this review are in Supplementary Tables 3–6 and risk of bias assessments of individual studies are in Supplementary Tables 7–10 (https://osf.io/q7wes/?view_only=420496c898b740f988e9077c3a9010e1). We identified 28 cross-sectional studies, 6 longitudinal studies lasting between 1 and 3 years, and 8 nonrandomized intervention studies lasting 1 to 14 days.

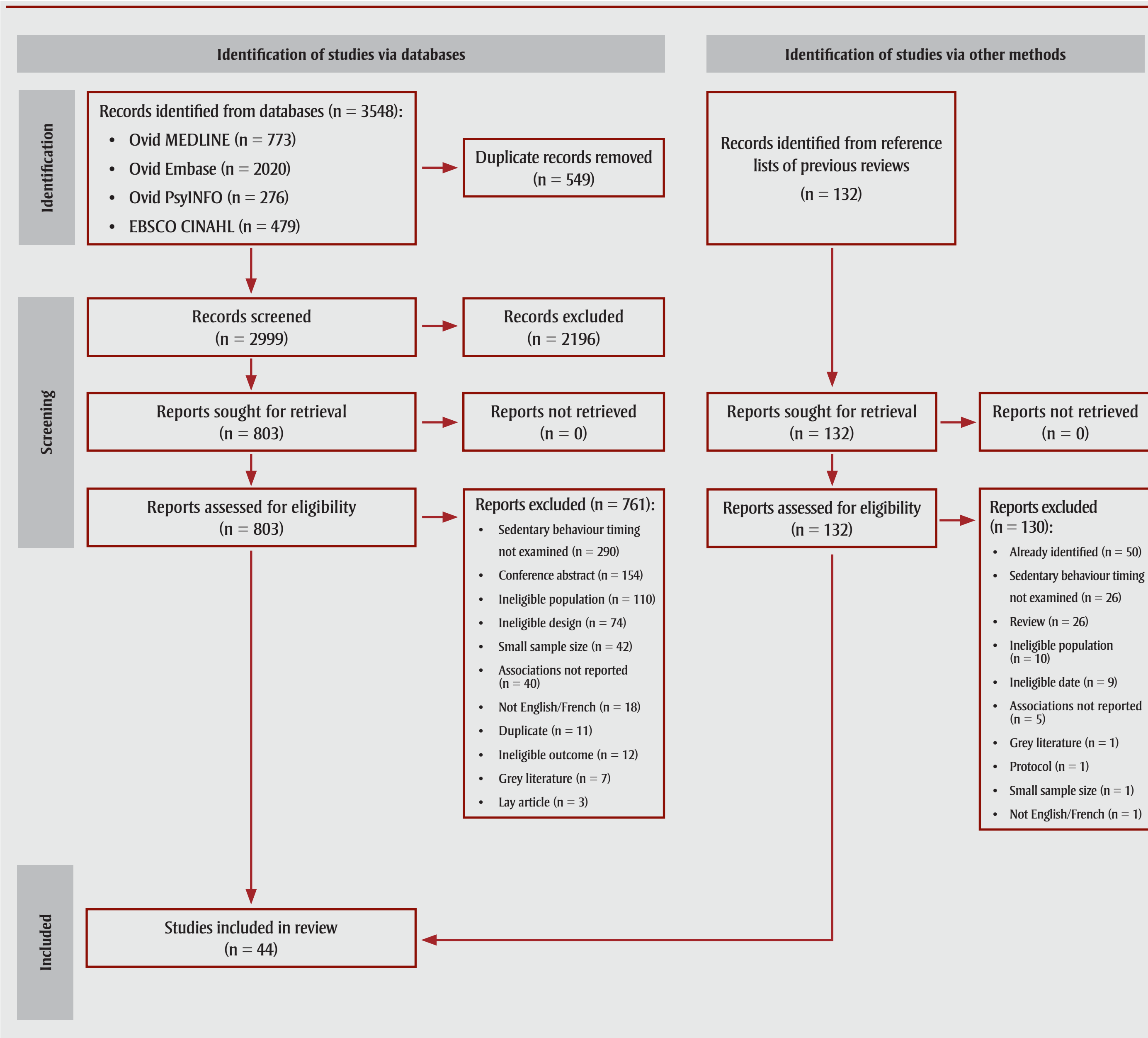
Sedentary behaviour was self- or parent-reported in 36 studies, device-measured in 1 study, and intervened upon by the research team in 5 nonrandomized intervention studies. Sleep duration and quality were device-measured in 7 of the 8 intervention studies and 1 of the 34 observational studies. Sedentary behaviour timing was categorized in a variety of ways across studies, including "morning," "after school," "dinner time," "after dinner," "before bedtime/sleep," "at night," "before and/or after lights out," "last hour before bed" and "in bed," as well as the specific time of use/last use. For this review, "morning," "after school" and "dinner time" were considered daytime, and all other time points, evening.

Thirty-one studies examined the impact of sedentary behaviour timing, while 16 studies examined the impact of sedentary behaviours in the bedroom (5 studies included both). Sleep duration was assessed in 34 studies, and sleep quality in 23, with 16 studies examining both eligible outcomes. Across all studies, there were 239267 participants from 23 countries. Mean ages ranged from 5.3 to 17.4 years.

Data synthesis

Because the heterogeneity in study design, measurement of sedentary behaviour and

FIGURE 1
PRISMA 2020 flow diagram[17] of search and inclusion of studies in this systematic review



Abbreviation: PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

sleep, and statistical analyses precluding the use of meta-analyses, we present our results as a narrative synthesis.

Sedentary behaviour timing and sleep duration

Four nonrandomized intervention studies[20-23] examined the relationship between sedentary behaviour timing and sleep duration. One 2-week-long intervention reported that reducing total screen time after 9 p.m. increased sleep duration by 17 ± 2 minutes.[20] Another 1-week-long intervention found that reducing mobile phone use in the hour before bed led to sleep lasting 21 minutes longer each night.[21] An intervention lasting a single night reported a negative correlation between video game time and sleep duration ($r = -0.92$; $p < 0.05$),[22] while another single-night intervention reported that playing video games for 150 minutes reduced sleep duration by 27 ± 12 minutes, compared to effects of playing the same game for 50 minutes.[23]

Quality of evidence was rated as very low for these experimental studies because of the lack of randomized trials, concerns related to bias and lack of evidence of large effects or dose–response relationships.

One longitudinal study lasting 3 years reported that, in comparison to those who did not use screens at any time after dinner, those who used screens after dinner had significant reductions in sleep duration (β = −0.10; 95% CI: −0.18, −0.02; $p = 0.01$).[24] However, there was no significant association between changes in screen use after dinner and changes in sleep duration (β = −0.08; 95% CI:

TABLE 1
Quality assessment and quality of evidence rating of studies included in this systematic review

Health outcome	Study design	No. of studies	No. of participants	Quality assessment indicator						Quality
				Risk of bias	Inconsistency	Indirectness	Imprecision	Large magnitude of effect	Dose response	
Sleep duration										
Sedentary timing	Nonrandomized trials	4	71	High risk of selection bias	Low	Low	Low	No	No	Very low
	Observational studies	21	208 801	Low risk of bias	Low	Low	Low	No	No	Low
Presence of sedentary behaviours in bedroom	Nonrandomized trials	0	0	NA	NA	NA	NA	NA	NA	NA
	Observational studies	15	36 711	Low risk of bias	Low	Low	Low	No	No	Low
Sleep quality										
Sedentary timing	Nonrandomized trials	8	361	High risk of selection bias	High	Low	Low	No	No	Very low
	Observational studies	12	154 836	Low risk of bias	Low	Low	Low	No	No	Low
Presence of sedentary behaviours in bedroom	Nonrandomized trials	0	0	NA	NA	NA	NA	NA	NA	NA
	Observational studies	5	11 154	Low risk of bias	Low	Low	Low	No	No	Low

Abbreviations: NA, not applicable; no., number.

−0.16, 0.01; $p = 0.07$). A longitudinal study that lasted 2 years reported that watching TV/using video games before bedtime was associated with reduced sleep duration ($\beta = -0.04$; 95% CI: −0.05, −0.12; $p < 0.05$).[25]

Nineteen cross-sectional studies examined the relationship between sedentary behaviour timing and sleep duration[26-44], 2 of which looked only at daytime sedentary behaviour[39,44]. Evening screen use was negatively associated with sleep in 15/17 studies[26-35,37,40-43], positively associated with sleep in 1/17 study[38], and showed one or more null associations in 5/17 studies[28,36,40-42]. Several studies reported associations for multiple modalities of screen use.

All 3 of the studies that examined daytime screen use reported negative associations with sleep duration.[33,39,44] One study reported that daytime homework/reading was negatively associated with sleep duration[39], while another reported no association[30].

Apart from video game use, the associations between evening screen use and deleterious sleep duration were consistent across devices. The majority of studies reported that sleep duration was negatively associated with evening use of smartphones (8/10 studies)[26-29,33-35,40], total screen time (6/8 studies)[30,33,34,40,42,43], watching TV (5/6 studies)[29,32-34,42], texting/instant messaging (6/6 studies)[27,28,31,35,37,42], using a computer (3/3 studies)[32,33,41] and accessing the Internet (3/3 studies)[28,29,42], but not video games (1/4 studies)[33].

In terms of non-screen-based sedentary behaviours, 1 study reported a positive association between evening homework/

TABLE 2
High-level summary of findings by health outcome

Sleep outcome	No. of studies	No. of participants	Quality of evidence	Summary of findings
Sleep duration	34	233 067	Very low	Evening screen use is negatively associated with sleep duration Reducing evening screen use may increase sleep duration Presence of screen-based devices in the bedroom may be associated with reduced sleep duration
Sleep quality	22	160 686	Low	Evening screen use and presence of screens in the bedroom are negatively associated with sleep quality Reducing evening screen use may increase sleep quality

Abbreviation: No., number.

reading and sleep duration[30], while 2 studies reported no association[29,43]. Listening to music on a phone or MP3 player in the evening was negatively associated with sleep duration in 2/2 studies[28,33], while listening to the radio was not associated with sleep duration in 1/1 studies[41]. Two cross-sectional studies examined the relationship between evening screen use in bed and sleep duration[30,41]. Of these, one reported that adolescents with the lowest self-reported sleep were more likely to report screen use in bed[30]; the other reported that self-reported sleep duration was lower among adolescents who used computers, but not other screen-based devices, in bed "almost every night" or more often[41].

Quality of evidence was rated as low for all observational studies because of the lack of large effects or dose–response relationships.

Access to sedentary activities in the bedroom and sleep duration

Three longitudinal[25,46,47] and 12 cross-sectional[41-45,48-54] studies examined the relationship between access to sedentary activities in the bedroom and sleep duration. The longitudinal studies provided mixed results: Cespedes et al.[45] found that the presence of a TV in the bedroom was associated with reduced sleep duration; King et al.[23] reported no association between bedroom screens and sleep duration; and Nuutinen et al.[46] reported that having a TV in the bedroom was negatively associated with weekend sleep duration among boys, and positively associated with weekend sleep duration among girls, with no significant associations observed between having a TV or computer in the bedroom and weekday sleep in either gender.

In the cross-sectional studies, associations between the use of screens in the bedroom and deleterious sleep duration were observed for computers (3/4 studies)[41,42,44] and all screen-based devices (3/3 studies)[40,42,52], with inconsistent results observed for TV watching (negative association observed for at least one analysis in 5/11 studies)[42,47,50,52,53], playing video games (negative association in 1/2 studies)[42] and using cell phones (negative association in 1/2 studies)[42].

The quality of evidence was rated as low; although bias was not a concern, there was no evidence of large magnitude of effect or dose–response relationships.

Sedentary behaviour timing and sleep quality

Eight nonrandomized intervention studies and 12 observational studies examined the relationship between sedentary behaviour timing and sleep quality. One intervention asked participants to avoid using screens after 9 p.m. on school nights for 2 weeks[20]. Compared to baseline, this intervention resulted in earlier sleep onset on school nights, by 20 minutes, with no change in sleep efficiency[20]. The other interventions lasted one night; they reported significant associations between evening screen use and sleep onset latency (negative in 2/6 studies)[23,54], sleep efficiency (negative in 2/3 studies)[23,55], number of arousals per hour (negative in 1/1 studies)[55] but not waking after sleep onset (0/1 studies)[55].

One intervention study also reported that exposure to violent video games before bed reduced overall sleep quality for those with low exposure to games in daily life (≤1 hour/day), but not for those with high exposure (≥3 hours/day)[56].

Of the 6 interventions investigating device-measured sleep quality[20,22,23,54,55,57], 4 reported negative associations between evening screen use and at least one outcome [20,23,54,55]. The quality of evidence for intervention studies was rated as very low because of the lack of randomized trials, high risk of selection bias and inconsistency of results, with no evidence of large effects or dose–response relationship.

Two longitudinal studies examined the relationship between timing of sedentary behaviour and sleep quality over 1 year[58] and 3 years[59]. Foerster et al.[58] reported that adolescents woken by their phone were more likely to develop restless sleep and problems falling asleep than those who were not woken up by their phone. Similarly, Vernon et al.[59] reported that nighttime phone use was also associated with poor sleep quality.

The relationship between timing and sleep quality was also assessed in 10 cross-sectional studies[32-35,37,39,40,43,60,61]. The use of screen-based devices in the evening was negatively associated with measures of sleep quality in 7/9 studies[33-35,37,40,60,61], positively associated with sleep quality in 1/9 studies[34] and demonstrated null associations in 3/9 studies[32,34,43]. (Several studies reported associations for multiple measures of sleep quality.)

Daytime screen use was negatively associated with measures of sleep quality in 2/2 studies[33,39] or had null associations in 1/2 studies[39].

Overall sleep quality was negatively associated with evening screen use in 3/4 studies[35,40,61], but was not associated with reading in 1/1 studies[43]. Sleep onset latency was positively associated with evening screen use in 2/3 studies[33,60], negatively associated with evening screen use in 1/3 studies[34] and positively associated with daytime screen use in 1/1 studies[33]. Sleep efficiency was negatively associated with evening screen access/use in 1/1 studies[40]. Insomnia symptoms were positively associated with evening screen use in 2/2 studies[35,37]. Waking up too early, difficulty falling asleep and sleeping restlessly were all positively associated with evening screen use in 1/1 studies[34]. Waking after sleep onset[34] and frequency of sleep disturbances[32] were not associated with evening screen use in 1/1 studies.

After-school homework and mobile phone use were positively associated with difficulty maintaining sleep in Grades 6 to 8 (but not Grades 4 to 5) and were not associated with difficulty falling asleep in either age group in 1/1 studies[39].

The quality of evidence for these observational studies was rated as low, as there was a low risk of bias with no evidence of large effects or dose–response relationships.

Access to sedentary activities in the bedroom and sleep quality

Of the 5 cross-sectional studies[40,43,52,53,61] that examined the relationship between access to screen-based devices in the bedroom and sleep quality, 4/5 reported negative associations between the presence of electronic screens in the bedroom and at least one measure of sleep quality[40,43,52,61], and 1/5 reported only null associations[53]. Overall sleep quality was negatively associated with the presence of screen-based devices in the bedroom in 3/3 studies[40,43,61], while both sleep efficiency[40] and perceived insufficient sleep[52] were negatively associated with screen-based sedentary behaviours in 1/1 studies. Sleep onset insomnia was not associated with the presence of screens in the bedroom in 1/1 studies[53].

The quality of evidence for these cross-sectional studies was rated as low; although risk of bias was low, there was no evidence of large effects or dose–response relationship.

Discussion

The purpose of this study was to systematically review the relationship between the timing of sedentary behaviours and access to sedentary activities in the bedroom with sleep duration and quality in children and youth. Our findings suggest that evening screen use and access to screen-based devices in the bedroom are associated with reduced sleep duration and quality in this age group. Intervention-based studies suggest that reducing evening screen use may lead to improved sleep duration and quality, although most interventions only examined a single night's sleep. In the 2 studies lasting 1 week or longer, restricting evening screen use resulted in a roughly 20-minute increase in each night's sleep[20,21], suggesting that the impacts may be clinically meaningful.

A secondary purpose of this review was to examine whether these relationships differ based on the mode of sedentary behaviour. In contrast to screen-based sedentary behaviours, our results suggest that reading and doing homework are not consistently associated with sleep duration or quality in this age group. Although only 3 studies reported on listening to music, 2 studies reported that listening to music on a cell phone or MP3 player was negatively associated with sleep duration[30,33], whereas listening to the radio was not associated with sleep duration[41].

Taken together, these findings suggest that screen-based sedentary behaviours are more likely to negatively impact sleep duration and quality, although relatively few studies examined the impact of non-screen-based sedentary behaviours. In contrast to previous research[10], we found that, with the exception of video games, both interactive (e.g. computers, phones) and passive (e.g. TV viewing) forms of screen use were consistently associated with reduced sleep duration.

Compared to evening screen use, far fewer studies examined the impact of daytime use on sleep duration[33,39,44] or quality[33,39]; only one study examined associations between both daytime and evening sedentary behaviours and sleep duration or quality[33]. However, all these studies reported deleterious relationships between daytime screen use and at least one measure of sleep duration or quality. This is in line with previous research that found that total screen time is consistently associated with poorer sleep outcomes among children and youth[10]. Unfortunately, the timing of sedentary behaviour was measured in various ways across studies, using broad descriptions such as "morning," "after school" or "before bedtime." This evidence gap makes it impossible to identify the optimal "cooling off" period prior to sleep. Further research is needed to directly compare the impact of sedentary behaviour during different periods of the day and night, as well as to examine the optimal interval between screen use and bedtime.

Our findings do suggest that children and youth are likely to benefit from following the recommendations of the American Academy of Pediatrics[15] and Canadian Pediatric Society[16], both of which include removing screens from bedrooms and avoiding screens for at least 1 hour before bed. Although the current findings are based on very low quality evidence, meeting these recommendations will likely still benefit sleep, with very low risk of harm. Removing screens from bedrooms is particularly important because bedroom screen use is most likely to directly displace or delay sleep. This may also be easier than reducing screen time during other periods of the day, when parents have less control over screen use. It is important that schools and teachers help to support students in limiting their evening screen time, by limiting the volume and frequency of screen-based homework that must be completed each day.

Although we cannot rule out the possibility of a bidirectional relationship, the evidence included in this review does not suggest that changes in sleep duration or quality lead to increases in evening screen use. Of the longitudinal studies we identify in the review, none reported that reductions in sleep quality or duration predicted subsequent increases in evening screen time. Further, the intervention studies included suggest that increases in evening screen use are associated with subsequent reductions in sleep duration and quality. Future studies should specifically investigate the directionality of the relationship between sedentary behaviour timing and sleep outcomes.

Strengths and limitations

This review has a number of strengths and limitations. We used a comprehensive search strategy, included all study designs, assessed risk of bias within studies and used the GRADE approach to determine the certainty of evidence across studies. However, GRADE takes a conservative approach, with all study designs other than randomized trials starting as "low quality" by default.[18]

All the cross-sectional studies (but not longitudinal or intervention studies) had to have a minimum of 1000 participants, which may have limited the number of included studies for some outcomes. Restricting inclusion to larger cross-sectional studies increases the likelihood of detecting a true effect[62], and the large number of included studies (n = 44) and participants (n = 239 267) increased the confidence in our findings. The studies excluded because of small sample size had altogether 17 603 eligible participants, which represents just 7% of participants in the papers in this review.

Our search strategy did not include grey literature and we did not contact content experts, although we believe this would be unlikely to impact our overall findings. Our review also identified relatively few intervention studies.

The studies did not differentiate between recreational and school-related screen time; nor did they indicate whether homework was screen or paper based. Future studies should employ randomized intervention studies to better understand the chronic impact of reductions in evening screen use, and to examine the associations between sleep and both recreational and school-related screen time.

All the observational studies in our review measured self- or parent-reported sedentary behaviour; using objective measures of sedentary behaviour timing would improve the quality of future research. Because of the heterogeneity in the included studies, we were unable to perform meta-analyses, which also precluded a formal assessment of publication bias or investigation of whether relationships varied by age or gender. However, only including studies published in the last 10 years could have partly mitigated the risk of publication bias, as many more journals publish null findings in recent years.

Finally, our review was limited to English and French language peer-reviewed papers, although available evidence suggests these restrictions are unlikely to impact our findings[63,64].

Conclusion

Our results suggest that engaging in screen-based sedentary behaviours in the evening and access to screen-based devices in the bedroom are associated with reduced sleep duration and quality among school-aged children and youth. In contrast, there were no consistent associations between non-screen-based sedentary behaviours and sleep duration or quality in this age group. In order to maximize sleep duration and quality, children and youth should minimize screen time prior to bedtime and remove screens from their bedrooms.

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Registration of the protocol

PROSPERO registration no. CRD42020189082, available from www.crd.york.ac.uk/PROSPERO/.

Conflicts of interests

TJS has received honorariums for public presentations on the health impact of sedentary behaviour. The other authors have no conflicts to declare.

Authors' contributions and statement

TJS, TM, JC, SAP and KD screened the papers.

TM and TJS extracted the data and performed the risk of bias and GRADE assessments.

TJS drafted the final version of the manuscript.

All authors were involved in the conception of the study, and all authors reviewed and approved the final version for publication.

The content and views expressed in this article are those of the authors and do not necessarily reflect those of the Government of Canada.

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Evidence synthesis

Sleep timing and health indicators in children and adolescents: a systematic review

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Abstract

Introduction: To continue to inform sleep health guidelines and the development of evidence-based healthy sleep interventions for children and adolescents, it is important to better understand the associations between sleep timing (bedtime, wake-up time, midpoint of sleep) and various health indicators. The objective of this systematic review was to examine the associations between sleep timing and 9 health indicators in apparently healthy children and adolescents 5 to 18 years old.

Methods: Studies published in the 10 years preceding January 2021 were identified from searches in four electronic databases. This systematic review followed the guidelines prescribed in PRISMA 2020, the methodological quality and risk of bias were scored, and the summary of results used a best-evidence approach for accurate and reliable reporting.

Results: Forty-six observational studies from 21 countries with 208 992 unique participants were included. Sleep timing was assessed objectively using actigraphy in 24 studies and subjectively in 22 studies. The lack of studies in some of the health outcomes and heterogeneity in others necessitated using a narrative synthesis rather than a meta-analysis. Findings suggest that later sleep timing is associated with poorer emotional regulation, lower cognitive function/academic achievement, shorter sleep duration/poorer sleep quality, poorer eating behaviours, lower physical activity levels and more sedentary behaviours, but few studies demonstrated associations between sleep timing and adiposity, quality of life/well-being, accidents/injuries, and biomarkers of cardiometabolic risk. The quality of evidence was rated as "very low" across health outcomes using GRADE.

Conclusion: The available evidence, which relies on cross-sectional findings, suggests that earlier sleep timing is beneficial for the health of school-aged children and adolescents. Longitudinal studies and randomized controlled trials are needed to better advance this field of research. (PROSPERO registration no.: CRD42020173585)

Keywords: *bedtime, wake-up time, midpoint of sleep, youth, public health, guideline*

Highlights

- Later sleep timing is generally associated with poorer health outcomes in children and adolescents.
- Findings in this research area are based on observational studies.
- Longitudinal studies and randomized trials are needed to investigate the health effects of sleep timing and determine whether these effects are independent of sleep duration.

Introduction

To many people, getting a good night's sleep is synonymous with sleeping a sufficient number of hours. There is no denying that sleep duration is an important component of physical and mental health[1]. Lack of sleep, often fuelled by a mismatch between the social and the internal clocks, has been associated with numerous adverse health outcomes in all ages[2-4].

Sleep experts agree that many characteristics of sleep, in addition to duration, are relevant for optimal health. The *Canadian 24-Hour Movement Guidelines for Children and Youth* were published in 2016 to provide clear public health guidelines for

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physical activity, recreational screen time and sleep for 5- to 17-year-olds[5]. Since then, in an effort to better inform the general population, many countries and organizations worldwide have adopted this holistic, streamlined approach and all-encompassing messaging for the movement behaviours across the full 24-hour period[6]. The sleep recommendations in the *Canadian 24-Hour Movement Guidelines for Children and Youth* include sleep duration targets and consistent bedtimes and wake-up times across the week to minimize sleep variability[2]. While the guidelines emphasize more than one important sleep characteristic (i.e. duration, quality and consistency), they do not mention sleep timing.

Sleep timing refers to the time of day that sleep occurs; it is often measured using bedtime, wake-up time or midpoint of sleep. Much like sleep needs, sleep timing varies among people, and it can be affected by intrinsic and extrinsic factors such as genetics, age, health status, school/work schedule, lifestyle, travel across time zones and light exposure, resulting in bedtimes and wake-up times that differ from individual preferences[7]. A recent systematic review reported that later sleep timing in healthy adults was associated with overall poorer health outcomes[8]. Whether sleep timing is also associated with health in the pediatric population has, to date, not been systematically examined, especially with the inclusion of multiple health indicators. The purpose of this systematic review was to examine the associations between sleep timing and various health indicators in apparently healthy children and adolescents to help inform public health sleep guidelines and the development of future evidence-based healthy sleep interventions in this population.

Methods

Protocol and registration

This systematic review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement to reduce risk of bias, improve transparency and ensure a more complete reporting of the findings[9]. This systematic review was also registered with the International Prospective Register of Systematic Reviews (PROSPERO Registration No.: CRD42020173585).

Eligibility criteria

To identify the research question and facilitate the search strategy, we adopted the Participants, Interventions, Comparisons, Outcomes and Study design (PICOS) framework[10].

Population

Apparently healthy children and adolescents between 5 and 18 years old, including those with overweight/obesity, but excluding those with other diagnosed medical diseases/conditions. Studies with children younger than 5 years or older than 17.99 years were considered as long as the mean age of the sample was between 5 and 18 years.

To capture more generalizable findings, we excluded studies specifically targeting clinical populations with a diagnosed sleep disorder or other diagnosed medical disease/condition. Also excluded were studies that focussed exclusively on a subset of the general population of school-aged children and adolescents, such as orphans, teen pregnancy, inpatient or institutionalized settings, athletes or individuals with a cognitive or a physical disability. Studies with mixed populations, that is, with individuals who met and did not meet the eligibility criteria, were included if the results pertaining to the population of interest were reported separately.

Intervention/exposure

The intervention or exposure of interest was sleep timing, which refers to the time of day that sleep occurs. For experimental studies, the intervention needed to target sleep timing exclusively and not multiple health behaviours simultaneously. Sleep timing is generally reported as sleep onset/sleep offset, bedtime/wake-up time or midpoint of sleep. Studies using objective (e.g. polysomnography, actigraphy/accelerometry) or subjective (e.g. self-report) measures of sleep timing (or both) were eligible. Only studies that quantified sleep timing were included. For example, we excluded studies examining diurnal preference (e.g. morningness/eveningness), chronotype (e.g. morning lark vs. night owl) or sleep consistency (e.g. sleep variability, social jetlag, catch-up sleep). These studies on other sleep characteristics are outside the scope of the present systematic review.

Comparison/control

Different levels of sleep timing were used as the comparator. However, a comparator or control group was not required for inclusion.

Outcomes

We agreed on a total of 9 health outcomes that targeted a comprehensive range. Of these, we deemed that 5 were critical (primary outcomes) and 4 were important (secondary outcomes). The 5 critical health outcomes were adiposity; emotional regulation (e.g. anxiety, depressive symptoms, stress, mood, hyperactivity/impulsivity); cognitive function and academic achievement (e.g. learning, memory, attention, concentration, grades); quality of life and well-being; and accidents/injuries. The 4 important health outcomes were biomarkers of cardiometabolic risk (e.g. insulin sensitivity/resistance, glucose tolerance, blood pressure, triglycerides); sleep duration and quality; eating behaviour; and physical activity and sedentary behaviour.

Study designs

All published or in-press peer-reviewed, observational or experimental studies were eligible for inclusion. Longitudinal studies with any follow-up length were eligible, but sleep timing had to be measured at least once in children or adolescents aged between 5 and 18 years old. There were no sample size restrictions.

Information sources and search strategy

To ensure a balance of sensitivity and specificity, the search strategy was developed by a research librarian (ARW) with expertise in systematic review searching; the search strategy was reviewed by a second research librarian (MS). The following electronic bibliographic databases were searched for relevant sources: Ovid MEDLINE, Ovid EMBASE, Ovid PsycINFO and EBSCO Cumulative Index to Nursing & Allied Health Literature (CINAHL). The search terms included these keywords for the subject headings and for sleep measurement: (1) headings: "Sleep" AND "Sleep Timing OR Midpoint of Sleep OR Sleep Consistency OR Regular Sleep OR Sleep Variability OR Sleep Schedule OR Catch-up Sleep OR Sleep Routine" OR "Bedtime OR Waketime"; and (2) sleep measurement: "Polysomnography" AND "Accelerometer OR Accelerometry" AND "Actigraphy" AND "Sleep Report OR Sleep

Questionnaire OR Sleep Diary OR Sleep Eval OR Sleep Log OR Sleep Journal."

The results were limited to full-text articles published in the previous 10 years. The initial search, conducted in March 2020, was for studies published from 1 March 2010 to 4 March 2020, in humans (children and adolescents), in English or French. Excluded were case studies and grey literature (e.g. conference abstracts, book chapters and dissertations). We decided on this limited date range to better manage the scope and to focus on the most recent and relevant body of evidence. The publication language was limited to English and French for reasons of feasibility; a recent meta-epidemiological study reported that excluding non-English publications does not impact conclusions[11]. An updated search was performed in January 2021 for studies published between 4 March 2020 and 13 January 2021. Finally, the reference lists of the included studies were reviewed to verify that no articles may have been missed during the search. The full search strategy is available online (https://osf.io/nzt23/?view_only=abcbea551fe545e6b73f44e60600da35).

Selection process

To remove duplicates, bibliographic records were imported into Reference Manager software (Thompson Reuters, San Francisco, CA, US). The individual bibliographical records were then imported into Covidence (Veritas Health Innovation, Melbourne, AU) for level 1 and level 2 screening. During level 1 screening, two reviewers (CD, CMS or BGC), working independently, screened the titles and abstracts of all the potentially relevant articles. Two reviewers (CD, CMS or J-PC), working independently, then reviewed all the full-text articles that passed the level 1 screening. Any discrepancies were resolved via discussion until the reviewers reached consensus. Agreement among the reviewers during the selection process was evaluated using Cohen's κ[12].

Microsoft Excel and Word (2007; Microsoft Corp., Redmond, WA, US) were used for data extraction. Data extraction was completed, in an unblinded manner, by one reviewer, and verified by another (CD, IP). Important features were extracted for each included article: authors' names; publication year; country of study; study design; sample size; participants' age range, mean age and school grade; exposure; comparator; outcome measurement; results; and covariates. When multiple models were reported on the same outcome measurement, results from the most fully adjusted model were extracted. We also reported on whether studies reported differences in effect by age, sex, race/ethnicity, socioeconomic status, weight status or sleep duration (when sleep duration was not the outcome of interest). See Figure 1 for the PRISMA 2020 flow diagram[9] for the identification and selection of studies.

Risk of bias and study quality assessment

The quality of primary research contributing to each health outcome was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework[13]. In accordance with the Cochrane Handbook, the risk of bias assessment was completed for all included studies individually and by outcome[14]. GRADE groups the quality of evidence into four categories ("high," "moderate," "low" and "very low"); the rating begins at "high" for randomized studies and at "low" for all other studies, including non-randomized experiments and all types of observational studies. The quality of evidence can be upgraded one level if there are no serious limitations and if there is a large magnitude of effect or evidence of a dose–response relationship. Conversely, the quality of evidence can be downgraded if there are serious limitations across studies (e.g. serious risk of bias, inconsistency of relative treatment effects, indirectness, imprecision, lack of evidence or other factors)[13]. The quality of evidence assessment was conducted by two authors (CD and IP) and verified by the remainder of the review team, including a systematic review methodology expert (ARW). Disagreements were resolved by discussion among the team members.

Results

Description of studies

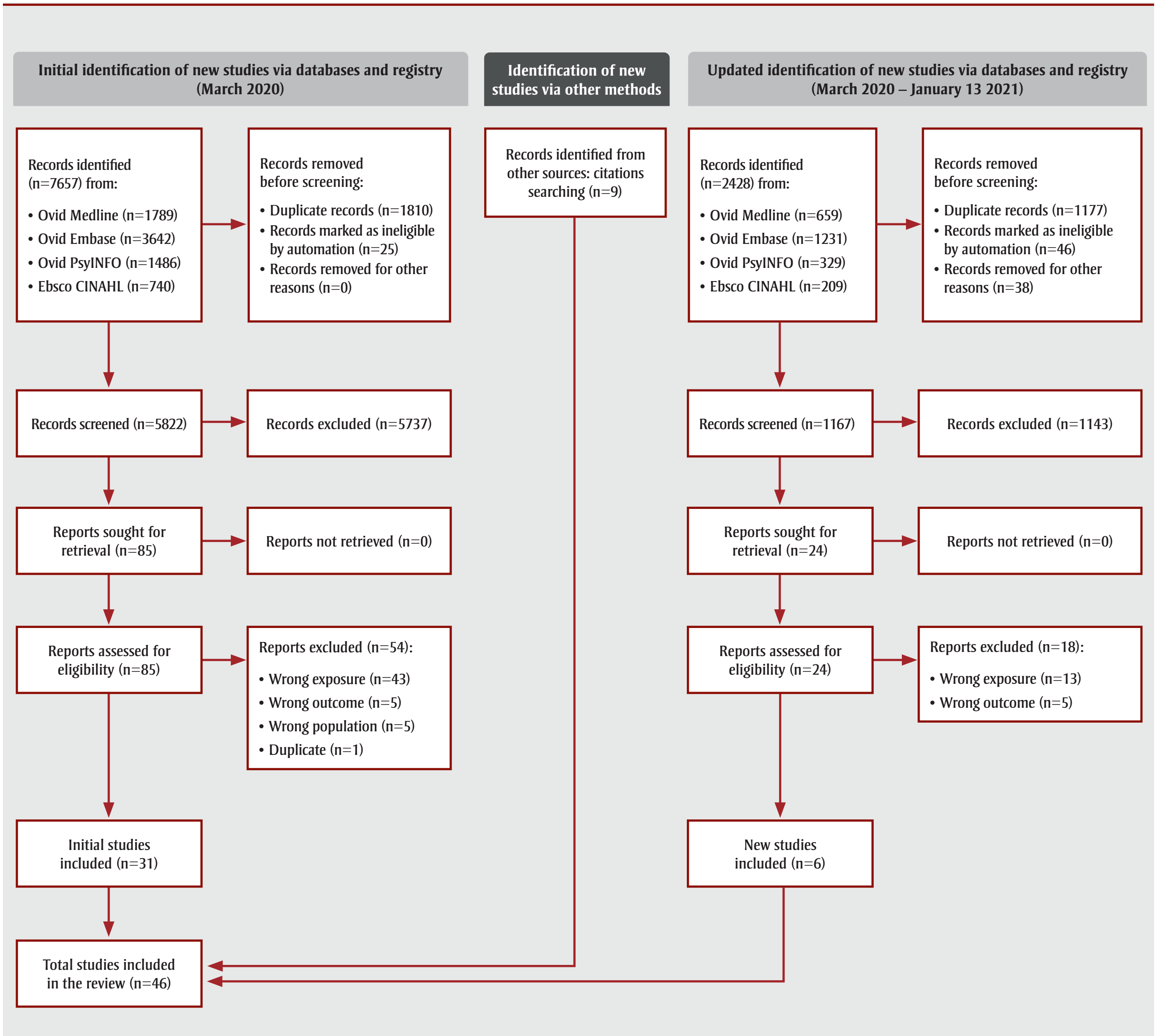
A total of 10 085 records were identified via the original and updated searches of the relevant electronic bibliographic databases (see Methods and Figure 1). After the removal of duplicates, a total of 6989 unique records remained for the level 1 title and abstract screening. The interrater reliability for the level 1 screening process was assessed for substantial agreement ($\kappa > 0.70$)[12].

Following level 1 screening, a total of 109 reports were sought for retrieval and assessed for eligibility. The level 2 eligibility review of the full-text articles excluded 72 articles, with 37 articles meeting the inclusion criteria. Out of the 72 articles excluded, 56 were excluded for having the wrong exposure, 10 for having the wrong outcome, 5 for having the wrong population and 1 for being a duplicate. The interrater reliability for the level 2 eligibility review of the full-text articles was assessed at near-perfect agreement ($\kappa > 0.85$)[12]. See Supplementary Table 1 (https://osf.io/nzt23/?view_only=abcbea551fe545e6b73f44e60600da35) for the complete list of full-text articles excluded. Reviewing the reference lists of included studies generated an additional 9 studies.

Of the 46 observational studies included, 5 were longitudinal and 41 were cross-sectional. Data were collected in 21 countries and included 208 992 unique participants. Twenty studies were included for a single outcome, and 26 were included for two or more outcomes. Sleep timing was assessed objectively, using an actigraphy device, in 24 studies, and subjectively, using questionnaires, sleep diaries or interviews (by proxy or self-report), in 22 studies. Sleep timing was assessed as midpoint of sleep in 14 studies, bedtime in 20 studies and a combination of bedtime/wake-up time or sleep onset/offset in 4 studies. Multiple measurements of sleep timing were independently analyzed in 8 studies. Variation of the effect between sleep timing and health outcomes caused by factors such as age, sex, race/ethnicity, socioeconomic status, weight status and sleep duration (when sleep duration was not the outcome) was only reported in 3 studies, partially addressed (mainly age and/or sex) in 13 studies and not reported in 30 studies.

Because of the small number of studies reporting some outcomes and the heterogeneity across studies in other outcomes, meta-analyses were not possible and we structured narrative syntheses around each health indicator to convey the findings. Population subgroups were defined as children (5–12 years) and adolescents (13–18 years), when possible.

FIGURE 1
PRISMA statement 2020 flow diagram[9] of the identification, screening, eligibility and inclusion of studies in this systematic review



Abbreviation: PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

Data synthesis

The full data extraction and findings of the individual studies, sorted by outcome and study design, are reported in Supplementary Tables 2 and 3 (available from: https://osf.io/nzt23/?view_only=abcbea551fe545e6b73f44e60600da35) for the critical and important health outcomes, respectively. The summarized findings for the individual studies, sorted by outcome and study design, are in Tables 1 and 2 for the critical and important outcomes, respectively. Quality of evidence assessment, sorted by outcome and study design, are in Table 3 for all outcomes. Finally, a high-level summary of findings is presented in Table 4 for all outcomes, sorted by outcome and study design. In Table 4, studies are classified as having mixed findings if (1) the association between sleep timing and the outcome was not consistent across measurements; (2) the measurements of sleep timing did not show consistent associations with the outcome; and (3) the association between sleep timing and the outcome showed variation based on sex, age or other factors.

Adiposity

A total of 20 observational studies—3 longitudinal and 17 cross-sectional studies—examined the association between sleep timing and adiposity in children and adolescents 4 to 18 years old. Two of the 3 longitudinal studies reported that later sleep timing was associated with higher adiposity[15,16], while the third reported null findings[17]. Of the 17 cross-sectional studies investigating the association between sleep timing and adiposity, 10 reported null findings; of these, 2 studies only investigated BMI[28,31], 1 study only investigated

TABLE 1
Summary of findings for the association between sleep timing and critical health outcomes, in apparently healthy children and adolescents

Study design and no. / No. of participants / age range	Measurement of sleep timing (no. of studies)	Findings
Adiposity		
Longitudinal (n = 3) 7756 participants 4–18 years	Objectively, using an actigraphy device (n=1) Subjectively, by self-report (n = 1) and proxy-report (n = 1)	Hierarchical linear models revealed a significant longitudinal association between self-reported later bedtime and increased BMI z-score from adolescence to adulthood (β = 0.035, $p < 0.05$)[15]. In children, adjusted linear regression analyses revealed that a higher total number of times that children were in proxy-reported late bedtime groups at data collection timepoints was significantly associated with higher BMI z-score ($p < 0.001$) and waist circumference ($p = 0.03$) at 8–9 y[16]. No significant longitudinal associations were found between objectively measured sleep onset or midpoint of sleep and BMI z-score[17].
Cross-sectional (n = 17) 38 798 participants 5–18 years	Objectively, using an actigraphy device (n = 10) Subjectively, by self-report (n = 5) and proxy-report (n = 2)	In a sample of children and adolescents, multivariable linear regression revealed that those in the late-sleep timing groups, established via self-report, had higher BMI z-score relative to those in the early-bed/early-rise group (late-bed/early-rise: β = 0.17, 95% CI: 0.00–0.35, $p = 0.05$; late-bed/late-rise: β = 0.20, 95% CI: 0.06–0.34, $p = 0.007$)[18]. In a sample of adolescents, general linear modelling showed that objectively measured later corrected midpoint of sleep was significantly associated with greater waist-to-height ratio (β = 0.015, 95% CI: 0.003–0.028, $p < 0.05$); however, no significant association was found between corrected midpoint of sleep and BMI[19]. In a sample who self-reported their sleep timing, multivariable logistic regressions revealed that the odds of overweight or obesity were 1.55 for the late-bed/early-rise group of children and 1.47 for the late-bed/late-rise group of adolescents, and the odds of obesity were 1.89 for the late-bed/early-rise group of children and 2.16 for the late-bed/late-rise group of adolescents, compared to participants in the early-bed/early-rise group[20]. In 5-year-old children, analysis of covariance revealed that proxy-reported earlier bedtime (before or at 20:00), was significantly associated with lower BMI z-score ($p < 0.01$), but no significant association was found between wake-up time and BMI z-score[21]. In a sample of adolescents, multivariable logistic regression revealed that self-reported later weekend midpoint of sleep was significantly associated with higher BMI z-score in females only (<3:30: reference; 4:00 to 4:29: OR = 1.81; 95% CI: 0.90–3.63; 4:30 to 5:04: OR = 1.82; 95% CI: 0.96–3.47; ≥5:05: OR = 1.68; 95% CI: 0.85–3.33, $p = 0.04$). Weekday midpoint of sleep was not associated with BMI z-score[22]. In children, proxy-reported late compared to normal midpoint of sleep over the whole week was significantly associated with higher fat mass percentage and waist circumference, but was not associated with BMI z-score or the sum of the skinfolds[23]. In a sample of children with obesity, multivariate linear regression analyses revealed that objectively measured later bedtime on weekdays was associated with greater percent overweight (β = 6.17, 95% CI: 1.42–10.92, $p < 0.05$), percent over 95th BMI percentile (β = 4.60, 95% CI: 1.07–8.13, $p < 0.05$), BMI (β = 1.03, 95% CI: 0.22–1.85, $p < 0.05$) and waist circumference (β = 2.06, 95% CI: 0.23–3.88, $p < 0.05$). Objectively measured later weekday wake-up time was also significantly associated with higher BMI (β = 0.85, 95% CI: 0.00061–1.70, $p < 0.05$) and waist circumference (β = 2.03, 95% CI: 0.13–3.93, $p < 0.05$). Neither objectively measured weekend bedtime nor weekend wake-up time was significantly associated with any of the adiposity outcomes. Of the proxy-reported sleep-timing measures, only later weekday bedtime was significantly associated with higher percent over 95th BMI percentile (β = 4.33, 95% CI: 0.038–8.63, $p < 0.05$) and BMI (β = 1.01, 95% CI: 0.021–2.00, $p < 0.05$)[24]. 10 studies reported no significant associations between objectively[25-32] and subjectively[33,34] measured sleep timing and adiposity.
Emotional regulation		
Longitudinal (n = 2) 6331 participants 4–18 years	Subjectively, by self-report (n = 1) and proxy-report (n = 1)	In adolescents, self-reported later school-year bedtime at timepoint 1 (T1; Grades 7–12) and later summertime bedtime at timepoint 2 (T2; Grades 8–12) were associated with higher odds of emotional distress at timepoint 3, 6–8 y later in young adulthood (T1 school-year bedtime: OR = 1.35, 95% CI: 1.0–1.8, $p < 0.05$; T2 summertime bedtime: OR = 1.35, 95% CI: 1.1–1.8, $p < 0.05$)[35]. In children, adjusted linear regression analyses revealed that a higher total number of times children were in proxy-reported late bedtime groups at data collection timepoints (from never to 3 times) was significantly associated with more parent-reported ($p = 0.03$) and teacher-reported ($p = 0.05$) behavioural problems at 8–9 y[16].

Continued on the following page

TABLE 1 (continued)
Summary of findings for the association between sleep timing and critical health outcomes, in apparently healthy children and adolescents

Study design and no. / No. of participants / age range	Measurement of sleep timing (no. of studies)	Findings
Cross-sectional (n = 7) 106 225 participants 7–20 years	Objectively, using an actigraphy device (n = 2) Subjectively, by self-report (n = 5)	In children, logistic regression revealed that self-reported bedtime after 22:00, compared to bedtime before or at 21:00, was associated with an increased odds of self-reported depressive symptoms (≤21:00: reference; 22:00–23:00: OR = 1.89, 95% CI: 1.0–3.6, $p < 0.05$; >23:00: OR = 4.66, 95% CI: 2.1–10.2, $p < 0.01$)[36]. In adolescents and young adults, adjusted Poisson regression modelling revealed that, compared to those with a self-reported bedtime at ~22:00 or earlier, those with bedtime at ~22:30 had better depression scores (β = −0.1, 95% CI: −0.2 to −0.1, $p < 0.0001$), while those with a bedtime at ~23:30 or later had worse depression scores (β = 0.5, 95% CI: 0.5–0.6, $p < 0.0001$). In addition, going to bed at ~23:30 or later, compared to ~22:00 or earlier, was associated with increased odds of having anxiety or nervousness during the last 6 months. Going to bed at ~22:30 or later, compared to ~22:00 or earlier, was associated with increased odds of being irritated and having tantrums during the last 6 months[37]. In 17-year-olds, Tobit regression modelling revealed that objectively measured later midpoint of sleep was significantly associated with 2 out of 10 youth self-report scales: more thought problems (β = 0.9, 95% CI: 0.01–1.8, $p < 0.05$) and more rule-breaking behaviour (β = 1.5, 95% CI: 0.6–2.4, $p < 0.001$). Later midpoint of sleep was also significantly associated with 2 out of 6 Diagnostic and Statistical Manual of Mental Disorders-oriented scales: more affective problems (β = 1.2, 95% CI: 0.05–2.3, $p < 0.05$) and more conduct problems (β = 1.2, 95% CI: 0.2–2.1, $p < 0.05$)[38]. In a sample of adolescents, self-reported later bedtime was significantly correlated with higher anxiety ($r(256) = 0.16$, $p < 0.05$) and depressed mood ($r(383) = 0.20$, $p < 0.01$)[39]. In a sample of adolescents with overweight or obesity, objectively measured later bedtime on weekdays, but not weekends, was associated with increased self-report of behavioural problem symptoms (β = 0.52, $p = 0.01$)[40]. In a sample of children and adolescents, self-reported later weekday and weekend bedtimes, but not wake-up times, were each correlated with higher subjective depression scores ($r(499) = 0.130$, $p = 0.003$ and $r(499) = 0.088$, $p = 0.049$, respectively)[41]. In adolescents, self-reported earlier wake-up time was significantly correlated with low subjective academic stress ($r(479) = 0.12$, $p < 0.01$)[42].
Cognitive function and academic achievement		
Longitudinal (n = 2) 6331 participants 4–18 years	Subjectively, by self-report (n = 1) and proxy-report (n = 1)	Longitudinal associations revealed that self-reported later school-year bedtime at T1 (mean age 15.4 y) and T2 (mean age 16.4 y) was associated with lower high-school cumulative GPA (β = −0.27, 95% CI: −0.37 to 0.17, $p < 0.001$, and β = −0.13, 95% CI: −0.24 to 0.023, $p < 0.01$, respectively). Summertime bedtime was not associated with cumulative GPA[35]. In children, no significant longitudinal associations were found between proxy-reported sleep-timing group and verbal cognition, non-verbal cognition, language literacy and mathematical thinking[16].
Cross-sectional (n = 5) 123 372 participants 7–20 years	Subjectively, by self-report (n = 4) and proxy-report (n = 1)	In a sample of adolescents, there was an increased odds of poor GPA in those who self-reported typical weekday bedtime before 22:00 (OR = 1.74, 95% CI: 1.31–2.33) and after 00:00 (00:00–00:59: OR = 1.6, 95% CI: 1.37–1.91; 01:00–01:59: OR = 2.19, 95% CI: 1.71–2.81; 2:00 or later: OR = 2.76, 95% CI: 1.93–3.94), relative to bedtime between 22:00 and 22:59[43]. In a sample of adolescents and young adults, self-reported bedtime at approximately 22:30 or later, relative to 22:00 or earlier, was associated with increased odds of self-reported trouble with following class education, completing homework assignments, preparing for examinations, writing tasks and reading tasks. In addition, bedtime at approximately 23:00 or later, relative to 22:00 or earlier, was associated with increased odds of having trouble with reading tasks[37]. In adolescents, hierarchical multiple regression analyses revealed that self-reported later bedtime (not waketime) was significantly associated with lower college entrance exam scores (β = 0.133, $p < 0.01$). No associations were found between bedtime or wake-up time and subjective academic performance[42]. 2 studies reported no significant associations between subjectively measured sleep timing and cognitive performance and academic achievement outcomes[41,44].

Continued on the following page

TABLE 1 (continued)
Summary of findings for the association between sleep timing and critical health outcomes, in apparently healthy children and adolescents

Study design and no. / No. of participants / age range	Measurement of sleep timing (no. of studies)	Findings
Quality of life and well-being		
Longitudinal (n = 1) 3631 participants 4–9 years	Subjectively, by proxy-report (n = 1)	In children, adjusted linear regression analyses revealed that a higher total number of times children were placed in proxy-reported late bedtime groups at data collection timepoints (from never to 3 times) was significantly associated with poorer proxy-reported psychosocial ($p = 0.001$) and physical health ($p = 0.002$) functioning at 8–9 y[16].
Cross-sectional (n = 1) 6266 participants 9–11 years	Objectively, using an actigraphy device (n = 1)	In an international sample of children, no overall associations were found between objectively measured weekday or weekend midpoint of sleep and health-related quality of life score[45].
Accidents/injuries		
Cross-sectional (n = 1) 103 859 participants 14–20 years	Subjectively, by self-report (n = 1)	In adolescents and young adults, logistic regressions revealed that, relative to those with self-reported bedtime at ~22:00 or earlier, the odds of reporting accidents requiring medical attention during recess and in other classes were lower among those with bedtime at ~23:00. A greater decrease in odds of having accidents on the way to school was observed in those with bedtime at ~23:00, than in those with bedtime at ~22:30, relative to those with bedtime at ~22:00 or earlier. There was no association found between bedtime and accidents requiring medical attention during gym class[37].

Abbreviations: BMI, body mass index; CI, confidence interval; GPA, grade point average; no., number; y, years.

TABLE 2
Summary of findings for the association between sleep timing and important health outcomes, in apparently healthy children and adolescents

Study design and no. / No. of participants / age range	Measurement of sleep timing (no. of studies)	Findings
Biomarkers of cardiometabolic risk		
Cross-sectional (n = 7) 3089 participants 8–19 years	Objectively, using an actigraphy device (n = 6) Subjectively, by self-report (n = 1)	In children and adolescents, adjusted linear regression analyses indicated that objectively measured later midpoint of sleep on weekends (β = 0.049, 95% CI: 0.004–0.093, $p = 0.03$), but not on weekdays (β = 0.041, 95% CI: 0.005–0.087, $p = 0.08$), was associated with higher insulin resistance, estimated using the Homeostatic Model Assessment of Insulin Resistance. In girls, each hour increase in weekday and weekend midpoint of sleep represented a significant increase in insulin resistance (β = 0.091, 95% CI: 0.027–0.16, $p = 0.006$, and β = 0.08, 95% CI: 0.017–0.14, $p = 0.01$, respectively)[46]. In children, after adjusting for covariates, analyses of covariance revealed that, on average, participants with objectively measured bedtime before 22:30 had significantly better triglyceride/high-density lipoprotein cholesterol ratio ($p = 0.026$) than participants with bedtime later than 23:15. There was no significant association between bedtime category and blood insulin level or mean arterial pressure[27]. In children, simple linear regression revealed that later midpoint of sleep was significantly associated with lower diastolic blood pressure (β = −0.002, $p = 0.04$); no significant associations were found between midpoint of sleep and systolic blood pressure, apolipoprotein B/A1 or glycoprotein acetyls[28]. In children and adolescents, adjusted multiple linear regression analyses revealed that objectively measured later bedtimes (total, during the week and on the weekend) were significantly associated with higher systolic blood pressure z-score (total: β = 0.22, $p = 0.02$; weekday: β = 0.21, $p = 0.02$; weekend: β = 0.23, $p = 0.02$). No associations were found between bedtime and insulin resistance, triglycerides z-score, high-density lipoprotein-C z-score, low-density lipoprotein-C or diastolic blood pressure z-score[29]. In a sample of adolescents with overweight or obesity, simple linear regression analyses showed that objectively measured earlier weekday bedtime was significantly associated with better fasting insulin resistance ($p = 0.04$) but was not associated with the Matsuda Index ($p = 0.23$)[47]. 2 studies reported no significant associations between objectively[30] and subjectively[33] measured sleep timing and cardiometabolic risk factors including blood pressure, fasting serum levels of glucose and insulin, and dyslipidemia.

Continued on the following page

TABLE 2 (continued)
Summary of findings for the association between sleep timing and important health outcomes, in apparently healthy children and adolescents

Study design and no. / No. of participants / age range	Measurement of sleep timing (no. of studies)	Findings
Sleep duration and quality		
Longitudinal (n = 1) 783 participants 6–10 years	Objectively, using an actigraphy device (n = 1)	In children, no significant longitudinal associations were found between objectively measured sleep onset or midpoint of sleep and sleep duration[17].
Cross-sectional (n = 10) 112 043 participants 5–20 years	Objectively, using an actigraphy device (n = 3) Subjectively, by self-report (n = 6) and proxy-report (n = 1)	In a sample of children and adolescents, self-reported earlier midpoint of sleep on both school and weekend nights was correlated with better self-reported sleep quality ($r = 0.16$, $p = 0.03$ and $r = 0.26$, $p = 0.002$, respectively). No significant association was found between midpoint of sleep on both school and weekend nights and subjectively measured sleep duration[48]. In children, objectively measured later sleep onset and earlier sleep offset were significantly correlated with decreased total sleep time ($r(1229) = -0.60$ and $r(1229) = 0.16$, respectively)[25]. In adolescents and young adults, adjusted Poisson regression modelling revealed that bedtime at ~22:30 or later, compared to ~22:00 or earlier, was associated with more sleep quality problems (~22:30: $\beta = 0.04$, 95% CI: 0.02–0.05, $p < 0.0001$; ~23:00: $\beta = 0.08$, 95% CI: 0.07–0.09, $p < 0.0001$; ≥23:30: $\beta = 0.2$, 95% CI: 0.2–0.2, $p < 0.0001$) and with an increased odds of having trouble falling asleep during the last 6 months[37]. In children and adolescents, self-reported later bedtime was associated with decreased self-reported sleep duration[20]. In a sample of adolescents, self-reported later bedtime was found to be significantly correlated with lower self-reported total sleep time and with greater report of unrefreshing sleep, $r(306) = -0.50$, $p < 0.001$ and $r(306) = 0.22$, $p < 0.001$, respectively[49]. In children, a significant correlation was found between objectively measured later bedtime and shorter total sleep time ($r = -0.61$, $p < 0.001$)[31]. Children in the proxy-reported late midpoint-of-sleep group had significantly less total sleep duration, by approximately 15 min during weekdays and during the whole week, compared to children in the normal midpoint-of-sleep group ($p < 0.01$)[23]. In a sample of children, fractional multinomial logit models revealed significant associations between objectively measured later bedtime (30 min above the mean compared to 30 min below the mean) and less total sleep time by 35.6 min/night at age 5 and by 39.0 min/night at age 7 ($p < 0.05$)[50]. 2 studies reported no significant associations between subjectively measured sleep timing and sleep duration[15,51].
Eating behaviours		
Cross-sectional (n = 13) 42 138 participants 5–18 years	Objectively, using an actigraphy device (n = 7) Subjectively, by self-report (n = 5) and proxy-report (n = 1)	In a sample of children and adolescents, self-reported later weeknight bedtime was associated with an increased odds of reporting missing breakfast (9–11 years: OR = 4.5, 95% CI: 3.3–6.0; 12–14 years: OR = 4.7, 95% CI: 4.1–5.4; 15–17 years: OR = 4.1, 95% CI: 2.3–7.5) and consuming junk food ≥5 times in a week (9–11 years: OR = 2.7, 95% CI: 2.0–3.5; 12–14 years: OR = 2.9, 95% CI: 2.6–3.3; 15–17 years: OR = 2.1, 95% CI: 1.4–3.3)[52]. In a sample of children, objectively measured later bedtime and sleep onset time were both significantly associated with higher self-reported restrained eating score ($\beta = 0.40$, $p < 0.05$ and $\beta = 0.41$, $p < 0.05$, respectively). No significant associations were found between sleep timing and emotional or external eating behaviours[53]. In an international sample of children, objectively measured later bedtime was associated with less healthy diet pattern ($\beta = -0.07$, 95% CI: −0.11 to −0.02, $p < 0.01$) and more unhealthy diet pattern ($\beta = 0.08$, 95% CI: 0.04–0.13, $p < 0.001$)[54]. In an international sample of children, objectively measured later bedtime was associated with greater frequency of cola and soft drink consumption per week ($p < 0.01$), while earlier bedtime was associated with higher frequency of energy drink and sports drink consumption (for both, $p < 0.01$)[55].

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TABLE 2 (continued)
Summary of findings for the association between sleep timing and important health outcomes, in apparently healthy children and adolescents

Study design and no. / No. of participants / age range	Measurement of sleep timing (no. of studies)	Findings
		In a sample of children and adolescents, multivariable linear regression revealed that, compared to those in the early-bed/early-rise self-reported sleep-timing group, those in the two late-bed groups had significantly lower total Dietary Guideline Index for Children and Adolescents scores (late-bed/early-rise: β = −3.09, 95% CI: −5.32 to −0.86, $p = 0.007$; late-bed/late-rise: β = −3.99, 95% CI: −5.66 to −2.32, $p < 0.001$). No significant association was found between sleep-timing group and energy intake[18]. In a sample of children, those in late-sleep groups had significantly lower fruits and vegetables dietary pattern scores (late-sleep/early-wake: mean = −0.1; late-sleep/late-wake: mean = −0.06; $p < 0.05$) than those in the early-sleep/early-wake group (mean = 0.19). Children in the late-sleep/late-wake group, compared to the early-sleep/early-wake group, also reported significantly lower weekly frequency of consumption of fruits and vegetables (mean = 16 vs. mean = 19, mean difference [95% CI]: −2.9 [−4.9 to −0.9], $p < 0.05$) and higher weekly frequency of consumption of sugar-sweetened beverages (mean = 7 vs. mean = 5, mean difference [95% CI]: 1.8 [0.2 to 3.3], $p < 0.05$), after adjusting for covariates. No significant associations were found between sleep-timing group and snack patterns or extra consumption[26]. In children, adjusted linear regression models revealed that objectively measured later bedtime was associated with greater fat (β = 0.02, $p < 0.02$) and lower carbohydrate (β = −0.02, $p < 0.05$) intake daily. No association was found between bedtime and daily caloric intake or daily protein intake. Later bedtime was associated with greater after-dinner caloric intake (β = 0.81, $p < 0.01$) in the form of protein (β = 0.08, $p < 0.04$) and fat (β = 0.37, $p < 0.02$), but not carbohydrate. Later bedtime was also associated with later timing of the last (β = 0.57, $p < 0.001$) and first (β = 0.76, $p < 0.001$) meals of the day[31]. Among children and adolescents who self-reported their midpoint of sleep, those in the late (vs. early) midpoint-of-sleep group had a significantly higher probability of consuming sweet and caffeinated beverages and sugary, salty and fatty foods, starting in the afternoon and for the rest of the day. No association was found between sleep-timing group and the probability of consumption of vegetables, proteins, fruits and carbohydrates. Those in the early (vs. late) midpoint-of-sleep group were more likely to report not skipping breakfast (96% vs. 30%, respectively, X^2 [2, N = 55] = 26.7, $p < 0.01$). No other associations were found between sleep-timing group and the two other meals[51]. In children, analyses of variance revealed that being in the proxy-reported late midpoint-of-sleep group on weekdays ($p < 0.05$) and weekend days ($p < 0.01$) was associated with an increased cumulative number of self-reported eating risk factors[23]. 4 studies reported no significant associations between objectively[24,29] and subjectively[15,56] measured sleep timing and eating behaviours.
Physical activity and sedentary behaviours		
Longitudinal (n = 1) 1059 participants 7–12 years	Objectively, using an actigraphy device (n=1)	In children, fixed effect models revealed that an incremental increase by 30 min in objectively measured sleep onset was significantly associated with less time spent in LPA, moderate physical activity, MVPA and VPA (by 12, 3.5, 6.2 and 0.4 min, respectively) and more sedentary time (by 31 min) (all $p < 0.001$)[57].
Cross-sectional (n = 15) 14 642 participants 5–18 years	Objectively, using an actigraphy device (n=10) Subjectively, by self-report (n=4) and proxy-report (n=1)	In a sample of children and adolescents with obesity, after adjusting for covariates, linear regression revealed a significant association between later midpoint of sleep and daily amount of screen time (β = 105.7, 95% CI: 36.4–175.1, $p < 0.01$). However, no significant associations were found between sleep timing and time spent in MVPA or sedentary time[56]. In children and adolescents, self-reported later midpoint of sleep on school days was significantly associated with higher total time spent watching TV, using a tablet, using a smartphone and watching TV at night (all $p < 0.04$) as well as lower smartphone use during the day ($p = 0.001$). No association was found between midpoint of sleep on school days and 4 of the screen-time use outcomes. In addition, later weekend midpoint of sleep was significantly associated with higher total time spent watching TV, using a smartphone, watching TV at night, using a cell phone at night (all $p < 0.02$) and lower tablet and smartphone use during the day (both $p < 0.05$). Weekend midpoint of sleep was not associated with 3 of the screen-time use outcomes[48]. In an international sample of children, adjusted analyses revealed that objectively measured later bedtime was associated with less time spent in MVPA (β = −1.08, 95% CI: −1.13 to −1.03, $p < 0.0001$), more time spent in sedentary behaviour (β = 0.36, 95% CI: 0.31–0.41, $p < 0.0001$) and higher screen-time score (β = 1.19, 95% CI: 1.14–1.25, $p < 0.0001$)[54].

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TABLE 2 (continued)
Summary of findings for the association between sleep timing and important health outcomes, in apparently healthy children and adolescents

Study design and no. / No. of participants / age range	Measurement of sleep timing (no. of studies)	Findings
		In a sample of children, those in both objectively measured late-wake sleep-timing groups were significantly less active (early-sleep/late-wake: mean = 72 min/day; late-sleep/late-wake: mean = 70 min/day) than those in the early-sleep/early-wake group (mean = 81 min/day). In addition, children in the late-sleep/late-wake group were significantly less active than those in the late-sleep/early-wake group (late-sleep/late-wake: mean = 70 min/day; late-sleep/early-wake: mean = 79 min/day). No significant association was found between objectively measured sleep timing and meeting screen-time guidelines[26]. In children, fixed interindividual analysis revealed that objectively measured later sleep onset was associated with less objectively measured time spent in MVPA per hour (β = –0.012, $p = 0.001$), independent of total sleep time[58]. In children, adjusted linear regression models revealed significant associations between objectively measured later midpoint of sleep (β = –0.11, $p < 0.05$), earlier bedtime (β = 0.10, $p < 0.05$) and later wake-up time (β = −0.13, $p < 0.05$) and less time spent in LPA. Also, later midpoint of sleep (β = 0.08, $p < 0.05$) and later wake-up time (β = 0.10, $p < 0.05$), but not bedtime, were significantly associated with more time spent being sedentary. No significant associations were found between sleep-timing variables and VPA, MVPA and moderate PA[32]. In children at timepoint 1 (mean age 12.3 y), objectively measured later midpoint of sleep was significantly associated with lower PA ($r(165) = -0.10$, $p = 0.03$), LPA ($r(165) = -0.10$, $p = 0.04$), MVPA ($r(165) = -0.10$, $p = 0.04$) and higher sedentary behaviour ($r(165) = 0.12$, $p = 0.02$). At timepoint 2 (mean age 16.9 y), no significant associations were found between sleep timing and PA or sedentary behaviour[59]. In children and adolescents who self-reported their sleep timing, the late-bed groups (vs. the early-bed/early-rise group) had the highest odds of lower PA and higher sedentary behaviour. No significant differences in odds of outcome were found between the two early-bed groups on each outcome studied. Compared to participants in the early-bed/early-rise group, the odds of low MVPA were 1.77 for the late-bed/late-rise group and 1.58 for the late-bed/early-rise group; the odds of high amounts of screen time were 2.92 for the late-bed/late-rise group and 1.94 for the late-bed/early-rise group; and the odds of both high amounts of screen time and low MVPA were 2.87 for the late-bed/late-rise group and 2.10 for the late-bed/early-rise group. In addition, on average, the early-rise groups engaged in significantly more minutes of MVPA, VPA, play and active transport per day and had higher daily pedometer step counts than the late-rise groups. The late-bed groups engaged in significantly more minutes of total sedentary time, screen time, watching television, playing videogames and computer time[20]. In children, fractional multinomial logit models at age 5 y revealed significant associations between later bedtime (30 min above the mean vs. 30 min below the mean) and more sedentary time and LPA time (10.1 and 21.6 min/day, respectively), but not with MVPA. At age 7 y, there were significant associations between later bedtime (30 min above the mean vs. 30 min below the mean) and more sedentary, LPA and MVPA time (14.7, 23.2 and 5.3 min/day, respectively)[50]. In children, objectively measured later weekday bedtime was associated with self-reported screen time that was longer by an average of 3.19 (1.42) h/week ($p < 0.05$). No significant associations were found between objectively or subjectively measured bedtime or wake-up time and time spent in MVPA[24]. 5 studies reported no significant associations between objectively[25,31,60] and subjectively[15,23] measured sleep timing.

Abbreviations: LPA, light physical activity; MVPA, moderate-to-vigorous physical activity; PA, physical activity; no., number; VPA, vigorous physical activity; y, years.

TABLE 3
Quality assessment and quality of evidence rating for the association between sleep timing and health outcomes in apparently healthy children and adolescents, by health outcome and study design

Health outcome	Study design	No. of studies	No. of participants	Quality assessment indicator					Quality (GRADE)[b]
				Risk of bias	Inconsistency	Indirectness	Imprecision	Other[a]	
Critical health outcomes									
Adiposity	Longitudinal	3	7756	Serious risk[c]	No serious risk	No serious risk	No serious risk	None	Very low
	Cross-sectional	17	38 798	No serious risk	Serious risk[d]	No serious risk	No serious risk	None	Very low
Emotional regulation	Longitudinal	2	6331	Serious risk[c]	No serious risk	No serious risk	No serious risk	None	Very low
	Cross-sectional	7	106 225	Serious risk[c]	No serious risk	No serious risk	No serious risk	None	Very low
Cognitive function and academic performance	Longitudinal	2	6331	Serious risk[c]	Serious risk[c]	No serious risk	No serious risk	None	Very low
	Cross-sectional	5	123 372	Serious risk[c]	No serious risk	No serious risk	No serious risk	None	Very low
Quality of life and well-being	Longitudinal	1	3631	No serious risk	Only one study	No serious risk	Serious risk[e]	None	Very low
	Cross-sectional	1	6266	No serious risk	Only one study	No serious risk	Serious risk[e]	None	Very low
Accidents/injuries	Cross-sectional	1	103 859	Serious risk[c]	Only one study	No serious risk	Serious risk[e]	None	Very low
Important health outcomes									
Biomarkers of cardiometabolic risk	Cross-sectional	7	3089	No serious risk	Serious risk[c]	No serious risk	No serious risk	None	Very low
Sleep duration and quality	Longitudinal	1	783	No serious risk	Only one study	No serious risk	Serious risk[e]	None	Very low
	Cross-sectional	10	112 043	Serious risk[c]	No serious risk	No serious risk	No serious risk	None	Very low
Eating behaviour	Cross-sectional	13	42 138	Serious risk[c]	No serious risk	No serious risk	No serious risk	None	Very low
Physical activity and sedentary behaviour	Longitudinal	1	1059	No serious risk	Only one study	No serious risk	Serious risk[e]	None	Very low
	Cross-sectional	15	14 642	Serious risk[c]	No serious risk	No serious risk	No serious risk	None	Very low

Abbreviations: GRADE, Grading of Recommendations Assessment, Development and Evaluation; no., number.

[a] Large magnitude of effect, dose response, and accounting for all plausible confounding.

[b] Quality was assessed using the GRADE framework as per the GRADE Working Group, which grades the quality of evidence as follows[13]: "high" means that further research is very unlikely to change our confidence in the estimate of effect; "moderate" means that further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate; "low" means that further research is very likely to have an important impact on our confidence in the estimate of effect and may change the estimate; and "very low" means that we are very uncertain about the estimate.

[c] One or more studies was published and both the exposure and outcome were measured via questionnaire with unknown psychometric properties.

[d] Mixed findings reported in an outcome, which resulted in the quality of the outcome to be downgraded.

[e] Serious imprecision due to the lack of evidence in the outcome, which resulted in the quality of the findings for the outcome to be downgraded.

waist circumference[27] and 7 studies used BMI and at least one additional measure of adiposity[25,26,29,30,32-34]. Five studies reported mixed findings in the associations between sleep timing and adiposity[19,21-24]. Two studies that assigned participants to one of four sleep-timing groups by dichotomizing bedtimes and wake-up times reported a significant association between sleep-timing groups and an adiposity outcome. Relative to the early-bed/early-rise group, those in the late-to-bed sleep-timing groups had higher BMI z-score[18] and greater odds of having overweight and obesity[20].

The quality of evidence for the 3 longitudinal studies investigating the association between sleep timing and adiposity was downgraded from low to very low due to a serious risk of bias. The quality of the evidence for the 17 cross-sectional studies investigating this association was downgraded from low to very low due to inconsistency in the findings.

Emotional regulation

A total of 9 observational studies—2 longitudinal and 7 cross-sectional—reported on the association between sleep timing and emotional regulation in children and adolescents 4 to 20 years old. In children, being categorized as having a late bedtime over multiple timepoints was significantly associated with more behavioural problems[16]. The other longitudinal study reported mixed findings between sleep timing at different time points and emotional distress[35]. Eight cross-sectional studies were initially extracted, but to avoid inflating the results in the emotional regulation outcome, one of the studies by Short and colleagues[49] was removed as the authors published twice on the same outcome measurement, using the same sample and the same statistical analysis. The study by Short et al.[39] had the highest number of outcome measurements within the emotional regulation health outcome and was therefore retained (see Supplementary Table 2). Of the remaining 7 cross-sectional studies, 2 reported mixed findings[38,41]. Three studies reported that later bedtime was associated with more behavioural problems[40], depressive symptoms[36,39] and anxiety[39]. Compared to a bedtime at approximately 22:00 or earlier, bedtime between 22:30 and 23:00 was associated with lower depression symptoms among adolescents, while bedtime at 23:00 or later was associated with higher depression symptoms, anxiety or nervousness, feeling irritated and having tantrums[37]. Wang and colleagues[42] reported that in Grade 12 adolescents, an earlier wake-up time was associated with less academic stress.

TABLE 4
High-level summary of findings and effect for the association between sleep timing and health outcomes in apparently healthy children and adolescents, by health outcome and study design

Health outcome	No. and type of studies / No. of participants / age range	Summary of findings
Critical health outcome		
Adiposity	3 longitudinal 7756 4–18 years	1 study reported a longitudinal association between later bedtime during adolescence and higher BMI z-score later in adolescence and adulthood 1 study reported a longitudinal association between reoccurring late bedtime over multiple timepoints and higher BMI z-score and waist circumference in children 1 longitudinal study reported null findings
	17 cross-sectional 38 798 5–18 years	1 study reported that children and adolescents in the late-to-bed groups had higher BMI z-score than those in the early-bed/early-rise group 1 study found that children and adolescents in the late-to-bed groups had greater odds of overweight and obesity than those in the early-to-bed/early-to-rise group 1 study with mixed findings reported an association between later midpoint of sleep and greater waist-to-height ratio, but not BMI, in adolescents 1 study with mixed findings reported an association between later bedtime, but not wake-up time, and higher BMI z-scores in 5-year-old children 1 study with mixed findings reported an association between later weekend midpoint of sleep, but not weekday midpoint of sleep, and increased odds of higher BMI z-score in female (but not male) children and adolescents 1 study with mixed findings reported that children in the late-sleep group had higher fat mass percentage and waist circumference but not higher BMI z-scores or the sum of the skinfolds 1 study with mixed findings reported an association between later weekday, not weekend, bedtime and greater adiposity in children with obesity 10 studies reported null findings
Emotional regulation	2 longitudinal 6331 4–18 years	1 study reported a longitudinal association between reoccurring late bedtime over multiple timepoints and higher behavioural problems in children 1 study with mixed findings reported a longitudinal association, between both late school-year and summertime bedtime, but not at all time points, and higher odds of emotional distress 6–8 years later in late adolescence or early adulthood
	7 cross-sectional 106 225 7–20 years	1 study in children reported an association between bedtime after 22:00 and increased odds of higher depressive symptoms 1 study in adolescents reported that, compared to a bedtime at ~22:00 or earlier, bedtime between ~22:30 and before 23:00 is associated with better depression score, while bedtime at ~23:00 or later is associated with worse depression scores, greater odds of having anxiety or nervousness, and greater odds of being irritated and having tantrums 1 study in adolescents reported an association between later bedtime and higher depressed mood and anxiety scores 1 study in adolescents with obesity reported an association between later bedtime and higher behavioural problems score 1 study in adolescents reported an association between later wake-up time and greater academic stress 1 study with mixed findings reported an association between later bedtime, but not wake-up time, and increased depression score in children and adolescents 1 study with mixed findings reported an association between later midpoint of sleep and psychiatric problems, including more thought problems, more rule-breaking behaviour, more affective problems and more conduct problems, but not with a majority of the scales, in adolescents

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TABLE 4 (continued)
High-level summary of findings and effect for the association between sleep timing and health outcomes in apparently healthy children and adolescents, by health outcome and study design

Health outcome	No. and type of studies / No. of participants / age range	Summary of findings
Cognitive function and academic performance	2 longitudinal 6331 4–18 years	1 study with mixed findings reported a longitudinal association between later school-year bedtime, but not summertime bedtime, and lower grades in adolescents 1 longitudinal study reported null findings
	5 cross-sectional 123 372 7–20 years	1 study in adolescents reported an association between bedtimes before 22:00 or after 00:00 with increased odds of lower grades relative to bedtime between 22:00 and 22:59 1 study in adolescents reported an association between bedtime at ~22:30 or later and increased odds of trouble with following class education, completing homework assignments, preparing for examinations, and writing tasks, while bedtime at ~23:00 or later is also associated with increased odds of having trouble with reading tasks 1 study with mixed findings reported a significant association between later bedtime, but not waketime, and lower college entrance exam scores, in adolescents 2 studies reported null findings
Quality of life and well-being	1 longitudinal 3631 4–9 years	1 study reported a longitudinal association between reoccurring late bedtime over multiple timepoints and poorer psychosocial and physical health functioning in children
	1 cross-sectional 6266 9–11 years	1 study reported null findings
Accidents / injuries	1 cross-sectional 103 859 14–20 years	1 study with mixed findings reported associations between bedtime at ~23:00 (relative to bedtime at ~22:00 or earlier) and lower odds of having an accident at recess, in the classroom, and on the way to school in adolescents. No association was found between bedtime and accidents during gym class
Important health outcome		
Biomarkers of cardiometabolic risk	7 cross-sectional 3089 8–19 years	1 study with mixed findings reported that, in children and adolescent boys and girls, later midpoint of sleep on weekends, but not on weekdays, is associated with higher insulin resistance. In girls, each hour increase in weekday and weekend midpoint of sleep represented a significant increase in insulin resistance 1 study with mixed findings reported that, in children, a bedtime before 22:30 is associated with better triglyceride/high-density lipoprotein cholesterol ratio compared to a bedtime later than 23:15. No significant association was found between bedtime category and blood insulin level nor mean arterial pressure 1 study with mixed findings reported that, in children, later midpoint of sleep is associated with lower diastolic blood pressure, but no significant associations were found between midpoint of sleep and systolic blood pressure, apolipoprotein B/A1 or glycoprotein acetyls 1 study with mixed findings reported that, in children and adolescents, later bedtime is associated with higher systolic blood pressure z-score, but that there were no associations between bedtime and insulin resistance, triglycerides z-score, high-density lipoprotein-C z-score, low-density lipoprotein-C or diastolic blood pressure z-score 1 study with mixed findings reported a significant association between an earlier bedtime and better fasting insulin resistance but not with the Matsuda Index in adolescents with overweight or obesity 2 studies reported null findings

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TABLE 4 (continued)
High-level summary of findings and effect for the association between sleep timing and health outcomes in apparently healthy children and adolescents, by health outcome and study design

Health outcome	No. and type of studies / No. of participants / age range	Summary of findings
Sleep duration and quality	1 longitudinal 783 6–10 years	1 longitudinal study reported null findings
	10 cross-sectional 112 043 5–20 years	1 study in children reported an association between earlier sleep onset and later offset with longer total sleep time 1 study in adolescents reported an association between a bedtime at ~22:30 or later and lower sleep quality, relative to a bedtime at ~22:00 or earlier 1 study in children and adolescents reported an association between later bedtime and lower sleep duration 2 studies in children reported a significant association between later bedtime and less total sleep time 1 study in adolescents reported significant associations between later bedtime and less total sleep time and more reports of unrefreshing sleep 1 study in children reported an association between later midpoint of sleep and less total sleep duration 1 study with mixed findings reported associations between earlier midpoint of sleep during both school and weekend nights and better sleep quality, but not sleep duration, in children and adolescents 2 studies reported null findings
Eating behaviour	13 cross-sectional 42 138 5–18 years	1 study in children and adolescents reported an association between later weeknight bedtime with increased odds of missing breakfast and of frequent junk food consumption 1 study in children reported associations between later bedtime and less healthy and more unhealthy diet patterns 1 study in children reported associations between later midpoint of sleep on weekdays and weekend and an increased cumulative number of self-reported eating risk factors 1 study with mixed findings reported associations between later bedtime and sleep onset and higher restrained eating score, but no other significant associations between sleep timing and all other eating behaviours, in children 1 study with mixed findings reported associations between later bedtime and greater frequency of cola and soft drinks consumption, and between earlier bedtime and greater frequency of energy and sports drink consumption, in children 1 study with mixed findings reported associations between children in the late-sleep/late-wake group, compared to children in the early-sleep/early-wake group, and lower fruits and vegetables dietary score, lower weekly frequency of consumption of fruits and vegetables and higher weekly frequency of consumption of sugar-sweetened beverages, but the sleep-timing groups were not associated with snacking patterns or extra consumption 1 study with mixed findings reported associations between the 2 late-to-bed groups, compared to the early-to-bed/early-to-wake group, and lower total dietary score but not energy intake, in children and adolescents 1 study with mixed findings reported associations between later bedtime and higher daily fat intake, lower daily carbohydrate intake, greater caloric intake after dinner and later timing of breakfast and dinner, but no associations with daily total caloric intake or protein intake, in children 1 study with mixed findings reported associations between later midpoint of sleep and higher sustained probability of consuming sweet and caffeinated beverages and sugary, salty and fatty foods, from the afternoon onwards, but no associations with the probability of consuming vegetables, proteins, fruits or carbohydrates, in children and adolescents 4 studies reported null findings

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TABLE 4 (continued)
High-level summary of findings and effect for the association between sleep timing and health outcomes in apparently healthy children and adolescents, by health outcome and study design

Health outcome	No. and type of studies / No. of participants / age range	Summary of findings
PA and sedentary behaviour	1 longitudinal 1059 7–12 years	1 study in children reported a longitudinal association between an incremental increase in sleep onset and less time spent in PA at all intensities and more time spent in sedentary behaviour the following day
	15 cross-sectional 14 642 5–18 years	1 study in children reported that later bedtime is associated with less time spent in MVPA and more time spent being sedentary and having more screen time 1 study in children reported that, at 5 years old, later bedtime is associated with more sedentary time and more LPA, but at 7 years old, it is also associated with more MVPA 1 study in children and adolescents reported numerous associations between later midpoint of sleep and more screen time across most devices on both week and weekend days 1 study in children reported an association between later sleep onset and less MVPA 1 study in children and adolescents reported associations between the late-to-bed sleep groups, compared to the early-to-bed/early-to-wake group, and lower odds of PA and higher odds of sedentary behaviours 1 study with mixed findings reported an association between later midpoint of sleep and more screen time, but not with time spent in MVPA or sedentary time, in children and adolescents with obesity 1 study with mixed findings reported associations between children in the late-to-wake sleep groups, compared to children in the early-to-bed/early-to-wake group, and less time spent being active but not with meeting the screen-time guidelines 1 study with mixed findings reported associations between later midpoint of sleep at 12 years old and lower amounts of PA overall, of LPA and of MVPA and more sedentary behaviour, but no associations were found at 17 years old 1 study with mixed findings reported associations between children's later midpoint of sleep, earlier bedtime and later wake-up time and less time spent in LPA, but not with higher intensities of PA. Later midpoint of sleep and later wake-up time, but not bedtime, are also associated with more time spent being sedentary 1 study with mixed findings reported an association between later weekday bedtime, but not wake-up time, with more screen time, but not with MVPA, in children 5 studies reported null findings

Abbreviations: BMI, body mass index; LPA, light physical activity; MVPA, moderate-to-vigorous physical activity; PA, physical activity.

The quality of evidence for the 2 longitudinal studies and the remaining 7 cross-sectional studies investigating the association between sleep timing and emotional regulation was downgraded from low to very low due to serious risk of bias.

Cognitive function and academic achievement

Of the 7 studies reporting on cognitive function/academic performance in children and adolescents 4 to 20 years old, 2 were longitudinal and 5 were cross-sectional. One longitudinal study reported null findings between sleep timing and cognitive performance[16], while the other reported mixed findings, with only school-year bedtime across the timepoints associated with academic performance[35]. Of the 5 cross-sectional studies, 2 studies reported null findings[41,44], 1 study reported mixed findings[42] and 2 studies reported significant associations[37,43]. In a large sample of older adolescents aged 14 to 20 years, compared to a bedtime between 22:00 and 22:59, bedtimes before 22:00 or after 00:00 were associated with increased odds of poor academic performance[37]. Among adolescents aged 16 to 19 years, compared to a bedtime at 22:00 or earlier, later bedtimes were associated with difficulties following in class, completing homework assignments, preparing for exams and with writing and reading tasks[43].

The quality of evidence was downgraded from low to very low due to serious risk of bias and inconsistency in the findings for the 2 longitudinal studies and due to serious risk of bias for the 5 cross-sectional studies.

Quality of life and well-being

Two studies, one longitudinal and the other cross-sectional, reported on the association between sleep timing and quality of life and well-being. Longitudinal findings revealed that reoccurring late bedtime over multiple timepoints was associated with lower psychosocial and physical health functioning in children aged 4 to 9 years[16]. The cross-sectional study, in children aged 9 to 11 years, reported null findings for the overall association between midpoint of sleep and health-related quality of life[45].

The quality of evidence for both studies was downgraded from low to very low, due to serious risk of imprecision for the longitudinal study and for the cross-sectional study.

Accidents/injuries

A single cross-sectional study reported on the association between sleep timing and accidents/injuries. A bedtime at approximately 23:00 for adolescents was associated with the lowest odds of having an accident at recess, in the classroom and on the way to school, relative to a bedtime at 22:00 or earlier; however, no association was reported between sleep timing and accidents during gym class[37].

The quality of evidence was downgraded from low to very low due to serious risk of bias and imprecision.

Biomarkers of cardiometabolic risk

Seven cross-sectional studies examined the association between sleep timing and biomarkers of cardiometabolic risk (e.g. insulin, lipid profile, blood pressure) in children and adolescents between 8 and 19 years old. Out of these 7 studies, 2 reported null findings[30,33] and 5 reported mixed findings[27-29,46,47].

The quality of the evidence for the 7 cross-sectional studies was downgraded from low to very low due to inconsistency in the findings.

Sleep duration and quality

Initially, 12 studies were extracted for the sleep duration and quality health outcome; however, to avoid inflating the results in this outcome, one of the studies by Short and colleagues[39] was removed because the authors published twice on the same outcome measurement and using the same sample and statistical analysis. The study by Short et al.[49] had the highest number of measurements within the sleep duration and quality health outcome and was therefore retained (see Supplementary Table 3 https://osf.io/nzt23/?view_only=abcbea551fe545e6b73f44e60600da35).

A total of 11 observational studies, 1 longitudinal and 10 cross-sectional, examined the association between sleep timing and sleep duration and quality. The longitudinal study reported null findings between sleep timing and sleep duration in children[17]. Of the 10 cross-sectional studies in children and adolescents 5 to 20 years old, 5 studies reported that later bedtime, wake-up time or midpoint of sleep were associated with significantly shorter total sleep time[20,23,25,31,50]; 1 reported that later bedtime was associated with shorter total sleep time as well as lower quality of sleep[49]; 1 reported that later bedtime was associated with more sleep quality problems[37]; 1 reported mixed findings with a significant association between later midpoint of sleep and lower sleep quality, but no association between midpoint of sleep and sleep duration[48]; and 2 reported null findings between sleep timing and sleep duration[15,51].

The quality of evidence for the longitudinal study was downgraded from low to very low due to imprecision in the findings. The quality of the evidence for the cross-sectional studies was downgraded from low to very low due to serious risk of bias.

Eating behaviours

A total of 13 cross-sectional studies examined the association between sleep timing and eating behaviours in children and adolescents between 5 and 18 years old. Of these 13 studies, 4 reported null findings[15,24,29,56]; 6 reported mixed findings[18,26,31,51,53,55]; and 3 reported significant associations[23,52,54]. In children and adolescents aged 9 to 17 years, later bedtime was associated with greater consumption of junk food and missing breakfast more often[52]. Later bedtime was also associated with a higher amount of unhealthy food consumption and a lower amount of healthy food consumption in children aged 9 to 11 years[54]. In children aged 6 to 10 years, a later midpoint of sleep was associated with a higher eating risk factor score[23].

The quality of evidence for the studies with the eating behaviour health outcome was downgraded from low to very low due to serious risk of bias.

Physical activity and sedentary behaviour

A total of 16 observational studies, including 1 longitudinal and 15 cross-sectional studies, examined the association between sleep timing and physical activity and sedentary behaviour. Antczak and colleagues'[57] longitudinal findings showed that later bedtime in children was associated with significantly higher sedentary time and lower amount of physical activity at all intensities. Of the 15 cross-sectional studies, 5 reported null findings[15,23,25,31,60]; 5 reported mixed findings[24,26,32,56,59]; and 5 reported significant associations between sleep timing and physical activity and sedentary behaviour[20,48,50,54,58]. Two studies in children and adolescents reported that later bedtime was significantly associated with less moderate-to-vigorous physical activity and more sedentary behaviours including screen time[20,54]. A study that measured bedtime and physical activity and sedentary behaviour at two different time points reported that later bedtime was associated with more sedentary time and more light physical activity at age 5 years; at age 7 years, later bedtime was also associated with more sedentary time and more light physical activity but also with more moderate-to-vigorous physical activity[50]. One study showed that later weekday and weekend midpoint of sleep was associated with more screen time across multiple devices in children and adolescents[48]. In children, 2 studies reported that later bedtime and sleep onset, independent of sleep duration or wake-up time, were associated with less physical activity[58].

The quality of evidence was downgraded from low to very low due to imprecision for the longitudinal study and due to serious risk of bias for the cross-sectional studies.

Discussion

Many characteristics of sleep are important for good health. We conducted the present systematic review to improve understanding of the association between sleep timing and health in a population of children and adolescents. Our objectives were to update the knowledge for the sleep recommendations in the *Canadian 24-Hour Movement Guidelines for Children and Youth*[5] and to provide evidence that can be used to better inform the development of future evidence-based healthy sleep interventions.

This systematic review synthesized peer-reviewed scientific evidence from 46 observational studies, including 5 longitudinal and 41 cross-sectional studies, across 21 countries. Overall, the findings suggest that later sleep timing may be associated with poorer emotional regulation, cognitive function/academic performance, eating behaviours, lower sleep duration and quality, and lower physical activity and higher sedentary behaviours. The findings were sparse or less consistent for the associations between sleep timing and adiposity, quality of life/well-being, accidents/injuries and cardiometabolic risk. The quality of the evidence was rated as very low according to GRADE for all outcomes.

The majority of studies that examined the critical outcomes reported on adiposity (n = 20), while studies on accidents/injuries (n = 1) and quality of life/well-being (n = 2) were underrepresented. Studies reporting on the important health outcomes were more evenly spread with 16 studies reporting on the physical activity and sedentary behaviour outcome, 13 on eating behaviour, 11 on sleep duration/quality and 7 on cardiometabolic risk (Table 3).

The evidence presented for the association between sleep timing and adiposity is inconsistent, as more than half of the studies reported null findings (n = 11), which mirrors findings from a recently published systematic review by Chaput et al. in adults[61]. Another finding in both this review and Chaput et al.'s[61] systematic review was that later sleep timing was associated with lower physical activity and higher sedentary behaviour. In addition, both these systematic reviews identified a lack of studies investigating the association between sleep timing and accidents/injuries or quality of life/well-being in their respective populations.

The findings between the two systematic reviews differed for some outcomes. Our current findings indicate that later sleep timing was generally associated with poorer emotional regulation and cognitive function/academic performance in children and adolescents, whereas in adults the associations for mental health and cognitive function were inconsistent[61]. In children and adolescents, more studies are needed to confirm these associations (especially longitudinal studies and randomized trials), including the mechanisms behind them.

Some of the health outcomes we considered in this systematic review differed from those chosen for the adult population[61]. For example, we reviewed the association between sleep timing and eating behaviour in this paper. In children and adolescents, later sleep timing was associated with poorer eating behaviours; this is of concern given that eating behaviours are also independently associated with health outcomes[62]. In addition, as children and adolescents do not always have full control over their eating behaviours, investigating the moderating effect of socioeconomic status, parental figure influence and family structure in the association between sleep timing and eating behaviours of children and adolescents is essential.

In the articles included in this present review, sleep timing was mainly assessed using bedtime, wake-up time, midpoint of sleep or a combination of dichotomized bedtime and wake-up times divided into four different sleep-timing groups. None of these measurements of sleep timing account for sleep duration; in fact, very few studies adequately controlled for sleep duration in their analyses. Controlling for sleep duration is important given the well-established associations between short sleep duration and higher adiposity, lower emotional regulation, lower academic achievement, lower quality of life/well-being[2], lower cognitive performance[63] and altered brain functions and structures[64].

Not surprisingly, one of the most consistent findings in the present systematic review is the association between later sleep timing and shorter sleep duration (given that school start times are fixed). In addition to controlling for sleep duration in observational studies, this research area requires intervention studies that modify sleep timing. Our systematic review did not identify even a single intervention study that focussed on sleep timing. Future intervention studies should try to manipulate sleep timing while maintaining a constant sleep duration (e.g. sleep duration of 8 hours in adolescents, with one group sleeping from 22:00 to 6:00 and the other from 00:00 to 8:00) to understand the effects of sleep timing, independent of sleep duration, on health outcomes.

Strengths and limitations

Our findings should be interpreted in light of the following limitations. The low number of studies and their heterogeneity made comparisons problematic and meta-analyses ill-advised for all health outcomes. Opting for a narrative synthesis prevents adequate weighting of the included studies. In addition, we could not assess publication bias, which is a pervasive problem in the reporting of scientific findings. However, choosing to only include studies published in the last 10 years could have somewhat mitigated that risk, as many more journals have published null findings more frequently in recent years.

A strength of this review is our comprehensive search strategy. However, the studies selected for this review were not without limitations; the quality of evidence included was rated as very low according to GRADE, even considering that GRADE defaults all study designs other than randomized trials to "low quality." The contributing factors for the quality of evidence included study design (mainly cross-sectional studies), serious risk of bias, imprecision and inconsistency. In addition, only a few of the included studies adequately controlled for sleep duration, which makes it difficult to interpret the findings. A large proportion of the included studies relied on a small sample size or used statistical analyses (e.g. correlations) that prevented controlling for important covariates. Almost half of the studies (n = 22) used a subjective assessment for sleep timing, with many using a single question or a questionnaire with unknown psychometric properties. Although this means that more than half of the studies (n = 24) used an objective measure of sleep timing, the number of nights recorded differed greatly across studies.

Conclusion

The evidence suggests that later sleep timing may be associated with poorer health outcomes in children and adolescents, namely emotional regulation, cognitive function/academic performance, sleep duration/quality, eating behaviours and physical activity and sedentary behaviours. However, the findings have predominantly been generated from cross-sectional evidence and studies with stronger designs are needed to investigate the association between sleep timing and health outcomes independent of sleep duration in the pediatric population.

No bedtime recommendation can be proposed based on the available evidence as the evidence presented was modest and the findings reported mostly linear associations. Nevertheless, having an early enough bedtime that allows children and adolescents to meet sleep duration recommendations would be a sensible public health recommendation based on the current findings and the body of evidence that links short sleep duration to adverse health outcomes.

Registration of the protocol

PROSPERO registration no. CRD42020173585; available from www.crd.york.ac.uk/PROSPERO/). No amendment was made to the protocol or information that was provided at registration.

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Conflicts of interests

No competing interests are declared by the authors.

Authors' contributions and statement

CD, CMS, BGC and JPC screened the papers.

CD and IP extracted the data and performed the quality assessment.

CD drafted the final version of the manuscript under the guidance of JPC.

All authors were involved in the study conception and reviewed and approved the final version of this article for publication.

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Commentary

Timing of 24-hour movement behaviours: implications for practice, policy and research

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Introduction

Physical activity, sedentary behaviour and sleep cannot be considered in isolation given their co-dependence: their integration within the 24-hour day has important health implications[1-3]. This paradigm shift to an integrated approach to movement behaviours has led to the Canadian Society for Exercise Physiology (CSEP) developing and releasing the world's first 24-hour movement guidelines (24HMGs) for all ages[4-7]. The 24HMGs are evidence-based recommendations for optimal levels of physical activity, sedentary behaviour and sleep according to age group: infants, toddlers and preschoolers (0–4 years)[5]; children and youth (5–17 years)[4]; and adults (18–64 years and 65 + years)[6]. The guidelines emphasize that the integration of these behaviours over a 24-hour period is important for health benefits, that is, "the whole day matters" for health.

With recent, focussed efforts to disseminate the 24HMGs in Canada,[8,9] the concept of "the whole day matters" is gaining traction. The tagline accompanying the guidelines—"Move more. Reduce sedentary time. Sleep well"—has simplified the recommendations into a single, generic message to help foster Canadians' confidence to meet the 24HMG recommendations[8,10].

While the 24HMGs (and tagline) offer guidance on *what* to do, the public, practitioners, policy makers and researchers have asked for advice about *how* to do it, including optimal timing for movement behaviours. In other words, should physical activity be done in the morning, afternoon or evening? Should recreational screen time be avoided before bed? Does it matter what time a person goes to bed if they get sufficient sleep?

Researchers recently synthesized the literature examining the health outcomes associated with the timing of movement behaviours[11-13]. The main findings of the systematic reviews in this special issue of the journal indicate that, for health benefits, Canadians need to:

- move when it suits them[11];
- remove screens from bedrooms and limit screen use prior to bedtime[12]; and
- adjust bedtime so that they can sleep the recommended amount[13].

This commentary aims to:

- offer evidence-informed advice for practice, policy and research regarding the optimal timing of movement behaviours across a number of settings; and
- draw attention to existing and new promotional materials for the 24HMGs that advise Canadians on *how* they can make their "whole day matter."

Highlights

- For health benefits, Canadians need to:
  - move when it suits them;
  - remove screens from bedrooms and limit screen use prior to bedtime; and
  - adjust bedtime so that they can sleep the recommended amount.
- The 24-Hour Movement Guidelines Communication Toolkit has resources that can be used across settings to help Canadians optimize movement behaviours throughout the day.

Keywords: *physical activity, sedentary behaviour, sleep, timing, knowledge translation, public health, 24-Hour Movement Guidelines*

Advice for practice, policy and research

Readers can refer to the CSEP (csepguidelines.ca) and ParticipACTION websites (ParticipACTION.com) for recommendations on physical activity, sedentary behaviour and sleep by age group. Given that 24HMGs exist for all age groups, it is impossible to develop an exhaustive list of end users or settings where the review findings could be applied. Instead, we

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have organized potential end users according to the settings in which they could consider the timing of movement behaviours[14,15]. We include advice for practice, policy and/or research where applicable to a given setting. The advice can be applied across the life course as studies exist to support findings across all ages[16] and the information is beneficial to Canadians' health regardless of age.

Household settings

A household encompasses a person living alone or a group of people living in the same dwelling, be it a family, several families or unrelated individuals of all ages[15]. End users in the household setting include infants, children, youth and adults. This setting is important to movement behaviour timing because this is where Canadians generally sleep and where movement behaviour habits are formed and perpetuated[15].

The 24HMGs specify that moderate-to-vigorous physical activity, as well as light physical activity, of sufficient duration (according to age group) are critical for health benefits. Given that physical activity is equally beneficial whether it is done in the morning, afternoon or evening,[11] choosing when to be active should be up to the individual as long as they maintain healthy sleep behaviours. This means that if you get up early to exercise because that is when it easiest for you to be active, you should go to bed early so that you get enough sleep.

The 24HMGs recommend daily limits for screen time that differ by age. Removing screen-based devices from bedrooms and eliminating screen time (i.e. scrolling through social media, watching TV or movies) prior to bed are strategies to optimize sleep duration and quality. While Saunders and colleagues[12] indicate that there is insufficient evidence to suggest a threshold for how much time we should have without screens before bed, the American Academy of Pediatrics[17] and the Canadian Pediatric Society[18] recommend avoiding screens for at least one hour before bed.

The 24HMGs also recommend uninterrupted sleep of sufficient duration (according to age) with consistent waking and bedtimes across the week. Later sleep timing (i.e. going to sleep at a later time) is associated with adverse health outcomes for children and youth[11] as well as adults[16]. Given that many people's school and work start times are fixed, early sleep times throughout the entire week (vs. variations between weekend and school/work week) are ideal.

Education settings

Education settings include schools and school-boards with childcare, elementary, secondary and postsecondary divisions. Education settings reach a large proportion of the Canadian population—infants, toddlers, preschoolers, young children, youth and young adults—and indirectly reach others—siblings, parents, grandparents, caregivers, teachers, administrators, etc.

In-class education settings can adjust how they operate to enable physical activity and limit screen use throughout the day as well as encourage earlier bedtimes. Presenting opportunities for and encouraging light physical activity (i.e. standing, active sitting/seated movement, breaks for stretching) and/or bursts of moderate-to-vigorous physical activity can foster a culture where students move more. Students will experience the immediate benefits of physical activity on their ability to focus[19] and learn to identify when their body prefers to move.

At the elementary and secondary levels, teachers should consider the volume, frequency and modality (e.g. paper-based vs. screen-based)[20] of homework to help students get to bed early enough and limit screen exposure near bedtime. Postsecondary instructors may choose to adjust the due times for assignments to during the day or early evening; the authors' experience is that this strategy successfully helps students avoid staying up late to submit assignments and use screens close to bedtime.

One policy lever to create a culture of healthy movement behaviours is through curriculum design and implementation. Specifically, we need to embed into all curricula an awareness of the importance of 24-hour movement behaviours as well as advice on "how to" apply the 24HMGs to lifestyles. The 24HMGs need to be reiterated at multiple points, in a similar way to how *Canada's Food Guide*[21] is integrated into childcare, elementary, secondary and postsecondary curricula. Also required is training and professional development to foster expertise among educators and enable the implementation of these new aspects of the curriculum as well as teachable moments.

A second policy lever is reconsideration of school hours. For example, delaying start times of secondary schools would help improve sleep duration among youth[22]; further research is required to determine how long to delay school start times.

Both policy levers require the action of administrators and policymakers who are responsible for system-level adjustments for what, how and when students learn.

Workplace settings

Workplace settings include all the organizations that employ Canadians—which amounts to a substantial proportion of the population. Workplaces can strive to ensure that their mandates, strategic plans, operating practices and external messages encourage employees and others to optimize movement behaviours.

Enacting an organizational policy to foster a culture that encourages physical activity (i.e. movement breaks) throughout the day and promotes less screen use in the evening (e.g. not expecting responses to email or work to be done in the evening) would support the implementation of findings published in this special issue of the journal. Some workplaces may also be able to enact a flexible work policy to help promote the preservation of sleep duration and consistency for employees and their household.

Settings with health and exercise professionals

Canadians consider health professionals—nurses, physicians, dietitians, physiotherapists, etc.—as experts and credible sources of information on movement behaviour[23]. Qualified exercise professionals (including CSEP Certified Personal Trainers, CSEP Clinical Exercise Physiologists and kinesiologists) are trained to educate and counsel the public about healthy lifestyles including physical activity, sedentary behaviours and sleep. Through their interactions with patients/clients and caregivers, professionals in this setting offer trusted information for healthy movement across the life course.

The findings about the optimal timing of movement behaviours may support conversations about lifestyles that health professionals have with patients/clients. The advice in this commentary can be given as practical tips and answers to commonly asked questions. We need changes to training curricula, additional professional development opportunities and tools so that practitioners are knowledgeable and can confidently discuss movement behaviours (including optimal timing of behaviours).

Community service settings

Community service settings include staff, coaches, instructors and administrators at physical activity, child/youth services and community organizations that offer programs and services to Canadians of all ages (e.g. after-school programs, arts and recreation programs, national and provincial sport organizations, local community centres). Encouraging optimal movement behaviour timing is important in these settings as their mandates generally focus on promoting the health and well-being of the individuals they serve.

Options to exercise need to be available at various times to make it easier for individuals to be physically active when it suits them. Practices or programs, particularly those for children and youth, should not be at times that interfere with their ability to get optimal sleep duration, consistency and timing. If early morning programming is unavoidable (e.g. access to pools or ice rinks), coaches/instructors need to encourage earlier bedtimes to balance the gains from physical activity against the threats of interrupted sleep among participants.

Note that there is some interdependence between this setting and the education setting, and delaying school start times would impact potential start times of programs. Policy changes to support optimal timing of movement behaviours among children and youth needs to be coordinated across these two settings—ideally in consultation with the household setting to ensure parent/guardian support for changes.

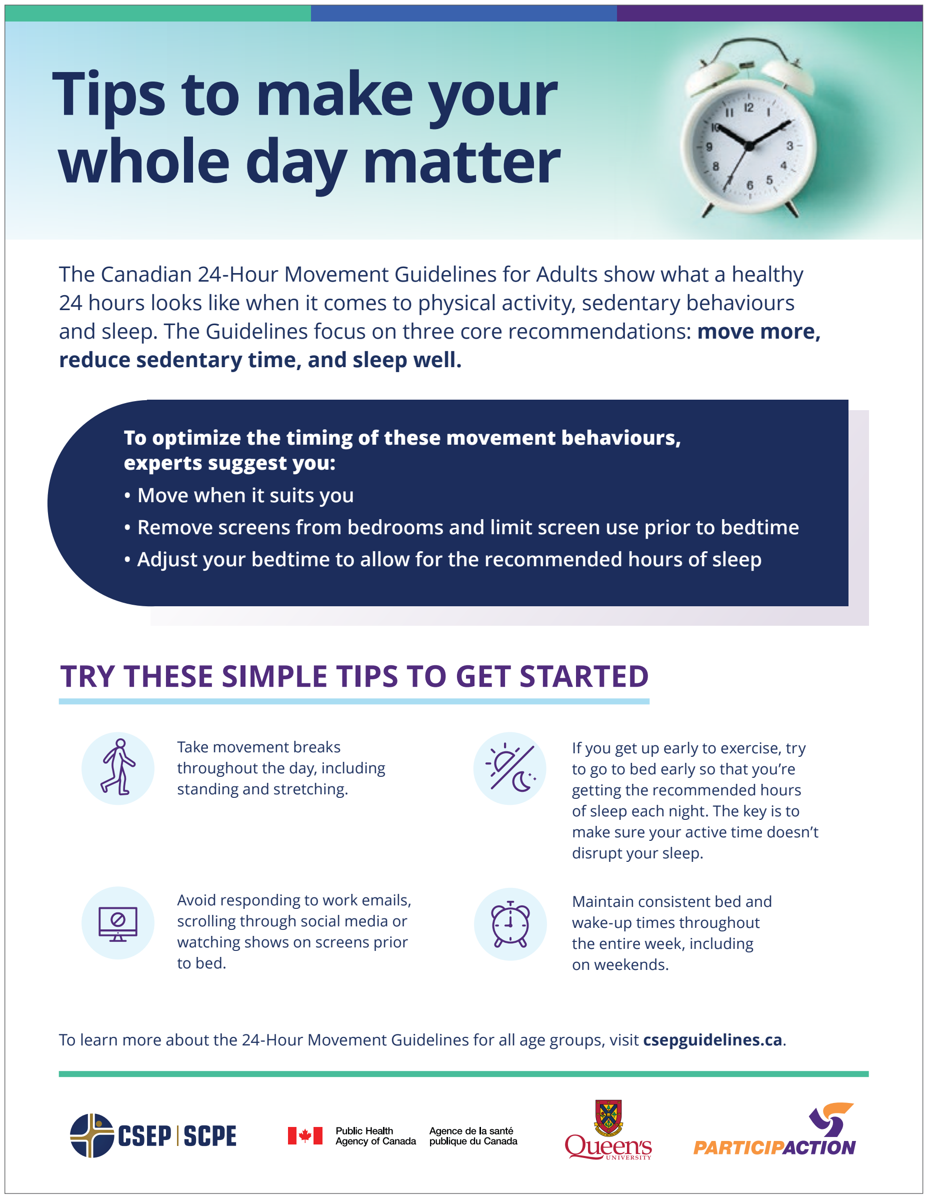
Settings that endorse or study movement, health and well-being

These settings include governmental and nongovernmental organizations, intermediary groups and workplaces that communicate health information to members of the general public (e.g. ParticipACTION, Canadian Public Health Association, PHE Canada, Lifeworks) or fund health research initiatives (e.g. Canadian Institutes of Health Research, Public Health Agency of Canada, Heart and Stroke Foundation). These settings have substantial reach, are seen as credible sources of health information and have a role to play in communicating and integrating the advice we present here into their practices.

Organizations that provide health funding can prioritize the research gaps identified in the systematic reviews published in this issue. Specifically, there is a need for high quality randomized intervention studies with larger sample sizes[11-13] that examine the chronic impact of changing behaviour timing on health outcomes[12]. Of note, while Janssen et al.[11] identified that there are no health implications based on the time of day that physical activity is performed, motivation to engage in physical activity may waiver throughout the day (e.g. people who plan to be active in the morning are more likely to carry through with their goal[24]). Additional research exploring the psychological antecedents of the timing of all three movement behaviours is warranted.

Several organizations in this category are involved in the surveillance of Canadians'

FIGURE 1
"Tips to make your whole day matter" poster



movement behaviours. Changes to surveillance measures are not required as a result of the new evidence presented in this special issue of the journal. However, current surveillance must be maintained to evaluate ongoing efforts to promote the "whole day matters" in the described settings.

24HMG promotional materials on how Canadians can make their "whole day matter"

The novel findings in this special issue complement the suite of Canadian 24HMGs[4-6] by providing evidence for optimizing the timing of movement behaviours with additional tips on how to implement the guidelines.

To assist with the dissemination of the review findings and the advice outlined in this commentary, the CSEP has developed a poster, *Tips to make your whole day matter*, highlighting key advice about optimal timing of movement behaviours for better health outcomes (see Figure 1). All 24HMG promotional materials, including this poster, are available in the 24-Hour Movement Guidelines Communications Toolkit on the CSEP (https://csepguidelines.ca/) and ParticipACTION (https://www.participaction.com/) websites.

Conclusion

The three systematic reviews in this special issue of the journal synthesized evidence about optimal timing of movement behaviours. The findings will have implications for how Canadians think about and engage in physical activity, sedentary behaviour and sleep throughout the 24-hour period. We have made suggestions and produced resources to help Canadians implement the review findings, and the 24HMGs, in their daily lives, across settings. It is critical that public health practitioners, policy makers and researchers heed the advice in a unified effort to help Canadians make their whole day matter.

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Conflicts of interest

TJS has received honorariums for public speaking on the relationship between sedentary behaviour, physical activity and health among children and youth. SMF received personal fees from the Canadian Society for Exercise Physiology during the development of this commentary.

Authors' contributions and statement

All authors conceptualized the ideas presented, contributed to figure development, provided a critical review of the commentary, and approved the final manuscript for submission.

JRT, IJ, TS and JPC contributed to the writing of this commentary.

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